Prefrontal cortical activation measured by fNIRS during walking: effects of age, disease and secondary task

Paulo H S Pelicioni, Mylou Tijmsa, Stephen R Lord, Jasmine Menant

1 Falls, Balance and Injury Research Centre, Neuroscience Research Australia, Sydney, NSW, Australia
2 School of Public Health and Community Medicine, University of New South Wales, Sydney, NSW, Australia
3 Catharina Hospital, Eindhoven, Netherlands

Corresponding Author: Jasmine Menant
Email address: j.menant@neura.edu.au

Background. Cognitive processes are required during walking to appropriately respond to environmental and task demands. There are now many studies that have used functional Near-Infrared Spectroscopy (fNIRS) to record brain activation to investigate neural bases of cognitive contributions in gait. The aim of this systematic review was to summarize the published research regarding Prefrontal cortical (PFC) activation patterns during simple and complex walking tasks in young adults, older adults and clinical groups with balance disorders using fNIRS. Our secondary aim was to evaluate each included study based on methodological reporting criteria important for good data quality. Methods. We conducted searches in June 2018 using four databases: Embase, PubMed, Scopus and PsycINFO. The strategy search used was: (((((near infrared spectroscopy) OR functional near infrared spectroscopy) OR fnirs) OR fnirs) AND (((gait) OR walking) OR locomotion) AND (((((young) OR adult) OR older) OR elderly) NOT children)) AND (((Brain) OR cortex) OR cortical) for our search. The papers included met the specific review criteria: (i) used fNIRS to measure PFC activation patterns; (ii) included walking tasks (simple and complex) and; (iii) assessed young people, older people and/or clinical groups with balance disorders. Results. Thirty five (describing 75 brain activation comparisons) of the 308 studies retrieved through our search met the inclusion criteria. Based on 6 methodological reporting considerations, 20 were of high quality, 10 were of medium quality and 5 were of low quality. Eleven/20 comparisons in young people, 23/37 comparisons in older people and 15/18 comparisons in clinical groups reported increased PFC activation with increased walking task complexity. The majority of comparisons that used verbal fluency, counting backwards or secondary motor tasks reported increases in PFC activation (83%, 64% and 58% of these studies, respectively). In contrast, no studies found secondary visual tasks increased PFC activation. Conclusion. Increased PFC activation was most common in studies that involved walks comprising secondary verbal fluency and arithmetic tasks. Clinical groups generally showed increased PFC activation irrespective of type of secondary task performed during walking which suggests these groups require more attentional resources for safe walking. Systematic review registration number: PROSPERO 2017 - CRD42017059501.
Prefrontal cortical activation measured by fNIRS during walking: effects of age, disease and secondary tasks

Paulo Henrique Silva Pelicioni¹,², Mylou Tijsma², Stephen Ronald Lord¹,², Jasmine Menant¹,²

¹Neuroscience Research Australia, University of New South Wales, New South Wales, Australia
²School of Public Health and Community and Medicine, University of New South Wales, New South Wales, Australia
³Catharina Hospital, Eindhoven, Netherlands

Corresponding Author:
Jasmine Menant¹,²
Neuroscience Research Australia, Margaret Ainsworth Building, 139 Barker Street, Sydney, NSW, 2031, Australia
Email address: j.menant@neura.edu.au
Abstract

Background. Cognitive processes are required during walking to appropriately respond to environmental and task demands. There are now many studies that have used functional Near-Infrared Spectroscopy (fNIRS) to record brain activation to investigate neural bases of cognitive contributions in gait. The aim of this systematic review was to summarize the published research regarding Prefrontal cortical (PFC) activation patterns during simple and complex walking tasks in young adults, older adults and clinical groups with balance disorders using fNIRS. Our secondary aim was to evaluate each included study based on methodological reporting criteria important for good data quality.

Methods. We conducted searches in June 2018 using four databases: Embase, PubMed, Scopus and PsycINFO. The strategy search used was: (((((near infrared spectroscopy) OR functional near infrared spectroscopy) OR nirs) OR fnirs) AND (((gait) OR walking) OR locomotion) AND (((young) OR adult) OR older) OR elderly) NOT children)) AND (((Brain) OR cortex) OR cortical) for our search. The papers included met the specific review criteria: (i) used fNIRS to measure PFC activation patterns; (ii) included walking tasks (simple and complex) and; (iii) assessed young people, older people and/or clinical groups with balance disorders.

Results. Thirty five (describing 75 brain activation comparisons) of the 308 studies retrieved through our search met the inclusion criteria. Based on 6 methodological reporting considerations, 20 were of high quality, 10 were of medium quality and 5 were of low quality. Eleven/20 comparisons in young people, 23/37 comparisons in older people and 15/18 comparisons in clinical groups reported increased PFC activation with increased walking task complexity. The majority of comparisons that used verbal fluency, counting backwards or secondary motor tasks reported increases in PFC activation (83%, 64% and 58% of these studies, respectively). In contrast, no studies found secondary visual tasks increased PFC activation.

Conclusion. Increased PFC activation was most common in studies that involved walks comprising secondary verbal fluency and arithmetic tasks. Clinical groups generally showed increased PFC activation irrespective of type of secondary task performed during walking which suggests these groups require more attentional resources for safe walking.

Systematic review registration number: PROSPERO 2017 - CRD42017059501.

Introduction

Walking relies heavily upon coordinated movement controlled by subcortical structures such as the Basal Ganglia (Takakusaki, Tomita and Yano, 2008). However, cognition is also important for locomotor tasks, particularly tasks that require attention and processing speed, such as multi-tasking and gait adaptability (Montero-Odasso et al., 2012; Caetano et al., 2017). Traditionally, the role of cognition has been assessed using dual-task paradigms (walking while performing a secondary cognitive task) which provide indications of the role of attention and executive function in the regulation of gait control (Montero-Odasso et al., 2012) and the negotiation of obstacles (Caetano et al., 2017, 2018). Impaired cognitive processing has been associated with
reduced gait speed and increased gait variability during complex gait (Killane et al., 2014; Hausdorff, 2005), however how higher level brain areas are activated during complex walking tasks is still unclear.

Functional near-infrared spectroscopy (fNIRS) is an optical neuroimaging technique for investigating cortical brain area activation while participants move freely. This technique is particularly useful for monitoring hemodynamic responses to brain activation (i.e. changes in oxygenated (oxyHB) and deoxygenated hemoglobin (deoxyHB)) in cortical regions before and after stimulation (i.e. resting followed by simple walking or simple walking followed by dual-task walking) (Leff et al., 2011).

Two overlapping theories have been posited for relative changes in cortical activity as measured with fNIRS. The first suggests reduced activity represents decreased use of a brain region and therefore increased efficiency (Lustig et al., 2009; Grady, 2012). The second suggests increased cortical activity is a compensatory mechanism and reflects over-recruitment and reduced efficiency (Cabeza et al., 2002; Reuter-Lorenz and Cappel, 2008; Grady, 2012).

Several reports of brain activation during walking using fNIRS have been published in the last decade. Activation of the Prefrontal Cortex (PFC) (easily accessible using fNIRS) has often been investigated during walking tasks (Leff et al., 2011). Brain motor areas investigated also include the Pre Motor Cortex (PMC), the Pre Supplementary Motor Area (preSMA), the Supplementary Motor Area (SMA) and the Sensory Motor Cortex (SMC) (Harada et al., 2009; Koenraadt et al., 2014; Lu et al., 2015; Suzuki et al., 2004, 2008). Thus, there is now considerable literature that requires synthesizing and systematic review of the main findings related to the brain activation as assessed by fNIRS during walking tasks.

Some recent reviews have examined fNIRS and gait. These reviews have addressed (i) methodological aspects (Herold et al., 2017; Vitório et al., 2017); (ii) data processing techniques (Vitório et al., 2017); (iii) or restricted their focus to ageing (Vitório et al., 2017; Stuart et al., 2018), Parkinson’s disease (PD) or Parkinsonism syndromes (Vitório et al., 2017; Gramigna et al., 2017; Stuart et al., 2018) or Stroke (Gramigna et al., 2017).

Further analysis and synthesis of published fNIRS studies are required to gain a better understanding of (i) brain activation changes during complex walking compared to simple walking or standing; (ii) brain activation patterns in young healthy people as this group provides the model of intact cognitive functioning; and (iii) brain functioning in diverse clinical groups with walking and neurological impairments. A methodological scale is also required to assist in the evaluation of the literature published to date.

Thus, we conducted a systematic review to summarize the published findings regarding brain activation patterns during simple and complex walking tasks in young adults, older adults and clinical groups with balance disorders, to gain an insight into neural processes required for ambulation. Our primary objectives were to determine whether (i) PFC activation patterns change when people perform gait tasks of increasing complexity requiring concomitant somatosensory, motor or cognitive tasks; (ii) PFC activation patterns during gait differ between young and older people and between patient groups and healthy controls. Our secondary aim was
to evaluate each included study based on six methodological reporting criteria important for
good data quality.

**Methodology**

**Search strategy**

We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses
(PRISMA) statements and those defined by Moher et al (2009) to identify and screen the articles
included in this systematic review. We conducted searches in June 2018 using four databases:
Embase, PubMed, Scopus and PsycINFO. A protocol was prospectively registered with the
International Prospective Register of Systematic Reviews (PROSPERO) (registration number:
PROSPERO 2017: CRD42017059501). We used the following Booleans terms: (((near
infrared spectroscopy) OR functional near infrared spectroscopy) OR nirs) OR fnirs) AND
(((gait) OR walking) OR locomotion) AND (((young) OR adult) OR older) OR elderly) NOT
children)) AND (((Brain) OR cortex) OR cortical) for our search. We considered papers in
English, Portuguese, Dutch and French.

**Selection criteria**

Study identification and screening were conducted independently by PP and MT or PP and JM
with disagreements resolved by consultation and input from a third researcher (JM or SL). At
stage 1 (identification), the researchers screened the manuscript titles and selected those that
were consistent with the broad inclusion criteria. Studies were excluded if: (i) they were not in
line with the review objectives; (ii) were conference abstracts with insufficient information for
data extraction; (iii) were conducted in animals; (iv) were conducted in children/infants; (v) used
fNIRS for other purposes (e.g. muscle studies); (vi) used fNIRS for standalone purposes (i.e. no
walking assessment); (vii) used a device other than fNIRS (e.g. electroencephalogram) and/or;
(viii) were published in a language other than English, Portuguese, Dutch or French.

At stage 2 (screening), the researchers screened the abstracts to identify papers that met the other
specific review criteria: (i) used fNIRS to measure PFC cortical activation patterns; (ii) included
walking tasks (simple and complex) other than stepping and; (iii) assessed young people, older
people and/or clinical groups with balance disorders (defined as any peripheral or neurological
condition that affects balance control). At stage 3 (eligibility), the full-text articles were assessed
for eligibility. A manual search for additional relevant references from published reviews and
articles was also conducted at this point. Articles were further excluded if: (i) they did not
include a walking analysis; (ii) gait tasks involved walking speeds slower than 3km/h; (iii) the
participants performed tasks other than walking (i.e. stepping tasks); (iv) there was no baseline
data comparison. Papers meeting all selection criteria were included at stage 4 (included papers)
and relevant information was extracted from the papers by three authors (PP, MT and JM).

The primary outcome of the review was PFC activity change post stimulation. This was
operationalized by changes in oxyHb, deoxyHb (gold standard measurement in brain magnetic
resonance imaging (Obrig and Villringer, 2003; Lindauer et al., 2010)), tissue oxygenation index
(ratio of oxygenated to total tissue hemoglobin) and total hemoglobin level (sum of both oxyHb and deoxyHb). All hemodynamic changes reported in this review reflect statistically significant results reported by the authors of each study, i.e. p values < 0.5.

Data extraction

From the included studies, relevant data were extracted and summarized for further analysis (Table 1). These included: (i) author and year; (ii) sample characteristics; (iii) study aims; (iv) gait assessment; (v) secondary task types; (vi) equipment details; (vii) fNIRS parameters used to describe the brain activation; (viii) control of motion artefacts and filtering; (ix) main findings; (x) study limitations; and (xi) conclusions.
Table 1: Summary of fNIRS studies.

| PFC: Prefrontal cortex; DT: dual-task; OxyHb: oxygenated hemoglobin; DeoxyHb: deoxygenated hemoglobin; fNIRS: functional near-infrared spectroscopy; TOI: tissue oxygenated index; MS: Multiple Sclerosis; HOA: healthy older adults; MCI: mild cognitive impairment; PMC: premotor cortex; SMA: supplementary motor area; SMC: sensorimotor cortex; S1: primary sensorimotor cortex; M1: primary motor cortex; Hb: hemoglobin; BA: Brodmann area; PD: Parkinson’s disease. |

A methodological reporting scale based on availability of information provided in the papers was devised. It comprised one point for the following 6 items: (i) equipment details described adequately, i.e. number of channels for the fNIRS, optode distances; (ii) movement artefacts/high frequency noise controlled for; (iii) use of either the 10-5, 10-10 or 10-20 electroencephalography electrode system to guide the optode placement; (iv) interference with external light controlled for; (v) heart rate changes and physiological noises controlled for; (vi) sample size in each group > 10. Papers were classified as follows: low methodological reporting quality: total score < 2 points; medium methodological reporting quality: total score 3 and 4 points; high methodological reporting quality: total score ≥ 5 points.

Results

A total of 308 study records were identified from the four databases; 103 unique studies with the removal of duplicates. The manual search of the references of these studies identified 12 further relevant studies. Of these 115 studies, 58 were deemed eligible for full-text assessment based on abstract review, with 35 meeting our final inclusion criteria (Figure 1). The data extracted from these studies are summarized in the Table 1. Nine studies involved young adults only (simple walking (1), fast walking (1), motor task (2), motor and cognitive tasks (2) and only cognitive tasks (3)); 4 studies involved young and older people (motor and cognitive tasks (1), only cognitive tasks (3)); 1 study involved young and older people and a clinical group with balance disorders (stroke survivors) performing simple walking, motor and cognitive tasks; 10 studies involved older people only (fast walking (2), motor and cognitive tasks (1), somatosensory and cognitive tasks (1), somatosensory and motor and cognitive tasks (1), only cognitive tasks (5)); 8 studies involved older people and clinical groups with balance disorders (simple walking (1), motor and cognitive tasks (2), somatosensory and cognitive tasks (1), only cognitive tasks (4)); 3 studies involved solely clinical groups with balance disorders (simple walking (1) and only cognitive tasks (2)). These studies are summarized in Table 2.

Thirteen studies (Beurskens et al., 2014; Chen et al., 2017; Clark et al., 2014a; Clark et al., 2014b; Hawkins et al., 2018; Lin and Lin, 2016; Lu et al., 2015; Maidan et al., 2016; Mirelman et al., 2014; Mirelman et al., 2017; Nieuwholf et al., 2016; Osofundiya et al., 2016) reported two or more comparisons, i.e. walking while crossing an obstacle and walking while performing a serial subtraction, both in comparison to a baseline condition such as simple walking. Many
studies also contrasted brain activation in more than one area. In total, 75 brain activation comparisons are included in this review.

