Monitoring multiple cortical regions during walking in young and older adults: dual-task response and comparison challenges

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Abstract

Performance of several tasks simultaneously (dual-tasks) is common in everyday walking. Studies indicate that dual-task walking performance declines with age together with cognitive function, but neural mechanisms underpinning deficits remain unclear. Recent developments in mobile imaging techniques, such as functional near infrared spectroscopy (fNIRS), allow real-time monitoring of cortical activity during walking. This study aimed to: 1) examine activity in motor and cognitive cortical regions when walking with a dual-task in young and older adults; and 2) determine the effect of cognition on dual-task cortical activity changes.

Seventeen young (20.3±1.2 years) and eighteen older adults (72.6±8.0 years) performed dual-task conditions, lasting 5-minutes, with alternating 30-second experimental blocks. The primary outcome was cortical activity, assessed by measuring changes in oxygenated haemoglobin (HbO_2) concentrations. Cortical regions of interest (ROI) included motor regions (premotor cortex (PMC), supplementary motor area (SMA), primary motor cortex (M1)), and cognitive regions (prefrontal cortex (PFC)). Cognitive domains were assessed using standard tests and accelerometers were used to extract gait features.

Cortical activity increased with a dual-task in PMC, SMA and M1 but not in PFC regions across groups, with response most evident with initial task exposure. Older adults did not increase SMA activity with a dual-task to the same level as young adults. Dual-task cortical response was consistently associated with greater executive function across groups.

In conclusion, both young and older adults responded in a similar manner to dual-task conditions. Dual-task walking activated multiple motor regions in both groups, but no significant change occurred for cognitive region activation. Cortical activation with a dual-task related to executive function.

KEYWORDS: Cortical activity, fNIRS, older adults, walking, cognition

1. Introduction

Real world walking often involves performance of several cognitive or motor tasks simultaneously (i.e. dual-tasks), such as walking while talking, using a mobile phone, navigating busy crowds or complex environments (1-3). Dual-task walking ability (i.e. safety and effectiveness) declines with age (4), with deficits in performance of gait or secondary tasks. For example, older adults tend to stop walking in order to talk (5). Importantly these difficulties with dual-task walking often lead to reduced mobility (6), increased distractibility and falls risk (7), which in turn affect quality of life (8).

The specific neural mechanisms that underpin dual-task walking difficulties with ageing remain unclear (9), although there is strong evidence that cognitive resources, particularly executive or attentional processes play a vital role (10-12). Executive function involves a range of cognitive processes, such as planning, organisation and appropriate allocation of attention (13, 14), which occurs at the pre-frontal cortex (PFC) and other regions within the frontal lobe (15), with attentional projections to various cortical and sub-cortical brain centres. Executive function is thought to be involved in dual-task walking (16, 17), through the allocation of attentional resources to the simultaneous tasks. Activation of the PFC and other regions is required for walking and balance (18-24). Altered cortical activity with ageing may explain dual-task walking dysfunction with ageing. Examination of cortical brain mechanisms or activation involved in walking in young and older adults, particularly under dual-task, may provide insights into gait impairment and aid in the development of therapeutic interventions.

Traditional imaging (i.e. Functional magnetic resonance imaging (fMRI), positron emission tomography (PET), Single Photon Emission Computed Tomography (SPECT) etc.) of the brain while walking, to uncover cortical and sub-cortical regions/networks involved, is currently impossible as the head has to remain in a static (still) position to use these techniques. As a result imaging studies are limited to mental imagery and virtual reality protocols, which may not truly represent the real-time execution of walking (25). Functional near-infrared spectroscopy (fNIRS) is an emerging non-invasive methodology that can measure changes in cortical oxygenated haemoglobin (HbO_2) and de-oxygenated haemoglobin (HHb) concentration levels while walking (26, 27), through monitoring near-infrared light (usually of 650-950nm wavelength). The use of fNIRS for monitoring cortical activity has been used for over 3 decades (28), validated against traditional imaging techniques (29) and a variety of algorithms are available to identify and effectively reduce motion artefacts (30), which makes it suitable for real-time monitoring of cortical activity when walking (24). fNIRS measures hemodynamic changes in blood flow in the local capillary network caused by neuron firings, which is commonly referred to as neurovascular coupling (31). It uses near-infrared light