**Figure 1: Flowchart of the articles selection process.**

**Table 2: Effect of the additional tasks relative to baseline conditions on regional cortical activation in healthy young adults, healthy older adults and clinical groups with balance disorders.**

PFC: Prefrontal cortex; preSMA: Pre-supplementary motor area; SMA: Supplementary motor area; S1: Primary sensorimotor cortex; M1: Primary motor cortex; PMC: Premotor cortex; mSMC: Medial sensorimotor cortex; (+) higher activation when performing the additional task; (-) lower activation when performing the additional task; (=) no changes in activation; Baseline comparison: ¹standing still; ²simple walking; ³easier level of the secondary task. Significant differences only for: ⁴first half of the task; ⁵second half of the task; ⁶obstacle negotiation and wearing a vest with 10% body weight conditions; ⁷walk vs. visual task; ⁸walk vs alphabet recall; ⁹overground walking; ¹⁰walking and counting backwards task. ¹Ataxia; ²Stroke; ³Parkinson’s disease; ⁴Obesity; ⁵Multiple Sclerosis; ⁶Mild Cognitive Impairment; ⁷Neurological gait.

Table 3 presents the individual and overall methodological reporting scores, and also describes how the scores were attributed for each paper. Twenty studies (57%) were classified as high quality, 10 (29%) as medium quality and five (14%) as low quality. Figure 2 shows the number of comparisons from the included studies showing an increase, decrease or no change in PFC activation when comparing either a) walking to standing or b) walking with an additional task to simple walking, according to group. In young people, 11 of the 20 comparisons from 13 studies reported significant increases in PFC activation (Lu et al., 2015; Suzuki et al., 2004; Lin and Lin, 2016; Hill et al., 2013; Holtzer et al., 2011; Maidan et al., 2018; Mirelman et al., 2017; Meester et al., 2014; Mirelman et al., 2014); five reported a reduction in PFC activation (Hawkins et al., 2018; Koenraadt et al., 2014; Lin and Lin, 2016) and four reported no change (Koenraadt et al., 2014; Beurskens et al., 2014; Hawkins et al., 2018; Takeuchi et al., 2016). Although the aim of the study was to report changes in PFC activation, three studies (four comparisons) have also investigated activation in additional cortical areas in young people (Table 1) (Lu et al., 2015; Koenraadt et al., 2014; Suzuki et al., 2004). Of these, two comparisons indicated increased cortical activation in the SMA (Lu et al., 2015), while one found no change in the SMA as well as no change in brain activation in the preSMA and motor and sensorimotor areas (Primary Motor Cortex (M1) and Primary Sensorimotor Cortex (S1)) (Koenraadt et al., 2014). One comparison also reported increased cortical activation in the PMC (Lu et al., 2015) while another found no change in activation in the PMC or the SMC (Suzuki et al., 2004). Of the 37 comparisons from 22 studies conducted in older adults, 23 reported significant increases in PFC activation with increasing locomotor task complexity (Lucas et al., 2018; Mirelman et al., 2017;...
Hawkins et al., 2018; Chaparro et al., 2017; Chen et al., 2017; Harada et al., 2009; Holtzer et al., 2011, 2015, 2016, 2017a, 2017b, Maidan et al., 2016; Verghese et al., 2017; Clark et al., 2014a, 2014b; Osofundiya et al., 2016; Hernandez et al., 2016); two reported a reduction in PFC activation (Beurskens et al., 2014; Clark et al., 2014a) and twelve reported no change (Hawkins et al., 2018; Eggenberger et al., 2016; Mori et al., 2018; Harada et al., 2009; Takeuchi et al., 2016; Clark et al., 2014b; Maidan et al., 2016; Caliandro et al., 2015; Al-Yahya et al., 2016).

Only one study investigated other cortical areas, reporting no change in pre-SMA or Medial Sensorimotor Cortex (mSMC) activation and an increase in SMA activation (Harada et al., 2009). Finally, of the 18 comparisons from twelve studies conducted in clinical groups, fifteen reported increased PFC activation (Thumm et al., 2018; Hawkins et al., 2017; Chaparro et al., 2017; Takeuchi et al., 2016; Osufondiya et al., 2016; Hernandez et al., 2016; Holtzer et al., 2016; Maidan et al., 2016; Caliandro et al., 2015; Al-Yahya et al., 2016; Doi et al., 2013) and three comparisons found no change (Mori et al., 2018; Maidan et al., 2016).

Table 3: Methodological reporting criteria ratings for the included studies.

Figure 2: Proportion of comparisons within each group showing increase (up arrows), decrease (down arrows) or no change (circle) in Prefrontal Cortex (PFC) activation when comparing walking with secondary task versus baseline.

There was no indication that the PFC activation was associated with methodological reporting scores; i.e. increased activation was reported in 23/36 (64%) comparisons in high quality studies, 14/18 (78%) comparisons in medium quality studies and 10/19 (53%) comparisons in low quality studies; ($\chi^2 = 2.56, df = 2, p = 0.279$) (Table 4). Regarding the effects of a secondary task during walking on PFC activation, 9/14 (64%) comparisons that used counting backwards reported increases, 20/24 (83%) that used verbal fluency reported increases, 11/19 (58%) that used complex motor tasks reported increases and 0/4 (0%) that used visual tasks reported increases (Table 5).

Table 4: Prefrontal cortical activation in relation to methodological reporting scale.

Table 5: Prefrontal cortical activation in relation to complex walking tasks.

Table 6 shows the effect of an additional motor or cognitive task relative to simple walking on gait outcomes in healthy young adults, healthy older adults and clinical groups with balance disorders. Reduced gait speed was reported in all studies investigating overground walking with the exception of one study that observed no changes in gait speed when older people walked while counting backwards by 3 or negotiated an obstacle course (Mirelman et al., 2017). No changes in gait speed were also observed in the two studies of treadmill walking where walking speed was controlled by the examiner (Clark et al., 2014a, 2014b). Shorter step/stride length was observed in all studies conducted on level surfaces except for one study that investigated
counting backwards from a 3-digit number while walking on a treadmill (Al-Yahya et al., 2016) where both older people and stroke survivors exhibited increased stride length compared with simple walking. As expected, higher spatiotemporal variability was observed when people performed a secondary motor task that manipulated spatiotemporal characteristics, such as obstacle crossing and precision stepping (Koenraadt et al., 2014; Clark et al., 2014b; Mirelman et al., 2017), but also in one study where older people performed a verbal fluency task (Clark et al., 2014a). No changes in gait variability were observed when young people walked while performing arithmetic tasks (Lu et al., 2015; Meester et al., 2014), when young people walked carrying a tray (Lu et al., 2015), when somatosensory information was manipulated in older people (Clark et al., 2014a, 2014b) and when young and older people walked while negotiating obstacles or while counting backwards by 3 (Mirelman et al., 2017). One study, by Nieuwholf and colleagues (2016), showed decreased stride length variability in people with PD when performing the digit span task while walking.

Table 6: Effect of the additional tasks on gait outcomes compared to simple walking in healthy young adults, healthy older adults and clinical groups with balance disorders.

- (+) increase of spatiotemporal parameter when performing the additional task during walking; (-) decrease of spatiotemporal parameter when performing the additional task; (=) no changes in spatiotemporal parameter.

Significant differences only for: 1 obstacle negotiation; 2 treadmill walking; 3 overground walking; 4 walking + subtracting by 7s; 5 walking while reciting digit spans.

Table 7 presents group comparisons with respect to brain activation changes resulting from undertaking a complex walk between (i) healthy older and young adults and (ii) clinical groups with balance disorders and healthy peers. Of the five studies that contrasted PFC activation changes when conducting a dual task walk between young and older adults, only one study showed greater increases in PFC activation in older adults in all tasks performed (Mirelman et al., 2017). Another study (Hawkins et al., 2018), reported greater PFC activation in older people in simple walking in only the first half of an obstacle negotiation task and not when walking and performing a verbal fluency task. Two other studies reported no group differences (Beurskens et al., 2014; Takeuchi et al., 2016) and one reported a relatively smaller increase in PFC activation in older people (Holtzer et al., 2011).

Table 7: Prefrontal cortical activation pattern differences between healthy young and older adults and between clinical groups with balance disorders and healthy peers.

DT: Dual-task; SW: Simple walking; OBS: Obstacle negotiation; a: first half of the task; b: second half of the task; PB: Partial body support; PS: Precision stepping; (+) higher activation when performing the additional task; (-) lower activation when performing the additional task; (=) no change in activation.
Thirteen comparisons from eight studies have contrasted PFC activation changes when conducting a dual task walk between clinical groups with balance disorders and healthy peers. Four of these reported a relatively larger increase in PFC activation in clinical groups with balance disorders. Two comparisons showed increased PFC activation when people with multiple sclerosis performed cognitive dual tasks (Chaparro et al., 2017; Hernandez et al., 2016), while the other comparisons showed increased PFC activation when stroke survivors walked while performing a cognitive dual task (Al-Yahya et al., 2016) or in the first half of an obstacle negotiation task (Hawkins et al., 2018). Six comparisons reported no between-group PFC activation differences. In three of these comparisons, stroke survivors (Hawkins et al., 2018), PD (Maidan et al., 2016) and obesity (Osofundiya et al., 2016) performed motor tasks (obstacle negotiation and precision stepping), while in three other comparisons, stroke survivors (Hawkins et al., 2018), neurological gait (Holtzer et al., 2016) and obesity (Osofundiya et al., 2016) performed cognitive tasks. Finally, the three reports of PFC decreases in clinical groups were observed when people with multiple sclerosis walked with partial body support (Chaparro et al., 2017) and when people with PD and stroke performed a cognitive dual task (Maidan et al., 2016; Mori et al., 2018).

**Discussion**

This systematic review summarizes the published findings regarding PFC cortical patterns of activation in healthy young adults, healthy older adults and clinical groups with balance disorders, to gain an insight into neural processes during simple and complex walking tasks. Approximately 60% of the studies comparisons reported that healthy young and older adults exhibited higher PFC activation when performing a complex task while walking compared with a baseline simple walking task; this was also the case for more than 80% of studies comparisons of clinical groups with balance disorders. Moreover, PFC activation appears to be related to the type of complex walk undertaken.

**Brain activation in healthy young adults**

Compared with simple walking, PFC activation increased when individuals performed (i) fast walks (Suzuki et al., 2004); (ii) negotiated expected obstacles (Mirelman et al., 2017; Maidan et al., 2018) and unexpected obstacles of different heights (Maidan et al., 2018a); (iii) a secondary task while walking (Holtzer et al., 2011; Mirelman et al., 2014); the last being the paradigm used in most studies that have assessed brain activation patterns in healthy young adults. In these studies, participants performed the following secondary tasks: subtracting numbers by 1, 3 or 7 (Hill et al., 2013; Meester et al., 2014; Mirelman et al., 2014; Mirelman et al., 2017), walking while talking (Holtzer et al., 2011) and talking and carrying a bottle of water on a tray (Lu et al., 2015). However, increased hemodynamic responses in the PFC appear to be task-specific. Indeed, several studies of healthy young adults (Hawkins et al., 2018; Koenraadt et al., 2014; Lin and Lin, 2016; Beurskens et al., 2014; Takeuchi et al., 2016) reported no change or even a decrement in PFC activation during either secondary motor task performance (e.g. precision
stepping, crossing obstacles or walking on a narrow pathway) or cognitive task performance (e.g.
visual checking, alphabet recall, memory task and manipulating a smartphone). Such findings
suggest that increasing balance/ locomotor changes does not require additional PFC activation in
healthy young adults, and might involve other cortical and subcortical areas involved in the
control of locomotion. In addition, secondary tasks involving working memory (Lin and Lin,
2016; Beurskens et al., 2014) might also involve cortical areas in addition to the PFC that were
not investigated in the published studies.

Brain activation in healthy older adults
Most studies (Lucas et al., 2018; Mirelman et al., 2017; Hawkins et al., 2018; Chaparro et al.,
2017; Chen et al., 2017; Holtzer et al., 2011, 2015, 2016, 2017a, 2017b; Clark et al., 2014a,
2014b; Osofundiya et al., 2016; Hernandez et al., 2016; Maidan et al., 2016; Verghese et al.,
2017) but not all (Al-Yahya et al., 2016; Beurskens et al., 2014; Takeuchi et al., 2016; Hawkins
et al., 2018; Eggenberger et al., 2016; Harada et al., 2009; Mori et al., 2018;) reported that when
healthy older adults performed cognitive or motor tasks while they walked, the PFC was more
activated in comparison to baseline conditions. It seems that in healthy older adults, PFC
activation increases with secondary cognitive tasks that involve attention and executive
functioning (e.g. walking while subtracting). In contrast, and similar to what is noted in healthy
young adults, the conduct of tasks that require speed manipulation (Harada et al., 2009;
Eggenberger et al., 2016), visual checking (Beurskens et al., 2014), unpractised tasks
(manipulating a smartphone) (Takeuchi et al., 2016), or obstacle negotiation (Hawkings et al.,
2018; Maidan et al., 2016) do not appear to increase PFC activation. As with young adults,
increased activation may occur in other cortical areas that process visual-spatial stimuli (Wu et
al., 2018).

Brain activation in healthy individuals - young: older comparisons
Healthy older adults usually walk slower and have more difficulty performing dual tasks than
healthy young adults, (Al-Yahya et al., 2011). However, of the five studies that investigated
between age-group effects when performing walks with secondary tasks, only one study
observed greater PFC activation in older people performing different secondary tasks (obstacle
negotiation and counting backwards) (Mirelman et al., 2017). PFC activation patterns were not
different between healthy young and older adults in three studies (Beurskens et al., 2014;
Takeuchi et al., 2016; Hawkins et al., 2018) and lower in older adults in one (Holtzer et al.,
2011). The limited number of studies which have explored the effects of aging as well as the
nature of the secondary task used in these studies might account for the lack of an age effect.

Brain activation in clinical groups with balance disorders
In most clinical groups with balance disorders, including stroke survivors (Al-Yahya et al., 2016;
Hawkins et al., 2018), obese individuals (Osofundiya et al., 2016), individuals with ataxia
(Caliandro et al., 2015), multiple sclerosis (Chaparro et al., 2017; Hernandez et a., 2016),
higher PFC activation has been reported regardless of the type of concomitant task performed during ambulation. This is also the case for comparisons made in studies in people with PD (Maidan et al., 2016, Thumm et al., 2018 Nieuwholf et al., 2016) with one exception; Maidan et al found no change in PFC activation when comparing walking whilst performing a concomitant subtracting task with simple walking (Maidan et al., 2016).