emitter-detector pairs to emit light into the skull that diffuses through brain tissues (including blood capillaries) resulting in scattering of multiple photons (32). These photons then exit the skull after passing through the cortex (typically ~1-2cm deep, with an emitter-detector optode distance of 3.5cm) and fNIRS detector channels measure their intensity. HbO_2 and HHb have different absorption coefficients for the different wavelengths of near-infrared light, which can be used within Beer-Lamberts law (see (33) for equations) to calculate the relationship between an exciting photon intensity and incident photon intensity allowing calculation of changes in HbO_2 and HHb (34).

To date, few studies have used fNIRS to examine real-time cortical activity when walking under dual-task in older adults compared to younger adults (18, 35-37). Holtzer, Mahoney (36) showed that PFC activity increased with a dual-task in both young and older adults, with greater increase in young adults. In contrast, Beurskens, Helmich (18) reported little change in PFC activity with a dual-task in young adults, but decreased activity in older adults. More recently, Fraser et al. (35) and Mirelman et al. (37) reported that both young and older adults increased PFC activity with a dual-task, with the latter reporting greater response in older adults. Discrepancies between study findings highlight a need for further robust investigation, as previous studies have been limited by methodological issues (38, 39). For example; studies have used different static baseline conditions for dual-task walking comparison; such as quiet standing (35-37) or sitting (18), which may impact findings.

Previous fNIRS studies have been limited to examination of only PFC activity with differences in the activation across other cortical areas under dual-task walking only investigated in young adults (20, 21, 40), therefore age-related regional differences are unknown (41). Imaging studies have demonstrated that gait is complex and involves multiple cortical regions (24, 42). Studies highlight the importance of the PFC, supplementary motor area (SMA), premotor cortex (PMC) and primary motor cortex (M1) in gait control (43, 44). However studies have primarily focussed on motor regions (i.e. SMA, PMC, M1), with few studies simultaneously examining cognitive regions (i.e. PFC) (24, 42). Recent imaging studies have shown that with age there is breakdown of network processes and connectivity between cortical regions involved in gait, executive function, attention and visuospatial ability (24, 45). Although limited by the static methodologies employed, these results highlight a shift from automatic to more conscious cortical control of gait with increased executive-attentional deployment required with ageing to overcome deficits in motor regions (42), which limits resources to implement on concurrent tasks. Monitoring real-time activity across cognitive and motor cortical regions in young and older adults will enhance understanding of age-related response to dual-tasks.

This study aimed to: 1) examine activity in motor and cognitive cortical regions when walking under single and dual-task in young and older adults; and 2) determine the effect of cognition

on dual-task cortical activity changes. Specifically, we compared changes in HbO_2 (activation) during walking in young and older adults within several motor (PMC, SMA, M1) and cognitive (PFC) regions of interest (ROI) bilaterally. To robustly interpret dual-task walking findings, this study involved three independent conditions; cognitive (digit vigilance), motor (walking) and dual-task (i.e. combined cognitive and motor task) (Figure 1). We hypothesised that older adults would demonstrate greater cortical activation during dual-task walking compared to young adults, particularly at the PFC. We also hypothesised that cortical activation in older adults would relate to cognition.

2. Materials and Methods

2.1. Participants

A convenience sample of 17 young and 18 older adults were recruited for this study through adverts placed on university notice boards. This sample size based upon previous fNIRS dual-task studies (39, 46). All participants provided written informed consent and the study was approved by a Newcastle University Research Ethics Committee. Participants were included if they were able to walk unaided for at least 5 minutes; community dwelling, had adequate hearing and vision, were on stable medication for the past month and within the age range of 20-40 years for young adults and ≥50 years for older adults. Exclusion criteria were: previous diagnosed major gait abnormality, psychiatric co-morbidity, clinical diagnosis of dementia, acute lower back or lower extremity pain, chronic musculoskeletal, respiratory, neurological or unstable cardiovascular disease. Adequate vision was assessed using a Snellen visual acuity chart placed at 6-metres (usual visual correction worn when walking was permitted) (47). All testing took place within the Motor Function Laboratory at the Institute of Neuroscience, Newcastle University. Potential participants were initially screened during a telephone call and then invited to attend a single visit, which lasted approximately 2-3 hours. One older adult participant was left handed, with all other participants being right handed.

2.2. Demographic and cognitive assessments

Age, sex, height and weight were recorded. Fear of falling was measured using the Falls Efficacy Scale (International version; FES-I) (48), depression with the Beck Depression Inventory (BDI) (49), and retrospective falls were obtained from self-report. Global cognition was measured with the Montreal Cognitive Assessment (MoCA) (50). Attention was examined using the simple reaction-time and choice reaction-time assessments of the NE visual perception battery (51). Executive function and visuo-spatial ability was assessed using stockings of Cambridge (CANTAB, Cambridge Cognition Ltd., Cambridge, England), clock drawing and copying, respectively (Royall's CLOX 1 and 2) (52). Working memory was assessed using forward digit span from the Wechsler adult intelligence scale (53).

2.3. Experimental design

2.3.1. Equipment

A tethered fNIRS optical imaging system (23.8Hz; LABNIRS; Shimadzu, Kyoto, Japan) was used to record cortical changes in HbO_2 and HHb when walking via continuous wave laser diodes with wave-lengths of 780, 805 and 830nm. The fNIRS system measured optical density of the raw signal and converted this to HbO2 and HHb using Beer-Lamberts law (34). The specific equations (where ∆OD is the change in optical density) used by the fNIRS system are;

$$\Delta(HbO2) = (-3.6132)x\ \Delta OD(780nm) + 1.1397x\ \Delta OD(805nm) + 3.0154x\ \Delta OD(830nm)$$

$$\Delta(HHb) = 3.7837\ x\ \Delta OD(780nm) + (-0.7833)x\ \Delta OD(805nm) + (-2.5679)x\ \Delta OD(830nm)$$

The fNIRS system consisted of 25 optodes (5x5) with light source emitter (n=13) and detector fibres (n=12) (total 40 channels) tethered to the LABNIRS device. The fNIRS optodes overlaid the frontal lobe (left and right hemispheres) and covered a 12x12cm area, with an emitter-detector distance of 3.5cm. Participants wore a whole-head fiber holder marked with labels of the international 10-10 EEG System (Whole-Head Fiber Holder, Shimadzu, Kyoto, Japan), which allowed for Cz position to be determined for each individuals' head. A digitizer (FASTRAK, Polhemus, VT, USA) was used to provide 3-dimensional (3D) morphological locations for cortical ROIs relative to scalp position and the fNIRS optode measure. A backpack was used to support fiber cables during walking tasks.

A tri-axial accelerometer (100Hz, Axivity Ltd., Newcastle upon-Tyne, United Kingdom) was placed on participants' lower back (over the 5th lumbar vertebrae) to measure gait characteristics of the participants while walking on the treadmill (54, 55).

2.4. Protocol and Experimental tasks

All participants stood still and walked on a treadmill at preferred speed under single or dual-task. The dual-task consisted of a digit vigilance task, where the researcher provided the participant with a number (1 to 9). Next, random numbers (1 to 9) were played over a speaker for 30-seconds, while participants counted mentally how many times the number occurred. Participants then called out the counted number at the end of the 30-second block. This dual-task reduced the potential for speech-related artefact data infiltration due to talking and enabled standardised blocks of exposure.

Preferred walking speed on the treadmill was determined by increasing belt speed until it was faster than the participant's preferred speed, then reducing belt speed until preferred speed was achieved (56). Participants performed standing tasks first to avoid any carryover effect.