Theoretical considerations

Our findings of enhanced hemodynamic responses in the PFC apparent when older adults and individuals with balance disorders perform complex walking tasks align particularly with the notion that increased cortical activity reflects a compensatory mechanism (Cabeza et al., 2002; Reuter-Lorenz and Cappel, 2008; Grady, 2012). This might reflect the need to allocate more attentional resources to walking while performing secondary tasks, or the need to use a more direct locomotor pathway due to deficits in automaticity (e.g. as generally observed in individuals with PD) (Herold et al., 2017). The age-related differences are also consistent with the frontal lobe hypothesis of aging (West, 1996) and the cognitive reserve theory which supports that older adults increase brain activity by a larger degree to cope with elevated cognitive task difficulty (Stern, 2009). Moreover, these functional effects of aging mirror age-related structural changes proposed by the “last-in-first-out” hypothesis where late maturing brain regions decline first in later life (Raz and Kennedy, 2009; Tamnes et al., 2013; Bender, Volkle and Raz, 2015) and explain gait disturbances.

Differential effects of secondary task type on PFC activation

Four secondary task types were commonly used in the included studies: counting backwards, verbal fluency, motor tasks and visual tasks. Of these, verbal fluency was the most consistent in increasing PFC activation (Lucas et al., 2018; Hawkins et al., 2018; Chaparro et al., 2017; Chen et al., 2017; Holtzer et al., 2011, 2015, 2016, 2017a, 2017b; Clark et al., 2014a, 2014b; Osofundiya et al., 2016; Hernandez et al., 2016; Verghese et al., 2017; Doi et al., 2013). Counting backwards also increased PFC in most studies (Lu et al., 2015; Hill et al., 2013; Meester et al., 2014; Mirelman et al., 2014; Mirelman et al., 2017; Maidan et al., 2016; Al-Yahya et al., 2016; Nieuwhof et al., 2016). Of the 9 comparisons that did not show increased PFC activation with verbal fluency or backward counting tasks, some were from studies of low (Hawkins et al., 2018) or medium methodological reporting quality (Lin and Lin, 2016) that did not report control for motion artefacts, external lighting and physiological noise, and in two studies (Beurskens et al., 2014; Al-Yahya et al., 2016) the secondary tasks were performed on a treadmill. This may be important as Clark et al (2014a) observed that when participants walked on treadmill no change in PFC activation was observed between dual-task (verbal task) and baseline condition, while changes were observed on overground walking. Half of the studies that examined the effects of motor tasks during walking in healthy individuals found increases in PFC. In the studies where PFC was not increased, three were performed on a
treadmill (Eggenberger et al., 2016; Harada et al., 2009; Koenraadt et al., 2014), one was of low methodological reporting quality (Hawkins et al., 2018), one did not control for important aspects that could have affected the interpretation of the data, such as motion artefacts, external lighting and physiological noise (Lin and Lin, 2016), and one was conducted in people with PD (Maidan et al., 2016). Obstacle negotiation and precision stepping tasks increased PFC in the three studies performed in clinical groups with balance disorders (Osofundiya et al., 2016; Maidan et al., 2016; Hawkins et al., 2018), but this may simply indicate any additional load may illicit such changes in such populations. Finally, visual tasks such as visual checking and manipulating a smartphone did not increase PFC activation (Beurskens et al., 2014; Takeuchi et al., 2016). For these task types, other brain areas such as the visual cortex might be more involved. However, further studies directly assessing visual cortex activation as well as other cortical regions are required to confirm this hypothesis.

Study limitations

Studies addressing gait with fNIRS are still at a relatively early stage, with best practice methodology evolving as experience with this technique is garnered. Studies may have not met particular quality criteria due to the pioneering nature of the studies using this new technology and/or omission of reporting of all methodological factors and most of the papers (89%) had one or more of the following methodological limitations: small sample sizes, no indication of removal or control of motion artefacts or physiological noise in data processing and sub-optimal number and positioning of optodes. Further, the secondary tasks used in many studies involved speaking (counting backwards and verbal fluency) requiring muscles adjacent to the PFC (Zimeo-Morais et al., 2018). Such muscle activity as well as different facial expressions (Balardin et al., 2017) may affect fNIRS signal quality.

To address the above, we recommend that in future studies, sample sizes be based on power analyses of expected effect sizes for spatiotemporal gait and hemodynamic measures to provide confidence in the study findings. Second, motion artefacts should be removed during the data processing or be controlled for; confounding physiological noise such as fluctuations in heart rate should either be monitored and reported, or controlled for using appropriate filtering. Third, baseline and test trials should be of sufficient duration to detect the slow changing hemodynamic signals as oxygenated blood starts flowing between 1 and 2s after stimuli onset and achieves its peak approximately 6s after stimulus onset (Holtzer et al., 2011). Finally, EEG standards (i.e. 10-5) and/or anatomical maps to define optode positions (i.e. Brodmann areas) for the brain regions of interest should be used. However, we acknowledge that given the limited number of fNIRS channels in current devices, this may prove to be an unavoidable limitation for some investigations (Koenraadt et al., 2014; Maidan et al., 2016).

We also acknowledge other limitations. First, there was considerable heterogeneity of study protocols. As such, variations in baseline conditions (e.g. sitting/standing/unspecified), walking speed (e.g. self-selected/controlled), duration and amount of trials, treadmill vs. overground
walking, montage, inter-optode distance, etc. limited the clustering of studies and hindered the overall interpretation of the data. Finally, factors such as motor repertoire, physical activity, practice and skill levels, risk of falling and hemispheric asymmetry (Ekkekakis, 2009; Erickson et al., 2007; Jancke, Shah and Peters, 2000; Naito and Hirose, 2014) can affect cortical activity but were beyond the scope of this review. Complementary studies and reviews are required to elucidate the influence these factors have on cortical activity and associated balance control.

Conclusion

This systematic review found the majority of studies found increased PFC activation with increased walking task complexity in young and older people and clinical groups with balance disorders. However, increased PFC activation was most common in studies that contained walks comprising secondary tasks of verbal fluency, arithmetic and alphabet reciting. The finding that clinical groups with balance disorders generally showed increased PFC activation irrespective of type of secondary task during walking suggests these groups require more attentional resources for safe walking.

References

Al-Yahya, E., Dawes, H., Smith, L., Dennis, A., Howells, K., Cockburn, J., 2011. Cognitive motor interference while walking: a systematic review and meta-analysis. Neurosci. Biobehav. Rev. 35, 715-728.

Al-Yahya, E., Johansen-Berg, H., Kischka, U., Zarei, M., Cockburn, J., Dawes, H., 2016. Prefrontal cortex activation while walking under dual-task conditions in stroke: a multimodal imaging study. Neurorehabil. Neural Repair 30, 591-599.

Balardin, J.B., Zimeo-Morais, G.A., Furucho, R.A., Trambaioli, L.R., Sato, J.R., 2017. Impact of communicative head movements on the quality of functional near-infrared spectroscopy signals: negligible effects for affirmative and negative gestures and consistent artifacts related to raising eyebrows. J. Biomed. Opt. 22, article 46010.

Bender, A.R., Volkle, M.C., Raz, N., 2015. Differential aging of cerebral white matter in middle-aged and older adults: a seven-year follow-up. Neuroimage. 125, 74-83.

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, 122-128.

Cabeza, R., Anderson, N.D., Locantore, J.K., McIntosh, A.R., 2002. Aging gracefully: compensatory brain activity in high-performing older adults. Neuroimage. 17, 1394-1402.
Caetano, M.J.D., Menant, J.C., Schoene, D., Pelicioni, P.H.S., Sturnieks, D.L., Lord, S.R., 2017. Sensorimotor and cognitive predictors of impaired gait adaptability in older people. J. Gerontol. A Biol. Sci. Med. Sci. 72, 1257-1263.

Caetano, M.J.D., Lord, S.R., Brodie, M.A., Schoene, D., Pelicioni, P.H.S., Sturnieks, D.L., Menant, J.C., 2018. Executive functioning, concern about falling and quadriceps strength mediate the relationship between impaired gait adaptability and fall risk in older people. Gait Posture 59, 188-192.

Caliandro, P., Serrao, M., Padua, L., Silvestri, G., Iacovelli, C., Simbolotti, C., Mari, S., Reale, G., Casali, C., Rossini, P.M., 2015. Prefrontal cortex as a compensatory network in ataxic gait: a correlation study between cortical activity and gait parameters. Restor. Neurol. Neurosci. 33, 177-187.

Chaparro, G., Balto, J.M., Sandroff, B.M., Holtzer, R., Izzetoglu, M., Motl, R.W., Hernandez, M.E., 2017. Frontal brain activation changes due to dual-tasking under partial body weight support conditions in older adults with multiple sclerosis. J. Neuroeng. Rehabil. 14, 65.

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.

Clark, D.J., Christou, E.A., Ring, S.A., Williamson, J.B., Doty, L., 2014a. Enhanced somatosensory feedback reduces prefrontal cortical activity during walking in older adults. J. Gerontol. A Biol. Sci. Med. Sci. 69, 1422-1428.

Clark, D.J., Rose, D.K., Ring, S.A., Porges, E.C., 2014b. Utilization of central nervous system resources for preparation and performance of complex walking tasks in older adults. Front. Aging Neurosci. 25, 217.

Doi, T., Makizako, H., Shimada, H., Park, H., Tsutsumimoto, Uemura, K., Suzuki, T., 2013. Brain activation during dual-task walking and executive function among older adults with mild cognitive impairment: a fNIRS study. Aging Clin. Exp. Res. 25, 539-544.

Eggenberger, P., Wolf, M., Schumann, M., de Bruin, E.D., 2016. Exergame and balance training modulate Prefrontal Brain activity during walking and enhance executive function in older adults. Front Aging Neurosci. 8, article 66.

Ekkekakis, P., 2009. Illuminating the black box: investigating prefrontal cortical hemodynamics during exercise with near-infrared spectroscopy. J. Sport Exerc. Psychol. 31, 505-553.
Erickson, K.I., Colcombe, S.J., Wadwha, R., Bherer, L., Peterson, M.S., Scalf, P.E., Kim, J.S., Alvarado, M., Kramer, A.F., 2007. Training-induced plasticity in older adults: effects of training on hemispheric asymmetry. Neurobiol. Aging 28, 272-283.

Grady, C., 2012. The cognitive neuroscience of aging. Nat. Rev. Neurosci. 13, 491-505.

Gramigna, V., Pellegrino, G., Cerasa, A., Cutini, S., Vasta, R., Olivadese, G., Martino, I., Quattrone, A., 2017. Near-infrared spectroscopy in gait disorders: is it time to begin? Neurorehabil. Neural Repair 31, 402-412.

Harada, T., Miyai, I., Suzuki, M., Kubota, K., 2009. Gait capacity affects cortical activation patterns related to speed control in the elderly. Exp. Brain Res. 193, 445-454.

Hausdorff, J.M., 2005. Gait variability: methods, modelling and meaning. J. Neuroeng. Rehabil. 2, 19.

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.

Hernandez, M.E., Holtzer, R., Chaparro, G., Jean, K., Balto, J.M., Sandroff, B.M., Izzetoglu, M., Moti, R.W., 2016. Brain activation changes during locomotion in middle-aged to older adults with multiple sclerosis. J. Neurol. Sci. 15, 277-283.

Herold, F., Wiegel, P., Scholkmann, F., Thiers, A., Hamacher, D., Schega, L., 2017. Functional near-infrared spectroscopy in movement science: a systematic review on cortical activity in postural and walking tasks. Neurophotonics 4, 041403.

Hill, A., Bohil, C., Lewis, J., Neider, K., 2013. Prefrontal cortex activity during walking while multitasking: an fNIR study. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 57, 1224-1228.

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. A Biol. Sci. Med. Sci. 66, 879-887.

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 15, 152-159.
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, 334-343.

Holtzer, R., Schoen, C., Demetriou, E., Mahoney, J.R., Izzetoglu, M., Wang, C., Verghese, J., 2017a. Stress and gender effects on prefrontal cortex oxygenation levels assessed during single and dual-task walking conditions. Eur. J. Neurosci. 45, 660-670.

Holtzer, R., Yuan, J., Verghese, J., Mahoney, J.R., Izzetoglu, M., Wang, C., 2017b. Interactions of subjective and objective measures of fatigue defined in the context of brain control of locomotion. J. Gerontol. A Biol. Sci. Med. Sci. 72, 417-423.

Jancke, L., Shah, N.J., Peters, M., 2000. Cortical activation in primary and secondary motor areas for complex bimanual movements in professional pianists. Brain Res. Cogn. Brain Res. 10, 177-183.

Killane, I., Donoqhue, O.A., Savva, G.M., Cronin, H., Kenny, R.A., Reilly, R.B., 2014. Relative association of processing speed, short-term memory and sustained attention with task on gait speed: a study of community-dwelling people 50 years and older. J. Gerontol. A Biol. Sci. Med. Sci. 69, 1407-1414.

Koenraadt, K.L., Roelofsen, E.G., Duysen, J., Keijsers, N.L., 2014. Cortical control of normal gait and precision stepping: an fNIRS study. Neuroimage 85, 415-422.

Leff, D.R., Orihuela-Espina, F., Elwell, C.E., Athanasiou, T., Delpy, D.T., Darzi, A.W., Yang, G.Z., 2011. Assessment of the cerebral cortex during motor task behaviours in adults: a systematic review of functional near infrared spectroscopy (fNIRS) studies. Neuroimage 54, 2922-2936.

Lin, M.I., Lin, K.H., 2016. Walking while performing working memory tasks changes the prefrontal cortex hemodynamic activations and gait kinematics. Front. Behav. Neurosci. 10, 92.

Lindauer, U., Dirnagl, U., Fuchtemeier, M., Bottiger, C., Offenhauser, N., Leithner, C., Royl, G., 2010. Pathophysiological interference with neurovascular coupling – when imaging based on haemoglobin might go blind. Front. Neuroenergetics 2, article 25.

Lu, C.F., Liu, Y.C., Yang, Y.R., Wu, Y.T., Wang, R.Y., 2015. Maintaining gait performance by cortical activation during dual-task interference: a functional near-infrared spectroscopy study. PLoS One 10, e0129390.
Lucas, M., Wagshul, M.E., Izzetoglu, M., Holtzer, R., 2018. Moderating effect of white matter integrity on brain activation during dual-task walking in older adults. J. Gerontol. A Biol. Sci. Med. Sci. accepted.

Lustig, C., Shah, P., Seidler, R., Reuter-Lorenz, P.A., 2009. Aging, training, and the brain: a review and future directions. Neuropsychol. Rev. 19, 504-522.

Maidan, I., Nieuwhof, F., Bernad-Elazari, H., Reelick, M.F., Bloem, B.R., Giladi, N., Deutsch, J.E., Hausdorff, J.M., Claassen, J.A., Mirelman, A., 2016. The role of the frontal lobe in complex walking among patients with Parkinson’s disease and healthy older adults: an fNIRS study. Neurorehabil. Neural Repair 30, 963-971.

Maidan, I., Shustak, S., Sharon, T., Bernard-Elazari, H., Geffen, N., Giladi, N., Hausdorff, J.M., Mirelman, A., 2018. Prefrontal cortex activation during obstacle negotiation: what’s the effect size and timing? Brain Cogn. 122, 45-51.

Meester, D., Al-Yahya, E., Dawes, H., Martin-Fagg, P., Piñon, C., 2014. Associations between prefrontal cortex activation and H-reflex modulation during dual task gait. Front. Hum. Neurosci. 8, 78.

Mirelman, A., Maidan, I., Bernard-Elazari, H., Nieuwhof, F., Reelick, M., 2014. Increased frontal brain activation during walking while dual tasking: an fNIRS study in healthy young adults. J. Neuroeng. Rehabil. 11, 85.

Mirelman, A., Maidan, I., Bernard-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.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., PRISMA Group, 2009. Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. PLoS Med. 6, e1000097.

Montero-Odasso, M., Verghese, J., Beauchet, O., Hausdorff, J.M., 2012. Gait and cognition: a complementary approach to understanding brain function and the risk of falling. J. Am. Geriatr. Soc. 11, 2127-2136.

Mori, T., Takeuchi, N., Izumi, S.I., 2018. Prefrontal cortex activation during a dual task in patients with stroke. Gait Posture 59, 193-198.
Naito, E., Hirose, S., 2014. Efficient foot motor control by Neymar’s brain. Front. Hum. Neurosci. 8, article 594.

Nieuwhof, F., Reelick, M.F., Maidan, I., Mirelman, A., Hausdorff, J.M., Rikkert, M.G.M.O., Bloem, B.R., Muthalib, M., Claassen, J.A.H.R., 2016. Measuring prefrontal cortical activity during dual task walking in patients with Parkinson’s disease: feasibility of using a new portable fNIRS device. Pilot Feasibility Stud. 2, 59.

Obrig, H., Villringer, A., 2003. Beyond the visible – imaging the human brain with light. J. Cereb. Blood Flow Metab. 23, 1-18.

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. 35, 42-48.

Raz, N., Kennedy, K.M., 2009. A systems approach to the aging brain: Neuroanatomic hanges, their modifiers, and cognitive correlates. Imaging the aging brain. Jagust, W., D’Esposito, M., New York, NY, Oxford University Press: 43-70.

Reuter-Lorenz, P.A., Cappell, K.A., 2008. Neurocognitive aging and the compensation hypothesis. Curr. Dir. Psychol. Sci. 17, 177-182.

Stern, Y., 2009. Cognitive reserve. Neuropsychologia 47, 2015-2028.

Stuart, S., Vitorio, R., Morris, R., Martini, D.N., Mancini, M., 2018. Cortical activity during walking and balance tasks in older adults and in people with Parkinson’s disease: a structured review. Maturitas 113, 53-72.

Suzuki, M., Miyai, I., Ono, T., Oda, I., Konishi, I., Kochiyama, T., Kubota, K., 2004. Prefrontal and premotor cortices are involved in adapting walking and running speed on the treadmill: an optical imaging study. Neuroimage 23, 1020-1026.

Suzuki, M., Miyai, I., Ono, T., Kubota, K., 2008. Activities in the frontal cortex and gait performance are modulated by preparation. An fNIRS study. Neuroimage 39, 600-607.

Takakusaki, K., Tomita, N., Yano, M., 2008. Substrates for normal gait and pathophysiology of gait disturbances with respect to the basal ganglia dysfunction. J. Neurol. 255, 19-29.
Takeuchi, N., Mori, T., Suzukamo, Y., Tanaka, N., Izumi, S., 2016. Parallel processing of cognitive and physical demands in left and right prefrontal cortices during smartphone use while walking. BMC Neurosci. 17, 9.

Tamnes, C.K., Walhivd, K.B., Dale, A.M., Ostby, Y., Grydeland, H., Richardson, G., Westlye, L.T., Roddey, J.C., Hagler, D.J.Jr, Due-Tonnessen, P., Holland, D., Fjell, A.M., Alzheimer’s Disease Neuroimaging Initiative, 2013. Brain development and aging: overlapping and unique patterns of change. Neuroimage 68, 63-74.

Thumm, P.C., Maidan, I., Brozgol, M., Shustak, S., Gazit, E., Shiratzki, S.S., Bernard-Elazari, H., Beck, Y., Giladi, N., Hausdorff, J.M., Mirelman, A., 2018. Treadmill walking reduces prefrontal activation in patients with Parkinson’s disease. Gait Posture 62, 384-387.

Verghese, J., Wang, C., Ayers, E., Izzetoglu, M., Holtzer, R., 2017. Brain activation in high-functioning older adults and falls: prospective cohort study. Neurology 88, 191-197.

Vitorio, R., Stuart, S., Rochester, L., Alcock, L., Pantall, A., 2017. fNIRS response during walking – artefact or cortical activity? A systematic review. Neurosci. Biobehav. Rev. 83, 160-172.

West, R.L., 1996. An application of prefrontal cortex function theory to cognitive aging. Psychol. Bull. 120, 272-292.

Wu, Z., Mazzola, C.A., Catania, L., Owoeye, O., Yaramothu, C., Alvarez, T., Gao, Y., Li, X., 2018. Altered cortical activation and connectivity patterns for visual attention processing in young adults post-traumatic brain injury: a functional near infrared spectroscopy study. CNS Neurosci. Ther. 24, 539-548.

Zimeo-Morais, G.A., Scholkmann, F., Balardin, J.B., Furucho, R.A., De Paula, R.C.V., Biazoli-Jr, C.E., Sato, J.R., 2018. Non-neuronal evoked and spontaneous hemodynamic changes in the anterior temporal region of the human head may lead to misinterpretations of the functional near-infrared spectroscopy signals. Neurophotonics 5, article 011002.
Figure 1: Flowchart of the articles selection process.
Figure 2

Figure 2: Proportion of comparisons within each group showing increase (up arrows), decrease (down arrows) or no change (circle) in Prefrontal Cortex (PFC) activation when comparing walking with secondary task versus baseline.
Table 1: Summary of fNIRS studies.

PFC: Prefrontal cortex; DT: dual-task; OxyHb: oxygenated hemoglobin; DeoxyHb: deoxygenated hemoglobin; fNIRS: functional near-infrared spectroscopy; TOI: tissue oxygenated index; MS: Multiple Sclerosis; HOA: healthy older adults; MCI: mild cognitive impairment; PMC: premotor cortex; SMA: supplementary motor area; SMC: sensorimotor cortex; S1: primary sensorimotor cortex; M1: primary motor cortex; Hb: hemoglobin; BA: Brodmann area; PD: Parkinson’s disease.
Beurskens et al., 2014
19 individuals with chronic stroke, 60–73 years old, 2 women; 20 healthy controls, 34–73 years old, 8 women.

To investigate PFC activation and relationships between PFC activation and gait variability while walking under single-task and DT conditions in individuals with stroke and healthy controls.

Walking on a treadmill at self-selected speed (5 trials). Gait variables estimated with a pendulum model using kinematic data from an inertial sensor attached at the level of the fourth lumbar vertebra (close to the centre of mass). Additional single task: counting while standing. Baseline: unclear.

Counting backward in 7 from a random number between 291 and 299 while walking (5 trials) for 30s. The outcomes were: rate and accuracy of correct answers. No advice given as to which task to prioritize during DT-walking.

To investigate whether PFC activation and gait variability are linked to compensatory variability of the ataxic gait.

Walking on a treadmill at self-selected speed (2 trials per condition). Baseline condition: rest period seating on a chair. Gait outcomes: step duration, step length and number of steps.

To compare the effects of completing a secondary visual checking task versus a verbal memory task during walking on PFC activity in young and HOA.

(i) visual checking (seated); (ii) alphabet recall (seated); (iii) walking and visual checking; (iv) walking and alphabet recall. All tasks duration: 30s. Secondary task outcomes: number of checked boxes per second (visual checking) and number of correctly recited letters per second (alphabet recall).

DYNOT Imaging System, NIRx Medical Technologies, LLC. Wavelengths: 760 nm and 830 nm. 14 channels. Interoptode position: 2.2 and 2.5 cm. Sampling rate: 1.81 Hz.

OxyHb and deoxyHb. PFC.

Blood pressure was measured at the beginning and after the end of each trial. To remove high-frequency noise (cardiac pulsation) fNIRS signals were then low-pass filtered at 0.67 Hz cut-off frequency.

OxyHb and deoxyHb analysed during 10s window between 6 and 16s post stimulus onset.

Increased oxyHb concentration and decreased deoxyHb in DT walking compared with simple-task walking and with standing while counting for both groups and hemispheres.

Increased PFC activity in DT walking vs simple task, among stroke patients.

No between-group differences in PFC activation during walking.

No between-group difference in brain activation across all channels. No significant effect of verbal memory secondary task (vs. simple walking task) on brain activation in young and HOA. Significant age x condition for visual checking DT: no significant effect of visual checking on hemodynamic response function low-pass filter and wavelet minimum description length-de-trending algorithm to remove possible global trends due to breathing, heartbeat, vasomotorism or experimental influences.

Tasks were conducted in a dimly illuminated room. Each channel was visually inspected and movement artefacts were corrected and data were reconstructed. Hemodynamic response function low-pass filter and wavelet minimum description length-de-trending algorithm to remove possible global trends due to breathing, heartbeat, vasomotorism or experimental influences.

To reduce movement artefacts the position of epoede were stabilized fixing them to the head by a double-sided adhesive tape. Velcro was used to reduce the influence of skin blood flow on fNIRS signal. Probe holders covered by a black cloth to avoid infrared light interferences. Two recordings 30min apart to verify influence of infrared system on and off on fNIRS signal. A 0.1 Hz low-pass filter applied to reduce cardiac, breathing signals and low frequency oscillations due to blood pressure. Blood pressure and heart rates recordings before and after motor task.

To verify influence of infrared system on and off on fNIRS signal. fNIRS signals were then low-pass filtered at 0.67 Hz cut-off frequency.

OxyHb and deoxyHb and TOI. PFC.

Increased oxyHb concentration in both channels when walking compared to baseline in patients with ataxia whereas no difference in the controls. No difference in deoxyHb in either group.

Positive correlation between increased oxyHb activity of the PFC bilaterally and wider. No significant correlations between bilateral PFC activation and variability of the joint kinematic parameters.

Manuscript to be reviewed

Author, year | Sample | Aims | Gait assessment | Secondary task | Equipment details | Measureable parameters | Brain areas | Controlling, artefacts and filtering | Results | Limitations | Conclusion
--- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | ---
Al-Yahya et al., 2016 | 19 young adults, 25+ 3 years; 10 HOA, 77 2.5 years old. | To investigate whether PFC (BA 10) functioning during ataxic gait is linked to compensatory mechanisms or to the typical intra-subject variability of the ataxic gait. | Walking on a treadmill at self-selected speed (10 trials). Baseline: last 10s of upright standing period between each trial once stable INIRS signal. Kinematic and spatiotemporal gait variables recorded with a motion capture system: stance, swing and double support duration; gait speed; step length and width; lower limb kinematics including temporal intra-subject variability of hip, knee and ankle joints. | Overground walking for 10m at a self-selected speed (10 trials). | NIRO-200, Hamatsu Photonics KK. Wavelengths: 775nm, 810nm and 850 nm. 2 channels. Interoptode position: 4 cm. Sampling rate: 2Hz. | None. | None. | Significant oxyHb concentration in both channels when walking compared to baseline in patients with ataxia whereas no difference in the controls. No difference in deoxyHb in either group. Positive correlation between increased oxyHb activity of the PFC bilaterally and wider. No significant correlations between bilateral PFC activation and variability of the joint kinematic parameters. | Small sample size which is acknowledged by the author. Influence of skin blood flow on fNIRS signals especially as interoptode distance is high (4 cm). | Likely shift of processing resources from the PFC to other brain regions (not analysed in this study) when HOA faced the challenge of walking and concurrently executing a visually demanding task.
Beurskens et al., 2014 | 15 young adults, 25+ 3 years; 10 HOA, 77 2.5 years old. | To compare the effects of completing a secondary visual checking task versus a verbal memory task during walking on PFC activation in young and HOA. | Walking on a treadmill at self-selected speed (2 trials per condition). Baseline condition: rest period seating on a chair. Gait outcomes: step duration, step length and number of steps. | Walking on a treadmill at self-selected speed (2 trials per condition). Baseline condition: rest period seating on a chair. Gait outcomes: step duration, step length and number of steps. | DYNOT Imaging System, NIRx Medical Technologies, LLC. Wavelengths: 760 nm and 830nm. 14 channels. Interoptode position: 2.2 and 2.5 cm. Sampling rate: 1.81 Hz. | OxyHb and deoxyHb. | OxyHb and deoxyHb. | Tasks were conducted in a dimly illuminated room. Each channel was visually inspected and movement artefacts were corrected and data were reconstructed. Hemodynamic response function low-pass filter and wavelet minimum description length-de-trending algorithm to remove possible global trends due to breathing, heartbeat, vasomotorism or experimental influences. | No between-group difference in brain activation across all channels. No significant effect of verbal memory secondary task (vs. simple walking task) on brain activation in young and HOA. Significant age x condition for visual checking DT: no significant effect of visual checking on hemodynamic response function low-pass filter and wavelet minimum description length-de-trending algorithm to remove possible global trends due to breathing, heartbeat, vasomotorism or experimental influences. | Increased PFC activity in DT walking vs simple task, among stroke patients. No between-group differences in PFC activation during walking.
Caliandro et al., 2014 | 19 individuals with chronic gait ataxia, 31-70 years old, 10 women; 15 healthy controls, 36-73 years old, 8 women. | To investigate whether PFC (BA 10) functioning during ataxic gait is linked to compensatory mechanisms or to the typical intra-subject variability of the ataxic gait. | Walking on a treadmill at self-selected speed (5 trials). Gait spatiotemporal parameters estimated with a pendulum model using kinematic data from an inertial sensor attached at the level of the fourth lumbar vertebra (close to the centre of mass). Additional single task: counting while standing. Baseline: unclear. | Walking on a treadmill at self-selected speed (5 trials). Gait spatiotemporal parameters estimated with a pendulum model using kinematic data from an inertial sensor attached at the level of the fourth lumbar vertebra (close to the centre of mass). Additional single task: counting while standing. Baseline: unclear. | OxyMk III system, Artnetis Medical Systems. Wavelengths: 782 and 859nm. 8 channels. Interoptode position 3.0 cm. Sampling rate: 10Hz. | Oxygen and heart rate parameters estimated using a self-calibrated model using kinematic data attached at the level of the fourth lumbar vertebra (close to the centre of mass). Additional single task: counting while standing. Baseline: unclear. | Oxygen and heart rate parameters estimated using a self-calibrated model using kinematic data attached at the level of the fourth lumbar vertebra (close to the centre of mass). Additional single task: counting while standing. Baseline: unclear. | Increased oxyHb concentration and decreased deoxyHb in DT walking compared with simple-task walking and with standing while counting for both groups and hemispheres. | Increased oxyHb concentration in both channels when walking compared to baseline in patients with ataxia whereas no difference in the controls. No difference in deoxyHb in either group. Positive correlation between increased oxyHb activity of the PFC bilaterally and wider. No significant correlations between bilateral PFC activation and variability of the joint kinematic parameters. | Small sample size which is acknowledged by the author. Influence of skin blood flow on fNIRS signals especially as interoptode distance is high (4 cm). | Likely shift of processing resources from the PFC to other brain regions (not analysed in this study) when HOA faced the challenge of walking and concurrently executing a visually demanding task.

MS patients exhibited higher activation patterns in all conditions (i.e., task and body weight support) when compared to HOA. Significantly greater PFC activation in DT compared with single walking task. Task x cohort interaction whereby greater PFC activation level in MS in DT compared to controls. Cohort x support condition interaction whereby controls showed greater activation in partial body-weight support compared with MS. Cohort x task x support condition whereby MS patients showed higher PFC activation in non-body-weight support condition in DT compared to the controls. No significant correlation between gait parameters and oxyHb levels. Similar levels of activation during the last 10s when compared to the first 10s of trials in controls during simple walking in partial body-weight support and in MS during the DT partial body-weight support trials; this indicates maintenance of PFC activation levels across the trial. Significant time x task x support condition x cohort x time interaction suggesting as difficulty increased and partial body-weight support was provided, HOA increased PFC activation levels while maintaining PFC activation patterns.

MS patients unable to maintain their PFC activation levels across DT walking condition, unless provided with partial body-weight support. Findings may suggest that the use of partial body-weight support may cause a therapeutic effect, which allows individuals with limitations in physical function to maintain their PFC activation levels.

MS participants exhibited higher activation patterns in all conditions (i.e., task and body weight support) when compared to HOA. Significantly greater PFC activation in DT compared with single walking task. Task x cohort interaction whereby greater PFC activation level in MS in DT compared to controls. Cohort x support condition interaction whereby controls showed greater activation in partial body-weight support compared with MS. Cohort x task x support condition whereby MS patients showed higher PFC activation in non-body-weight support condition in DT compared to the controls. No significant correlation between gait parameters and oxyHb levels. Similar levels of activation during the last 10s when compared to the first 10s of trials in controls during simple walking in partial body-weight support and in MS during the DT partial body-weight support trials; this indicates maintenance of PFC activation levels across the trial. Significant time x task x support condition x cohort x time interaction suggesting as difficulty increased and partial body-weight support was provided, HOA increased PFC activation levels while maintaining PFC activation patterns.

MS patients unable to maintain their PFC activation levels across DT walking condition, unless provided with partial body-weight support. Findings may suggest that the use of partial body-weight support may cause a therapeutic effect, which allows individuals with limitations in physical function to maintain their PFC activation levels.

MS participants exhibited higher activation patterns in all conditions (i.e., task and body weight support) when compared to HOA. Significantly greater PFC activation in DT compared with single walking task. Task x cohort interaction whereby greater PFC activation level in MS in DT compared to controls. Cohort x support condition interaction whereby controls showed greater activation in partial body-weight support compared with MS. Cohort x task x support condition whereby MS patients showed higher PFC activation in non-body-weight support condition in DT compared to the controls. No significant correlation between gait parameters and oxyHb levels. Similar levels of activation during the last 10s when compared to the first 10s of trials in controls during simple walking in partial body-weight support and in MS during the DT partial body-weight support trials; this indicates maintenance of PFC activation levels across the trial. Significant time x task x support condition x cohort x time interaction suggesting as difficulty increased and partial body-weight support was provided, HOA increased PFC activation levels while maintaining PFC activation patterns.

MS patients unable to maintain their PFC activation levels across DT walking condition, unless provided with partial body-weight support. Findings may suggest that the use of partial body-weight support may cause a therapeutic effect, which allows individuals with limitations in physical function to maintain their PFC activation levels.
Clark et al., 2014a

To determine if enhancing somatosensory feedback (with a textured insole) can reduce controlled processing during walking, as assessed by PFC activation.

(i) Participants walked for 100m (5 consecutive laps around a 20m course) with a 5.2 m instrumented walkway on the pathway for 66-120s. (ii) Participants walked on a treadmill at a self-selected speed. The participants performed 1 trial per task. Baseline: normal walking with normal shoes. Gait outcomes: walking speed, step length, double support time, variability of step length and of double support time.

(i) Walking for 90m (5 consecutive laps around an 18m course) over a 5.2 m instrumented walkway (1 trial per baseline). Baseline: simple walking. Each trial split into 10s epochs immediately prior to task start (preparation) and full steady-state walking period (performance). Gait outcomes: spatiotemporal parameters.

(ii) Walking at a self-selected pace along a 10m corridor. 3 trials per condition. Each trial block: 16s standing still, 20s walk, 30s standing still. Back and forth for 30s (3 trials). Baseline: first 10s pre-walking and final 10s post walking. Gait outcome: gait speed.

(iii) The individuals walked on a treadmill at preferred and fast walking speed (4 trials per condition). Baseline: very slow walking at 0.2km/h after each trial for 30s. Fast speed (complex condition): addition of 2 km/h to preferred gait speed.

NIR-200, Hamatsu Photonics KK. Intereptode position: 3cm. OxyHb, deoxyHb and TOI. PFC.

1 walking trial per condition: (i) barefoot; (ii) own shoes (iii) own shoes with a textured insole (to enhance somatosensory feedback) (iv) with normal shoes performing a verbal fluency task.

(i) verbal fluency task; (ii) Participants walked in a dark room; (iii) Participants carried a tray while walking; (iv) Participant stepped over small obstacles along the walking path; (v) Participants wore an adjustable weighted vest with a load equal to 10% of body weight. Tasks and baseline condition had same duration. No instructions regarding task prioritization.

Walking speed was slower during DT walking compared with simple walking. Increased bilateral PFC activation during DT was observed only in overground walking and not for walking on treadmill.

The authors pointed that use of multi-distance TOI during performance phase: TOI significantly increased compared with control in all tasks but verbal. Significant effect of task on TOI during performance phase: TOI significantly increased in verbal, obstacles and vest tasks. No significant increase of TOI between preparation and performance phases within any task (trend for verbal). High response subgroup (increased PFC activation during control task preparation and complex tasks performance) had less gait disturbance for 76% of the variables.

No significant difference in PFC activation at baseline. Relative to baseline, barefoot walking yielded lower PFC for treadmill walking, but not overground walking. Increased bilateral PFC activation during DT was observed only in overground walking and not for walking on treadmill.

The authors pointed that increased right PFC activation for treadmill walking versus overground. Relative to baseline, textured insoles yielded a bilateral reduction of PFC activity for treadmill walking and for overground walking. Relative to baseline, barefoot walking yielded lower PFC for treadmill walking, but not overground walking. Increased bilateral PFC activation during DT was observed only in overground walking and not for walking on treadmill.

The authors did not report any controlling for movement artefacts blood pressure or heart rate changes. Some missing data meaning that each comparison includes data from at least 11 out of 14 participants.

Enhanced somatosensory feedback reduces PFC activity during walking in HOA. This suggests a less intensive utilization of controlled processing during walking.

To examine PFC activation during DT walking and executive function (strudop interference).

To investigate if 8 weeks (3 x 30min/week) of exercise training (interactive cognitive-training without balance and stretching training) ex- tends changes in PFC activation levels during challenging treadmill walking (and elicits associated changes in cognitive executive functions).

The individuals walked on a treadmill at preferred and fast walking speed (4 trials per condition). Baseline: very slow walking at 0.2km/h after each trial for 30s. Fast speed (complex condition): addition of 2 km/h to preferred gait speed.

Oxiplex TS Tissue spectrometer. Wavelengths: 690 and 830nm. Two sensors. Sampling rate: 1Hz.

OxyHb and deoxyHb. PFC.

Motion artefacts in oxyHb and deoxyHb were excluded based on specified ranges. Procedure to minimise bias from Mayer waves also applied. Use of multi-distance NIRS instrument to eliminate measurement bias from skin blood flow changes.

OxyHb and deoxyHb. PFC.

No significant difference between left and right PFC activation at baseline. No significant difference in PFC activation at baseline between fast and preferred walking conditions.

Increased gait speed from preferred to fast while walking on a treadmill did not induce increased PFC activation in HOA.
To evaluate changes in cortical activation patterns during walking at low, moderate, and high speeds and to determine whether gait capacity is associated with regional activation patterns in HOA.

Walking at preferred pace on an 18-m oval-shaped course. The healthy groups: 5 laps; stroke survivors: 7 laps.

The authors pointed out that the small sample size was a limitation.

Increased PFC activation in DT walk versus simple walk, compared to healthy controls. Despite similar gait speed and cognitive performance.

To investigate between-group differences in executive control of gait and to determine the extent to which walking-related PFC activity fits existing cognitive framework of the PFC over-activation.

Walking at normal pace along an electronic pathway at self-selected speed for 45meters in a continuous looping (1 trial). Baseline: 15s standing trial with participants counting silently in their head. Gait outcome: gait speed.

Walking while talking: Reciting alternate letters of the alphabet while walking. Instruction to pay equal attention to walking and talking.

Tasks and baseline condition of equal duration to the gait assessment. The outcomes were: correct letter rate and errors per minute.

Half of the participants counted backwards by 1 (easy) and the other half of participants counted backwards by 7 (difficult) while walking. Tasks and baseline condition of equal duration to the gait assessment. The outcome was counting performance.

A low-pass filter was applied to eliminate interference from heart rate, respiration, and other unwanted noise signals. Motion artefact rejection routine applied to eliminate uninterpretable data due to excessive head movement.

Significantly greater oxygenation level in PFC in the difficult versus easy condition. Some regions were not controlled for interference from heart rate, respiration, and other unwanted noise signals. Motion artefact rejection routine applied to eliminate uninterpretable data due to excessive head movement.

No control for movement artefacts. No description of pipeline placement, neither for controlling of external light and heart changes confounding. Finally, the sample size of one group was 10 participants. Groups walking speeds are different.

Increased PFC activation in DT walk versus simple walk, compared to healthy controls. Despite similar gait speed and cognitive performance.

To investigate the levels of PFC activation during gait under single and DT conditions in community-dwelling individuals with and without MS using INIRS.

Walking at normal pace along an electronic pathway at self-selected speed for 45meters in a continuous looping (1 trial). Baseline: 15s standing trial with participants counting silently in their head. Gait outcome: gait speed.

Walking while talking: Reciting alternate letters of the alphabet while walking. Instruction to pay equal attention to walking and talking. Tasks and baseline condition of equal duration to the gait assessment. The outcomes were: correct letter rate and errors per minute.

Half of the participants counted backwards by 1 (easy) and the other half of participants counted backwards by 7 (difficult) while walking. Tasks and baseline condition of equal duration to the gait assessment. The outcome was counting performance.

A low-pass filter was applied to eliminate interference from heart rate, respiration, and other unwanted noise signals. Motion artefact rejection routine applied to eliminate uninterpretable data due to excessive head movement.

A greater increase in oxyHb in the left PFC and the SMA during walking at 70% intensity than at 30% or 50%. Increased activation in the medial SMC and SMA was correlated with increased gait speed and cadence. At 70%, age-related decline in gait capacity was observed.

Young adults have more remaining PFC resources for attending to complex walking conditions and/or secondary cognitive tasks during walking. There is a heightened use of executive control resources in HOA and stroke survivors during walking. The level of PFC resource utilization, particularly during complex walking tasks may approach the ceiling of available resources for individuals who have walking impairments.
To evaluate whether increased PFC activation would be detected during walking while talking as compared with normal walking, and whether the increase in PFC activation during walking would be greater in young compared with HOA.

Holtzer et al., 2011

11 HOA aged 69-88 years old, 7 women; 11 healthy young aged 19-29 years old.

Walking on an electronic pathway at self-selected speed for 4.5m (6 trials). Baseline: 5s standing trial pre-walk. Gait outcome: gait speed.

Reciting alternate letters of the alphabet while walking. Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

Sensor: Drexel Biomedical Engineering Laboratory; Light sources: Epitex Inc. Wavelength: 730, 850nm. 16 channels. Interoptode position: 2.5cm. Sampling rate: 2Hz.

OxyHb. PFC.

Low-pass filter with a finite impulse response filter at 0.14Hz to eliminate possible respiration, heart rate signals, and unwanted high-frequency noise. Using a combined independent component analysis/principal component analysis, environmental and equipment noise and signal drifts were removed from the raw intensity measurements.

Significant age x condition interaction, whereby significant increase in activation levels in PFC bilaterally in WWT compared with NW. The increase is also significantly more pronounced in young compared with the old.

Time course of trial was short as well as the time of baseline condition.

OxyHb levels are increased in the PFC during walking while talking compared with normal walking in healthy young and HOA. HOA may underutilize the PFC in attention-demanding locomotion tasks.

OxyHb levels in all 16 channels were significantly higher in walking while talking trials compared to normal walking trials. Elevated PFC OxyHb levels were maintained throughout the course of walking while talking but not during the normal walking condition. Increased oxygenation levels in the PFC were related to greater stride length and better cognitive performance but not to faster gait velocity in walking while talking. Increased OxyHb levels during walking while talking were related to increased rate of correct letter generation.

PFC plays a functional role in monitoring and allocating cognitive resources during locomotion, especially when cognitive demands are increased.

OxHb levels are more vulnerable to the effect of perceived stress on the change in PFC OxyHb levels across walking conditions that vary in terms of cognitive demands.

To eliminate possible respiration, heart rate signals, and unwanted high-frequency noise, raw intensity measurements at 730 and 850nm were low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.14Hz. Motion artefacts remained were eliminated by visual inspection of an expert fNIRS data analyst. Lighting in the test room: 150lx or 1/3 of typical office lighting.

Attention in increase in OxyHb levels, in high compared to low perceived stress levels, from the two single-task conditions to walking while talk was observed only in men.
Koenraadt et al., 2014

Holtzer et al., 2016

3 continuous loops of walking on an electronic pathway (6 straight line trials of 4.5 m-long) at self-selected speed. Baseline: 10s standing trial pre-walk, counting silently in the head at rate of one number per second. Gait outcome: stride velocity. Reciting alternate letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

To determine whether subjective fatigue was associated with objective fatigue measures, assessed during single and attention-demanding DT walking conditions, in HOA.

Koenraadt et al., 2014

11 healthy young adults, 23 ± 4 years old, 8 women.

To understand the neural mechanism of precision stepping in comparison with normal gait. Also, to evaluate the role of different motor areas in the neural control of gait.

Walking on a treadmill at 3km/h for 35s (10 trials). Baseline: 25 to 35s quiet standing prior to each walking trial. Gait outcome: step time variability.

Left hemisphere: S1, M1, SMA, pre-SMA and PFC.

Precision stepping walking on a treadmill at 3km/h (10 trials).

OxyHb and deoxyHb.

OxyHb and deoxyHb.

To eliminate possible respiration, heart rate signals, and unwanted high-frequency noise, raw intensity measurements at 730 and 850nm were low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.14Hz. Noise (saturation or dark current conditions) was observed in 4% of the data that were subsequently excluded.

To eliminate possible respiration, heart rate signals, and unwanted high-frequency noise, raw intensity measurements at 730 and 850nm were low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.14Hz. Saturation or dark current conditions were excluded.

Second order low-pass Butterworth filter with a cut-off frequency of 0.125Hz was conducted to reduce high frequency noise. A second order high-pass Butterworth filter with a cut-off frequency of 0.01Hz was used to reduce low frequency drift caused by NIRS. After the correction for superficial interference, a second order low pass Butterworth filter with a cut-off frequency of 1Hz was conducted. Continuous blood pressure monitoring. Short separation channels were used to remove hemodynamic changes in superficial tissue layers.

Imager 1000 (NIRx Devices LLC, Potomac MD). Wavelength: 730, (805 not used) and 850nm. 16 channels. Interepode position: 2.5cm. Sampling rate: 2Hz.

Imager 1000 (NIRx Devices LLC, Potomac MD). Wavelength: 730, 850nm. 6-channel motor cortices unit and a 3-channel PFC unit. Interepode position 1.0 and 4.0cm. Sampling rate: 25Hz.

Higher oxyHb levels during walking while talking significantly higher compared with normal walk in normal.

Central neural gait abnormalities was associated with significantly attenuated changes in oxyHb levels in walking while talking compared to single walking task. Among participants without neurological gait abnormalities, higher oxyHb levels (versus lower oxyHb levels-median split) were related to better cognitive performance, but faster gait velocity. In contrast, higher oxyHb levels during walking while talking among older adults with peripheral neurological gait abnormalities were associated with worse cognitive performance, but faster gait velocity.

To determine the effect of neurological gait abnormalities on the functional neural correlates of locomotion in older adults with regards to the posture first hypothesis.

3 continuous loops of walking on an electronic pathway (6 straight line trials of 4.5 m-long) at self-selected speed. Baseline: 10s standing trial pre-walk, counting silently in the head at rate of one number per second. Gait outcome: stride velocity. Reciting alternate letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

Unknown if lighting conditions were controlled for.

OxyHb.

PFC.

To eliminate possible respiration, heart rate signals, and unwanted high-frequency noise, raw intensity measurements at 730 and 850nm were low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.14Hz. Noise (saturation or dark current conditions) was observed in 4% of the data that were subsequently excluded.

To determine whether subjective fatigue was associated with objective fatigue measures, assessed during single and attention-demanding DT walking conditions, in HOA.

Holtzer et al., 2017b

314 HOA, 76.8 ± 6.7 years old, 176 women.

To determine whether subjective fatigue was associated with both the increase of oxyHb levels from normal walking to walking while talking and the trajectory of oxyHb during the course of walking while talking. The trajectory of oxyHb during simple walking, however, was not associated with subjective fatigue.

Worse subjective fatigue was associated with attenuation in both the increase of oxyHb levels from normal walking to walking while talking and the trajectory of oxyHb during the course of walking while talking. A prolonged walk-while-talk.

The authors pointed as limitation the small number of episodes used in this study.

The lack of M1/S1 activation during gait suggests that even in the current precision stepping task the control of ongoing gait depended mostly on subcortical automatisms, while motor cortices contributions did not differ significantly.

Unknown if lighting conditions were controlled for.

OxyHb.

PFC.

OxyHb.

PFC.

OxyHb.

PFC.

Neural confirmation of the posture first hypothesis emerged among older adults whose postural and locomotive abilities were compromised. Increased activation in the PFC during locomotion may have a compensatory function that is designed to support gait among older adults with peripheral neurological gait abnormalities.

Worse subjective fatigue was associated with attenuation in both the increase of oxyHb levels from normal walking to walking while talking and the trajectory of oxyHb during the course of walking while talking. The trajectory of oxyHb during simple walking, however, was not associated with subjective fatigue.

To eliminate possible respiration, heart rate signals, and unwanted high-frequency noise, raw intensity measurements at 730 and 850nm were low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.14Hz. Noise (saturation or dark current conditions) was observed in 4% of the data that were subsequently excluded.

To determine whether subjective fatigue was associated with objective fatigue measures, assessed during single and attention-demanding DT walking conditions, in HOA.

Holtzer et al., 2016

167 HOA with no gait impairments, 74.4 ± 6.0 years old, 85 women; (ii) 40 older adults with peripheral neurological gait abnormalities, 77.0 ± 6.3 years old, 17 women; (iii) 29 older adults with central neurological gait abnormalities, 79.6 ± 7.4 years old, 20 women.
To investigate the influence of cognitive task complexity and walking road condition on the neural correlates of executive function and postural control in DT walking.

Lin & Lin, 2016

24 healthy young adults, 20-27 years old, 12 women.

Lu et al., 2015

17 healthy young adults, 25.1 ± 1.5 years old, 8 women.

Lucas et al., 2018

55 older adults, 74.8 ± 5.0 years old, 49% female. Participants were divided into a low white matter integrity group (n=27) and a medium-high white matter integrity group (n=28).

All tasks were performed for 60s (split in 3 20s periods to analyse time effects) - 2 trials per condition: (i) walking on a narrow pathway (0.5m width); (ii) obstacles (5 traffic cones) avoidance; (ii) easy walking memory task (1-back task); (ii) hard working memory task (3-back task). Cognitive tasks outcomes: ratio of the number of correct responses to the number of all responses; average reaction time of the correct responses. No explicit instructions regarding task prioritization.

Walking on a 20m walkway, 2m in width for 60s (1 trial).

Baseline: 40s quiet standing while fixing a cross on a smartphone held by participants (20s prior and 20s after the task). Gait outcomes: spatiotemporal and kinematic measures.

Walking at a self-selected pace over a 5.50m long-electronic walkway for 60s (split in early phase: 5-20s and late phase: 21-50s) (3 trials). The first 5s and the last 10 were excluded due to hemodynamic effects. Baseline: 5s standing still. Gait outcomes: Temporal-spatial measures.

3 trials in each condition, block-randomized: (i) walking while performing a cognitive task (subtracting 7 from an initial 5-digit number); (ii) walking while performing a motor task (carrying a bottle on a tray). Tasks duration and baseline condition are equal the gait assessment.

3 continuous loops of walking on an electronic walkway (6 straight line trials of 4.5 m-long) at self-selected speed. Baseline: 1sts standing trial pre-walk, counting silently in the head at rate of one number per second. Gait outcome: stride velocity.

Repeating alternate letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

Walking on 20m walkway, 2m in width for 60s (1 trial).

Baseline: 40s quiet standing while fixing a cross on a smartphone held by participants (20s prior and 20s after the task). Gait outcomes: spatiotemporal and kinematic measures.

Data was low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.2Hz to attenuate the noises from non-evoked neurovascular coupling. OxyHb levels changed significantly over time in all conditions. Relative changes in oxyHb concentration levels were all significantly different across the task complexity and walking conditions. OxyHb levels were all lower during DT walking than normal walking. Compared to wide and obstacle conditions, walking on the narrow road was found to elicit a smaller decrement in oxyHb levels. No significant correlation between the RT and the accuracy of the b-back tasks and fNIRS data.

Healthy young adults are inclined to focus on the challenging working memory task and sacrificed gait performance to some extent through altered neural activations in the PFC and adapted coordination of lower-extremity kinematics.

To determine possible respiration, heart rate signals, and unwanted high-frequency noise, raw intensity measurements at 730 and 850nm were low-pass filtered with a finite impulse response filter with a cut-off frequency of 0.14Hz. Saturation or dark current conditions were excluded. Visual inspection to manually remove movement artefacts, saturation and dark current levels.

OxyHb levels increased from single to DT walking. White matter microstructural integrity moderated the effect of DT on oxyHb after controlling for gait performance. The authors did not record the cognitive task and motor task performances in the DT conditions compared with the single tasks.

The authors did not focus on the control mechanism for maintaining gait performance during DT.

PFC, PMC and SMA were divided into a healthy young adults, 20-27 years old, 12 women. 55 older adults, 74.8 ± 5.0 years old, 49% female. Participants were divided into a low white matter integrity group (n=27) and a medium-high white matter integrity group (n=28).

To examine the relationship between white matter microstructural integrity and changes in PFC oxyHb during active walking in older adults.

To the relationship between white matter microstructural integrity and changes in PFC oxyHb during active walking in older adults.

To examine the relationship between white matter microstructural integrity and changes in PFC oxyHb during active walking in older adults.

To present the relationship between white matter microstructural integrity and changes in PFC oxyHb during active walking in older adults.

To examine the relationship between white matter microstructural integrity and changes in PFC oxyHb during active walking in older adults.

To examine the relationship between white matter microstructural integrity and changes in PFC oxyHb during active walking in older adults.
To explore the effects of obstacle negotiation in people with PD.

To assess the effect of PFC activation during normal walking compared with HOA.

Maidan et al., 2016

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

(i) to examine changes in PFC activation during obstacle negotiation and DT walking, as compared with normal walking in HOA; (ii) to investigate changes in PFC activation during normal walking, DT and obstacle negotiation in people with PD; (iii) to compare PFC activation during the walking conditions between HOA and people with PD.

Overground walking at a self-selected pace (30m) for 50s (5 trials).

Baseline: 5 s standing still (out of 20s before and 20s after each trial).

Gait outcomes: gait speed and stride length.

5 trials in each condition: (i) DT: walking while serially subtracting 3 from a given 3-digit number. The outcomes were: gait speed, stride length, DT cost and percentage of correct response; (ii) obstacle negotiation. The outcomes were: gait speed, duration of stepping over the obstacle and percentage change in step duration between steps over obstacle and normal steps.

Overground walking at a self-selected pace (30m) for 50s (5 trials).

Baseline: 5 s standing still (out of 20s before and 20s after each trial).

Gait outcomes: gait speed and stride length.

5 trials in each condition: (i) DT: walking while serially subtracting 3 from a given 3-digit number. The outcomes were: gait speed, stride length, DT cost and percentage of correct response; (iii) obstacle negotiation. The outcomes were: gait speed, duration of stepping over the obstacle and percentage change in step duration between steps over obstacle and normal steps.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

(i) to examine changes in PFC activation during obstacle negotiation and DT walking, as compared with normal walking in HOA; (ii) to investigate changes in PFC activation during normal walking, DT and obstacle negotiation in people with PD; (iii) to compare PFC activation during the walking conditions between HOA and people with PD.

Overground walking on an elliptical path of 50m. 4.5s before each obstacle. Gait outcomes: gait speed and stride length.

One trial of overground walking on an elliptical path of 50m. 4.5s before each obstacle. Gait outcomes: gait speed and stride length.

3 trials in each of 4 conditions: anticipated and unanticipated obstacles with 2 different heights (50 and 100 mm). The baseline condition and the gait outcomes were the same as the simple walking. 3 phases of 5s analysed: before, over and after obstacles.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

(i) to examine changes in PFC activation during obstacle negotiation and DT walking, as compared with normal walking in HOA; (ii) to investigate changes in PFC activation during normal walking, DT and obstacle negotiation in people with PD; (iii) to compare PFC activation during the walking conditions between HOA and people with PD.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

(i) to examine changes in PFC activation during obstacle negotiation and DT walking, as compared with normal walking in HOA; (ii) to investigate changes in PFC activation during normal walking, DT and obstacle negotiation in people with PD; (iii) to compare PFC activation during the walking conditions between HOA and people with PD.

Overground walking on an elliptical path of 50m. 4.5s before each obstacle. Gait outcomes: gait speed and stride length.

One trial of overground walking on an elliptical path of 50m. 4.5s before each obstacle. Gait outcomes: gait speed and stride length.

3 trials in each of 4 conditions: anticipated and unanticipated obstacles with 2 different heights (50 and 100 mm). The baseline condition and the gait outcomes were the same as the simple walking. 3 phases of 5s analysed: before, over and after obstacles.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

To explore the effects of obstacle height and available response time on PFC activation.

Maidan et al., 2018

20 healthy young adults, 30.1 ± 1.0 years old, T0 women.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.

Walking on a treadmill at a self-selected pace and 20% faster for 30s trials at normal speed, fast speed, with and without secondary task. Baseline: 10s standing still in the middle of resting time between trials. Gait outcome: step time.
To study the effects of aging on gait and PFC activation in complex walking task with internal and external task demands. 5 trials of walking on a 30m walkway at self-selected speed. Baseline: 20s standing still pre-trial. Gait outcomes: spatiotemporal variables from an electronic mat placed in the middle of the walkway.

(i) walking while serially subtracting 7 from a pre-determined 3 digit number; (ii) walking while negotiating two physical obstacles. Tasks duration and baseline condition are equal to the gait assessment. The DT score was also calculated.

3 blocks (i) control period: the participants were instructed to repeat the number 1-10 in sequence; (ii) calculation period: participants performed subtractions of 3, beginning with a random number between 100 and 199. Participants performed calculation tasks while standing and walking. Mean values of correct and mistaken answers in each condition were compared.

Walking at a comfortable pace around a circle with a radius of 2.5m for 60s. Baseline: 40s prior to calculation task and 20s after the task. The outcome measured was the trunk linear acceleration.

To investigate the association between PFC activity and DT interference on physical and cognitive performance in stroke survivors.

A band-pass filter with a low pass (0.5Hz) was applied to account for the effects of Mayer waves and high-frequency fluctuations, whereas that with a high pass (60Hz) was used for baseline drift.

A band-pass filter with frequency of 0.01-0.14Hz was used to reduce physiological noise such as heart beat and drift of the signal. To remove motion artefacts a wavelet filter was used, followed by correlation based signal improvement. Probes were shielded from ambient light using a black cloth.

A band-pass filter with a high pass (0.01 Hz) was applied to account for the effects of Mayer waves and high-frequency fluctuations, whereas that with a high pass (60Hz) was used for baseline drift.

To investigate the association between PFC activity and DT interference on physical and cognitive performance in stroke survivors.

Walking at a comfortable pace around a circle with a radius of 2.5m for 60s. Baseline: 40s prior to calculation task and 20s after the task. The outcome measured was the trunk linear acceleration.

(i) walking while serially subtracting 7 from a pre-determined 3 digit number; (ii) walking while negotiating two physical obstacles. Tasks duration and baseline condition are equal to the gait assessment. The DT score was also calculated.

A band-pass filter with frequency of 0.01-0.14Hz was used to reduce physiological noise such as heart beat and drift of the signal. To remove motion artefacts a wavelet filter was used, followed by correlation based signal improvement. Probes were shielded from ambient light using a black cloth.
(ii) 10 obese, 80.5 ± 7.4 years old, 8 women; adults: (i) 10 non-adults, 28.1 ± 7.4 obese, 80.6 ± 7.5 20 community-years old, 2 women.

To determine the obesity-specific activation of the PFC using fNIRS during simple and complex ambulatory tasks in older adults.

Walking back and forth at a self-selected pace for 30s (4 trials). Baseline: 30s quiet sitting. 10s quiet standing in between each trial and 2 min of seated rest between blocks. Gait outcome: gait speed.

Three locomotor tasks: walking at 3km/h, 5 km/h and walking at 9km/s on a treadmill for 90s (1 trial). Baseline: 20s standing still. Gait outcome: cadence. 60s rest between trials (30s before, 30s after).

Increase in locomotor speed. Task data in the 13-s period just before reaching each constant speed were used for analysis.

OxyHb and total Hb levels. PFC, PMC, medial SMC and lateral SMC.

Blood pressure, heart rate and arterial oxygen saturation were measured immediately before and after each task.

PFC activation was significantly greater when the participants ran at 9km/h than when they walked at 3km/h and 5km/h. Activations in the PFC, PMC and medial SMC were significantly greater than that in the lateral SMC.

The authors pointed out limitations: the small sample; that they did not control blood pressure simultaneously with fNIRS that they did not control for superficial hemodynamics using short reference channels for example.

In order to maintain gait performance, obesity was associated with higher forefoot load, and this was augmented during ambulatory tasks requiring greater precision control.

The PFC was significantly more activated during the periods before reaching a constant speed in the 9km/h run compared with the 5km/h walk and compared with the 3km/h walk. PFC might be involved together with other structures in controlling locomotion to adapt to the increasing speed in the acceleration of phase of locomotion.

No mention of filtering or controlling for movement artefacts and ambient light in this study.

Using the new wireless fNIRS devices described in this paper, it is feasible to measure the PFC activity in PD during DT walking.
To assess how a verbal instruction before walking would affect cortical activation and walking performance using fNIRS.

Treadmill walking at 3 km/h in 2 conditions: (i) Simple walking – 40 s of walking; (ii) Prepared walking: after verbal instruction walking for 30 s (10 s standing pre-walking but post “ready” instruction, also recorded). 4 trials in each condition. Pseudorandomized rest (10, 15, 20 and 25 s). Baseline: 10 s standing still. Gait outcomes: cadence and stride length.

5 trials in DT condition: performing a number-selecting task on a smartphone while walking for 30 s. Cognitive-only task: same smartphone while they were seated. Cognitive outcomes: number of correct responses and errors. Tasks duration was similar across conditions. DT cost of cognitive and gait performance compute. Participants were instructed not to continuously prioritize to either task.

To evaluate the correlation between PFC activity and DT cost during smartphone use while walking in young and HOA.

Five 30s-trials at self-selected speed in each condition in the following fixed order: (i) overground walk: in a 30m corridor; (ii) treadmill walk. Baseline: 20 s standing still before and after each trial. Gait outcomes: gait speed and stride time.

Three continuous loops of walking on an electronic pathway (6 straight line trials of 4.5 m-long) at self-selected speed. Baseline: 10 s standing trial pre-walk, counting silently in the head at a rate of one number per second. Gait outcome: stride velocity.

To determine whether PFC activity during walking predicts falls in HOA.

Repeating alternate letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

To investigate whether during treadmill walking, PFC activation in people with PD is lower as compared to overground walking.

To analyze PFC activation while performing a number-selecting task on a smartphone while walking for 30 s. Cognitive-only task: same smartphone while they were seated. Cognitive outcomes: number of correct responses and errors. Tasks duration was similar across conditions. DT cost of cognitive and gait performance compute. Participants were instructed not to continuously prioritize to either task.

Jump speed measurement was used in various studies: (i) Simple jump: 40 s of walking. Baseline: 10 s standing still. Gait outcomes: cadence and stride length.

5 trials in DT condition: performing a number-selecting task on a smartphone while walking for 30 s.

3 continuous trials of walking on an electronic pathway (4.5 m-long) at self-selected speed. Baseline: 10 s standing trial pre-walk, counting silently in the head at a rate of one number per second. Gait outcome: stride velocity.

To determine whether PFC activity during walking predicts falls in HOA.

Repeating alternating letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

To assess how a verbal instruction before walking would affect cortical activation and walking performance using fNIRS.

Treadmill walking at 3 km/h in 2 conditions: (i) Simple walking – 40 s of walking; (ii) Prepared walking: after verbal instruction walking for 30 s (10 s standing pre-walking but post “ready” instruction, also recorded). 4 trials in each condition. Pseudorandomized rest (10, 15, 20 and 25 s). Baseline: 10 s standing still. Gait outcomes: cadence and stride length.

5 trials in DT condition: performing a number-selecting task on a smartphone while walking for 30 s. Cognitive-only task: same smartphone while they were seated. Cognitive outcomes: number of correct responses and errors. Tasks duration was similar across conditions. DT cost of cognitive and gait performance compute. Participants were instructed not to continuously prioritize to either task.

To investigate whether during treadmill walking, PFC activation in people with PD is lower as compared to overground walking.

Five 30s-trials at self-selected speed in each condition in the following fixed order: (i) overground walk: in a 30m corridor; (ii) treadmill walk. Baseline: 20 s standing still before and after each trial. Gait outcomes: gait speed and stride time.

3 continuous loops of walking on an electronic pathway (6 straight line trials of 4.5 m-long) at self-selected speed. Baseline: 10 s standing trial pre-walk, counting silently in the head at a rate of one number per second. Gait outcome: stride velocity.

To determine whether PFC activity during walking predicts falls in HOA.

Repeating alternate letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.

To assess how a verbal instruction before walking would affect cortical activation and walking performance using fNIRS.

Treadmill walking at 3 km/h in 2 conditions: (i) Simple walking – 40 s of walking; (ii) Prepared walking: after verbal instruction walking for 30 s (10 s standing pre-walking but post “ready” instruction, also recorded). 4 trials in each condition. Pseudorandomized rest (10, 15, 20 and 25 s). Baseline: 10 s standing still. Gait outcomes: cadence and stride length.

5 trials in DT condition: performing a number-selecting task on a smartphone while walking for 30 s. Cognitive-only task: same smartphone while they were seated. Cognitive outcomes: number of correct responses and errors. Tasks duration was similar across conditions. DT cost of cognitive and gait performance compute. Participants were instructed not to continuously prioritize to either task.

To investigate whether during treadmill walking, PFC activation in people with PD is lower as compared to overground walking.

Five 30s-trials at self-selected speed in each condition in the following fixed order: (i) overground walk: in a 30m corridor; (ii) treadmill walk. Baseline: 20 s standing still before and after each trial. Gait outcomes: gait speed and stride time.

3 continuous loops of walking on an electronic pathway (6 straight line trials of 4.5 m-long) at self-selected speed. Baseline: 10 s standing trial pre-walk, counting silently in the head at a rate of one number per second. Gait outcome: stride velocity.

To determine whether PFC activity during walking predicts falls in HOA.

Repeating alternate letters of the alphabet while walking 3 continuous loops as in the single walking task (6 straight line trials of 4.5 m-long). Instruction to pay equal attention to their walking and talking. Outcomes: letter rate and errors per minute.
Table 2: Effect of the additional tasks relative to baseline conditions on regional cortical activation in healthy young adults, healthy older adults and clinical groups with balance disorders.

PFC: Prefrontal cortex; preSMA: Pre-supplementary motor area; SMA: Supplementary motor area; S1: Primary sensorimotor cortex; M1: Primary motor cortex; PMC: Premotor cortex; mSMC: Medial sensorimotor cortex; (+) higher activation when performing the additional task; (-) lower activation when performing the additional task; (=) no changes in activation;  
Baseline comparison: ¹standing still; ²simple walking; ³easier level of the secondary task.  
Significant differences only for: ⁴first half of the task; ⁵second half of the task; ⁶obstacle negotiation and wearing a vest with 10% body weight conditions; ⁷walk vs. visual task; ⁸walk vs alphabet recall; ⁹overground walking; ¹⁰walking and counting backwards task. ⁹⁰Ataxia; ⁹²Stroke; ⁹³Parkinson’s disease; ⁹⁴Obesity; ⁹⁵Multiple Sclerosis; ⁹⁶Mild Cognitive Impairment; ⁹⁷Neurological gait.
### Healthy young adults | Healthy older adults | Clinical groups with balance disorders
--- | --- | ---
Simple walking
Caliandro et al., 2015¹ | PFC (+) | PFC (+)
Lin; Lin, 2016¹ | PFC (+) | PFC (+)³
Hawkins et al., 2018¹ | PFC (+) | PFC (+)³, PFC (=)⁵
Thumm et al., 2018¹ | PFC (+) | PFC (+)³, PFC (=)⁵, b

Fast walking
Harada et al., 2009¹ | PFC (+) | PFC (+)³
Eggenberger et al., 2016² | PFC (=) | PFC (=)³
Suzuki et al., 2004² | PFC (+) | PFC (+)³, PFC (=)⁵, b
Thumm et al., 2018¹ | PFC (+) | PFC (+)³

Motor task
Chen et al., 2017² | PFC (+)⁶ | PFC (+)⁶
Clark et al., 2014a² | PFC (+)⁶ | PFC (+)⁶
Koenraadt et al., 2014² | PFC (+), presMA (=), SMA (=), S1 (=), M1 (=) | PFC (+)⁶
Lin; Lin, 2016¹ | PFC (+)⁶ | PFC (+)⁶
Lu et al., 2015² | PFC (+)⁶ | PFC (+)⁶
Maidan et al., 2016² | PFC (+)⁶ | PFC (+)⁶
Maidan et al., 2018² | PFC (+)⁶ | PFC (+)⁶
Mirelman et al., 2017² | PFC (+)⁶ | PFC (+)⁶
Osofundiya et al., 2016¹,² | PFC (+)⁶ | PFC (+)⁶
Hawkins et al., 2018¹ | PFC (+)⁶ | PFC (+)⁶

Somatosensory task
Chaparro et al., 2017¹,³ | PFC (+)⁶ | PFC (+)⁶
Clark et al., 2014a² | PFC (+)⁶ | PFC (+)⁶
Clark et al., 2014b² | PFC (+)⁶ | PFC (+)⁶

Cognitive task
Al-Yahya et al., 2016² | PFC (+)⁶ | PFC (+)⁶
Beurskens et al., 2014² | PFC (+)⁶ | PFC (+)⁶
Chaparro et al., 2017¹,³ | PFC (+)⁶ | PFC (+)⁶
Chen et al., 2017² | PFC (+)⁶ | PFC (+)⁶
Clark et al., 2014a² | PFC (+)⁶ | PFC (+)⁶
Clark et al., 2014b² | PFC (+)⁶ | PFC (+)⁶
Doi et al., 2013² | PFC (+)⁶ | PFC (+)⁶
Hernandez et al., 2016² | PFC (+)⁶ | PFC (+)⁶
Hill et al., 2013³ | PFC (+)⁶ | PFC (+)⁶
Hawkins et al., 2018¹ | left PFC (+)⁶ | PFC (+)⁶
Holtzer et al., 2011² | PFC (+)⁶ | PFC (+)⁶
Holtzer et al., 2015² | PFC (+)⁶ | PFC (+)⁶
Holtzer et al., 2016² | PFC (+)⁶ | PFC (+)⁶
Holtzer et al., 2017a² | PFC (+)⁶ | PFC (+)⁶
Holtzer et al., 2017b² | PFC (+)⁶ | PFC (+)⁶
Lin; Lin, 2016¹ | PFC (+)⁶ | PFC (+)⁶
Lu et al., 2015² | PFC (+)⁶ | PFC (+)⁶
Lucas et al., 2018² | PFC (+)⁶ | PFC (+)⁶
Maidan et al., 2016² | PFC (+)⁶ | PFC (+)⁶
Meester et al., 2014² | right PFC (+)⁶ | PFC (+)⁶
Mirelman et al., 2014² | PFC (+)⁶ | PFC (+)⁶
Mirelman et al., 2017² | PFC (+)⁶ | PFC (+)⁶
Mori et al., 2018¹,² | PFC (+)⁶ | PFC (+)⁶
| Study                      | Cat 1 | Cat 2 | Cat 3 |
|---------------------------|-------|-------|-------|
| Nieuwoolf et al., 2016   | PFC (+)|       |       |
| Osofundiya et al., 2016   | PFC (+)|       |       |
| Takeuchi et al., 2016     | PFC (−)|       |       |
| Verghese et al., 2017     | PFC (+)|       |       |

Note: Cat 1: PFC (+); Cat 2: PFC (−); Cat 3: PFC (+)
Table 3 (on next page)

Table 3: Methodological reporting criteria ratings for the included studies.
| Study                  | Equipment details provided | Movement artefacts considered | Optode placement specified | External light confounding effect considered | Heart changes confounding effect considered | Sample size (n>10 per group) | Score | Quality criteria |
|-----------------------|-----------------------------|-------------------------------|---------------------------|---------------------------------------------|---------------------------------------------|-------------------------------|-------|------------------|
| Al-Yahya et al., 2016 | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Beurskens et al., 2014| 1                           | 1                             | 1                         | 1                                           | 1                                           | 1                             | 6     | High quality     |
| Caliandro et al., 2015| 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Chaparro et al., 2017 | 1                           | 0                             | 0                         | 0                                           | 1                                           | 1                             | 3     | Medium quality   |
| Chen et al., 2017     | 1                           | 1                             | 0                         | 1                                           | 1                                           | 1                             | 5     | High quality     |
| Clark et al., 2014a   | 0                           | 0                             | 0                         | 0                                           | 0                                           | 1                             | 1     | Low quality      |
| Clark et al., 2014b   | 0                           | 0                             | 0                         | 0                                           | 0                                           | 1                             | 1     | Low quality      |
| Doi et al., 2013      | 1                           | 1                             | 1                         | 0                                           | 0                                           | 1                             | 4     | Medium quality   |
| Eggenberger et al., 2016| 1                         | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Harada et al., 2009   | 1                           | 0                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Hawkins et al.,2018   | 1                           | 1                             | 0                         | 0                                           | 0                                           | 0                             | 2     | Low quality      |
| Hernandez et al., 2016| 1                           | 1                             | 1                         | 1                                           | 1                                           | 0                             | 5     | High quality     |
| Hill et al., 2013     | 1                           | 1                             | 0                         | 0                                           | 1                                           | 0                             | 3     | Medium quality   |
| Holtzer et al., 2011  | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Holtzer et al., 2015  | 1                           | 1                             | 1                         | 1                                           | 1                                           | 1                             | 6     | High quality     |
| Holtzer et al., 2016  | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Holtzer et al., 2017a | 1                           | 1                             | 0                         | 0                                           | 1                                           | 1                             | 4     | Medium quality   |
| Holtzer et al., 2017b | 1                           | 1                             | 0                         | 0                                           | 1                                           | 1                             | 4     | Medium quality   |
| Koenraadt et al., 2014| 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Lin & Lin, 2016       | 1                           | 0                             | 1                         | 0                                           | 0                                           | 1                             | 3     | Medium quality   |
| Lu et al., 2015       | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Lucas et al., 2018    | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Maidan et al., 2016   | 1                           | 1                             | 0                         | 1                                           | 1                                           | 1                             | 5     | High quality     |
| Maidan et al., 2018   | 1                           | 1                             | 1                         | 1                                           | 1                                           | 1                             | 6     | High quality     |
| Meester et al., 2014  | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Mirelman et al., 2014 | 1                           | 0                             | 1                         | 0                                           | 0                                           | 1                             | 3     | Medium quality   |
| Mirelman et al., 2017 | 1                           | 1                             | 1                         | 1                                           | 1                                           | 1                             | 6     | High quality     |
| Mori et al., 2018     | 1                           | 1                             | 1                         | 0                                           | 1                                           | 1                             | 5     | High quality     |
| Nieuwhof et al., 2016 | 1                           | 1                             | 0                         | 1                                           | 1                                           | 1                             | 5     | High quality     |
| Reference               | 1 | 0 | 1 | 1 | 1 | 1 | 4 | Quality    |
|------------------------|---|---|---|---|---|---|---|-----------|
| Osofundiyi et al., 2016|   |   | 1 | 1 | 1 | 1 | 4 | Medium quality |
| Suzuki et al., 2008    | 1 | 0 | 0 | 0 | 0 | 0 | 1 | Low quality |
| Suzuki et al., 2004    | 1 | 0 | 0 | 0 | 1 | 0 | 2 | Low quality |
| Takeuchi et al., 2016  | 1 | 0 | 1 | 0 | 0 | 1 | 3 | Medium quality |
| Thumm et al., 2018     | 1 | 0 | 1 | 0 | 0 | 1 | 3 | Medium quality |
| Verghese et al., 2017  | 1 | 1 | 1 | 0 | 1 | 1 | 5 | High quality  |
Table 4: Prefrontal cortical activation in relation to methodological reporting scale.
|                         | Increase | No change | Decrease |
|------------------------|----------|-----------|----------|
| **Healthy young adults** |          |           |          |
| Suzuki et al., 2008    | low       | medium     | high      |
| Hill et al., 2013      | medium    | medium     | medium    |
| Lu et al., 2015        | high      | high       | high      |
| Lin et al., 2016       | low       | medium     | high      |
| Mirelman et al., 2014  | low       | medium     | high      |
| Hawkins et al., 2018   | low       | medium     | high      |
| Takeuchi et al., 2016  | low       | medium     | high      |
| Lin et al., 2016       | low       | low        | medium    |
| Koenraad et al., 2014  | low       | low        | medium    |
| **Healthy older adults** |          |           |          |
| Clark et al., 2014a    | low       | medium     | high      |
| Holtzer et al., 2017a  | medium    | medium     | medium    |
| Holtzer et al., 2017b  | high      | high       | high      |
| Osofundiya et al., 2016| low       | medium     | high      |
| Osofundiya et al., 2016| medium    | medium     | medium    |
| Chaparro et al., 2017  | high      | high       | high      |
| Clark et al., 2014b    | low       | medium     | high      |
| Hawkins et al., 2018   | medium    | medium     | medium    |
| Takeuchi et al., 2016  | high      | high       | high      |
| Caliandro et al., 2015 | low       | medium     | high      |
| Beursken et al., 2014  | low       | low        | medium    |
| Al-Yahya et al., 2016  | low       | low        | medium    |
| Harada et al., 2009    | low       | low        | medium    |
| Mirelman et al., 2017  | low       | medium     | high      |
| Maidan et al., 2016    | low       | medium     | high      |
| Holtzer et al., 2011   | low       | medium     | high      |
| Chen et al., 2017      | low       | medium     | high      |
| Hernandez et al., 2016 | low       | medium     | high      |
| Holtzer et al., 2011   | low       | medium     | high      |
| Holtzer et al., 2016   | low       | medium     | high      |
| Maidan et al., 2016    | low       | medium     | high      |
| Verghez et al., 2017   | low       | medium     | high      |
| **Clinical groups with balance disorders** |          |           |          |
| Hawkins et al., 2018   | low       | medium     | high      |
| Hawkins et al., 2018   | medium    | medium     | medium    |
| Hawkins et al., 2018   | high      | high       | high      |
| Osofundiya et al., 2016| low       | medium     | high      |
| Chaparro et al., 2017  | medium    | medium     | medium    |
| Al-Yahya et al., 2016  | high      | high       | high      |
| Maidan et al., 2016    | low       | medium     | high      |
| Holte et al., 2016     | low       | medium     | high      |
| Osofundiya et al., 2016| low       | medium     | high      |
| Caliandro et al., 2015 | low       | medium     | high      |
| Beursken et al., 2014  | low       | low        | medium    |
| Al-Yahya et al., 2016  | low       | low        | medium    |
| Harada et al., 2009    | low       | low        | medium    |
| Mirelman et al., 2017  | low       | medium     | high      |
| Maidan et al., 2016    | low       | medium     | high      |
| Holtzer et al., 2011   | low       | medium     | high      |
| Chen et al., 2017      | low       | medium     | high      |
| Hernandez et al., 2016 | low       | medium     | high      |
| Holtzer et al., 2011   | low       | medium     | high      |
| Holtzer et al., 2016   | low       | medium     | high      |
| Maidan et al., 2016    | low       | medium     | high      |
| Verghez et al., 2017   | low       | medium     | high      |
Table 5: Prefrontal cortical activation in relation to complex walking tasks.
| Increase | No change | Decrease |
|----------|-----------|----------|
| **Healthy young adults** | | |
| Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards |
| Hill et al., 2013 | Lu et al., 2015 | Koenraadt et al., 2014 | Beurskens et al., 2014 | Lin; Lin, 2016 |
| Lu et al., 2015 | Suzuki et al., 2004 | Hawkins et al., 2018 | Beurskens et al., 2014 | Koenraadt et al., 2014 |
| Meester et al., 2014 | Maidan et al., 2018 | Mirelman et al., 2017 | Takasugi et al., 2016 | Lin; Lin, 2016 |
| Mirelman et al., 2014 | Mirelman et al., 2017 | Verbal fluency | Motor task | Visual task |
| **Healthy older adults** | | |
| Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards | Verbal fluency | Motor task | Visual task |
| Maidan et al., 2016 | Al-Yahya et al., 2016 | Harada et al., 2009 | Beurskens et al., 2014 | Lin; Lin, 2016 |
| Mirelman et al., 2017 | Hawkins et al., 2018 | Mirelman et al., 2017 | Beurskens et al., 2014 | Mirelman et al., 2017 |
| Chaparro et al., 2017 | Hernandez et al., 2016 | Clark et al., 2014b | Mirelman et al., 2017 |
| Chen et al., 2017 | Holtz et al., 2011 | Clark et al., 2014a |
| Honduras et al., 2016 | Holtz et al., 2011 |
| Holtz et al., 2015 | Holtz et al., 2015 |
| Holtz et al., 2016 | Holtz et al., 2016 |
| Holtz et al., 2017 | Holtz et al., 2017 |
| Holtz et al., 2017 | Holtz et al., 2017 |
| Osuofiudia et al., 2016 | Osuofiudia et al., 2016 |
| Vengse et al., 2017 | Vengse et al., 2017 |
| Clark et al., 2014b | Clark et al., 2014b |
| Lucas et al., 2018 | Lucas et al., 2018 |
| **Clinical groups with balance disorders** | | |
| Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards | Verbal fluency | Motor task | Visual task |
| Al-Yahya et al., 2016 | Hawkins et al., 2018 | Eggenberger et al., 2016 | Takasugi et al., 2016 | Beurskens et al., 2014 |
| Niehsolf et al., 2016 | Hawkins et al., 2018 | Hawkins et al., 2018 |
| Chaparro et al., 2017 | Mirelman et al., 2017 |
| Hernandez et al., 2016 | Harada et al., 2009 |
| Doi et al., 2013 | Doi et al., 2013 |
| Holtz et al., 2016 | Maidan et al., 2016 |
| Osuofiudia et al., 2016 | Osuofiudia et al., 2016 |
| **Healthy young adults** | | |
| Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards |
| Hill et al., 2013 | Lu et al., 2015 | Koenraadt et al., 2014 | Beurskens et al., 2014 | Lin; Lin, 2016 |
| Lu et al., 2015 | Suzuki et al., 2004 | Hawkins et al., 2018 | Beurskens et al., 2014 | Koenraadt et al., 2014 |
| Meester et al., 2014 | Maidan et al., 2018 | Mirelman et al., 2017 | Takasugi et al., 2016 | Lin; Lin, 2016 |
| Mirelman et al., 2014 | Mirelman et al., 2017 | Verbal fluency | Motor task | Visual task |
| **Healthy older adults** | | |
| Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards | Verbal fluency | Motor task | Visual task |
| Maidan et al., 2016 | Al-Yahya et al., 2016 | Harada et al., 2009 | Beurskens et al., 2014 | Lin; Lin, 2016 |
| Mirelman et al., 2017 | Hawkins et al., 2018 | Mirelman et al., 2017 | Beurskens et al., 2014 | Mirelman et al., 2017 |
| Chaparro et al., 2017 | Hernandez et al., 2016 | Clark et al., 2014b | Mirelman et al., 2017 |
| Chen et al., 2017 | Holtz et al., 2011 | Clark et al., 2014a |
| Honduras et al., 2016 | Holtz et al., 2011 |
| Holtz et al., 2015 | Holtz et al., 2015 |
| Holtz et al., 2016 | Holtz et al., 2016 |
| Holtz et al., 2017 | Holtz et al., 2017 |
| Holtz et al., 2017 | Holtz et al., 2017 |
| Osuofiudia et al., 2016 | Osuofiudia et al., 2016 |
| Vengse et al., 2017 | Vengse et al., 2017 |
| Clark et al., 2014b | Clark et al., 2014b |
| Lucas et al., 2018 | Lucas et al., 2018 |
| **Clinical groups with balance disorders** | | |
| Counting backwards | Verbal fluency | Motor task | Visual task | Counting backwards | Verbal fluency | Motor task | Visual task |
| Al-Yahya et al., 2016 | Hawkins et al., 2018 | Eggenberger et al., 2016 | Takasugi et al., 2016 | Beurskens et al., 2014 |
| Niehsolf et al., 2016 | Hawkins et al., 2018 |
| Chaparro et al., 2017 | Mirelman et al., 2017 |
| Hernandez et al., 2016 | Harada et al., 2009 |
| Doi et al., 2013 | Doi et al., 2013 |
| Holtz et al., 2016 | Maidan et al., 2016 |
| Osuofiudia et al., 2016 | Osuofiudia et al., 2016 |
Table 6: Effect of the additional tasks on gait outcomes compared to simple walking in healthy young adults, healthy older adults and clinical groups with balance disorders.

(+) increase of spatiotemporal parameter when performing the additional task during walking; (-) decrease of spatiotemporal parameter when performing the additional task; (=) no changes in spatiotemporal parameter. Significant differences only for: ¹obstacle negotiation; ²treadmill walking; ³overground walking; ⁴walking + subtracting by 7s; ⁵walking while reciting digit spans.
| Study                           | Motor secondary task                                                                 | Somatosensory task                                                                 | Cognitive secondary task                                                                 |
|--------------------------------|--------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Chen et al., 2017               | Gait speed (-)                                                                        | step length variability (+)                                                         | Gait speed (-)                                                                           |
| Clark et al., 2014b             |                                                                                      |                                                                                      |                                                                                        |
| Hawkins et al., 2018            | Gait speed (-)                                                                        |                                                                                      |                                                                                        |
| Koenraadt et al, 2014           | Step time variability (+)                                                            |                                                                                      |                                                                                        |
| Lin; Lin, 2016                  | Gait speed (-), step length (-)                                                        |                                                                                      |                                                                                        |
| Lu et al., 2015                 | Gait speed (-), cadence (-), stride length (-), gait variability (-)                  |                                                                                      |                                                                                        |
| Mirelman et al., 2017           | Gait speed (-), stride length (+), gait variability (+)                               |                                                                                      |                                                                                        |
| Osofundiya et al., 2016         |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Clark et al., 2014a              |                                                                                      | step length (=), gait speed (=), step length (=), gait speed (=)                      |                                                                                        |
| Clark et al., 2014b             |                                                                                      | gait speed (+), step length variability (+)                                          |                                                                                        |
| Chaparro et al., 2017           |                                                                                      |                                                                                      |                                                                                        |
| Al-Yahya et al., 2016           | Stride length (+), cadence (-)                                                        |                                                                                      |                                                                                        |
| Beurskens et al., 2014          | Step length (-)                                                                       |                                                                                      |                                                                                        |
| Chaparro et al., 2017           | Stride length (=)                                                                    |                                                                                      |                                                                                        |
| Clark et al., 2014a              |                                                                                      | step length (=), step length variability (=)                                         |                                                                                        |
| Clark et al., 2014b             |                                                                                      |                                                                                      |                                                                                        |
| Doi et al., 2013                 |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Hernandez et al., 2016          | Gait speed (-)                                                                        |                                                                                      |                                                                                        |
| Hill et al., 2013                |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Holtzer et al., 2011             | Gait speed (-)                                                                        |                                                                                      |                                                                                        |
| Holtzer et al., 2015             |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Holtzer et al., 2016             |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Holtzer et al., 2017a            |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Holtzer et al., 2017b            |                                                                                      | Gait speed (-)                                                                        |                                                                                        |
| Lin; Lin, 2016                  | Gait speed (-), step length (-)                                                        |                                                                                      |                                                                                        |
| Lu et al., 2015                  |                                                                                      |                                                                                      |                                                                                        |
| Lucas et al., 2018               |                                                                                      |                                                                                      |                                                                                        |
| Meester et al., 2014             |                                                                                      |                                                                                      |                                                                                        |
| Mirelman et al., 2014            |                                                                                      |                                                                                      |                                                                                        |
| Mirelman et al., 2017            |                                                                                      |                                                                                      |                                                                                        |
| Nieuwholf et al., 2016           |                                                                                      |                                                                                      |                                                                                        |
| Osofundiya et al., 2016          |                                                                                      |                                                                                      |                                                                                        |
| Verghese et al., 2017            |                                                                                      |                                                                                      |                                                                                        |
Table 7: Prefrontal cortical activation pattern differences between healthy young and older adults and between clinical groups with balance disorders and healthy peers.

DT: Dual-task; SW: Simple walking; OBS: Obstacle negotiation; a: first half of the task; b: second half of the task; PB: Partial body support; PS: Precision stepping; (+) higher activation when performing the additional task; (-) lower activation when performing the additional task; (=) no change in activation.
| Study                                      | PFC activity                                      |
|--------------------------------------------|--------------------------------------------------|
| **Healthy older vs. healthy young adults** |                                                  |
| Beurskens et al., 2014                     | DT (=)                                           |
| Holtzer et al., 2011                       | DT (-)                                           |
| Takeuchi et al., 2016                      | DT (=)                                           |
| Hawkins et al., 2018                       | SW (+)/ OBS a (+)/ OBS b (=)/ DT (=)             |
| Mirelman et al., 2017                      | SW (+)/ OBS (+)/ DT (+)                          |
| **Clinical group with balance disorders vs.**|                                                  |
| **healthy peers**                          |                                                  |
| Al-Yahya et al., 2016 (Stroke)             | DT (=)                                           |
| Chaparro et al., 2017 (Multiple Sclerosis) | DT (+)/ PB (-)                                   |
| Hawkins et al., 2018 (Stroke)              | SW (=)/ OBS a (=)/ OBS b (+)/ DT (=)             |
| Hernandez et al., 2016 (Multiple Sclerosis)| DT (+)                                           |
| Holtzer et al., 2016 (Neurological gait)   | DT (=)                                           |
| Maidan et al., 2016 (Parkinson’s disease)  | DT (-)/OBS (=)                                   |
| Mori et al., 2018 (Stroke)                 | DT (-)                                           |
| Osofundiya et al., 2016 (Obesity)          | DT (=)/ PS (=)                                   |