Testing was conducted in line with current recommendations (38, 39) and included a cognitive task, motor task and dual-task (Figure 1).

<<Insert Figure 1 here>>

2.5. Data Analysis and Outcome Measures

The fNIRS data was analysed using the open-access software package NIRS-statistical package metric mapping (NIRS-SPM Version 4, http://www.nitrc.org/projects/nirs_spm), which was implemented within MATLAB 2010a (Mathworks, MA, USA) due to incompatibility with later versions. NIRS-SPM allows registration of fNIRS channel data onto the Montreal Neurological Institute (MNI) standard space (57) (Figure 2). NIRS-SPM used probabilistic registration of the fNIRS co-ordinate data to determine channels that related to ROIs at the group level, which is described in detail by Singh et al. (2005) (57, 58). Overall, HbO_2 changes were recorded bilaterally (left and right) within several ROI, including; PFC, SMA, PMC and the M1. Digitizer 3D results adjusted for individual variation by showing that the following Brodmann areas (BA) corresponded to the ROIs; BA8, 9, 10, 45 and 46 for PFC, BA6 lateral for PMC, BA6 medial for SMA and BA4 for M1.

The fNIRS data was processed using time-series analysis within NIRS-SPM, which has been described in detail elsewhere by Ye et al. (2009) (59). This was conducted in several steps;

1. **Filtering:** a low-pass filter (cut-off 0.15Hz) based on canonical hemodynamic response function removed high-frequency noise; for detailed information and formula for this process see Friston et al. (2000) (60).
2. **De-trending:** wavelet-minimum description length algorithm decomposed fNIRS measurement into global trends (artefacts), hemodynamic signal and uncorrected noise components. The exact formula involved in this processing stage have been described in detail by Jang et al. (2009) (61). This step corrected signal distortions due to artefact caused by breathing, cardiac cycle, vasomotor or other error related to movement.
3. **Baseline correction:** signal zeroed to the initial time point of the first trial (i.e. average of initial data sample taken from entire fNIRS recording).

Following NIRS-SPM processing, HbO_2 data was exported to MATLAB (R2015a, The MathWorks, Inc., Natick, Massachusetts, United States) for further processing with our customised algorithm. Channels were averaged per ROI for each hemisphere (i.e. left and right, PFC, PMC, SMA and M1). Signals were then normalised for each ROI by dividing them by the corresponding block signal average amplitude (20), which reduced amplitude differences and allowed data comparison between the participants. The 5 minute trials were divided into 30 second blocks and the first and last 5 seconds from each block were removed

to account for time taken for a change in haemodynamic response. HbO_2 concentrations were averaged over the central 20 seconds (35 to 55 seconds for each trial) of the experimental task and over 10 seconds of the control task (15 to 25 seconds for each trial) (Figure 1).

The primary outcome measure was HbO_2 concentration, which was used as a marker for cortical activation. HbO_2 rather than HHb was used due to its sensitivity to walking and cognitive tasks (22, 62). Averaged HbO_2 ($normHbO_2$) concentrations for each trial (Block 1 to 5) and differences in HbO_2 ($diffHbO_2$) between the control (walk or stand) and experimental (dual-task, cognitive or motor (walk)) conditions were calculated.

Secondary outcomes included gait characteristics of step length, velocity, step time, swing time and stance time. Gait outcomes were calculated using our validated custom-made MATLAB algorithms, for further information see; (54, 55). In brief, continuous wavelet transform (convolution of the accelerometer data and an analyzing function, i.e. mother wavelet) estimated initial contact and final contact of the foot with the ground from the vertical acceleration trace, which allowed calculation of the gait outcomes.

<<Insert Figure 2 here>>

2.6. Statistical Analysis

Data were analysed using SPSS (v21, IBM, Chicago, Il., USA) and assessed for normality, with parametric and non-parametric analysis used where relevant (63). Outcomes assessed with non-parametric analysis are detailed in Table 1. Descriptive statistics for demographics, cognitive and visual outcomes were calculated. Linear mixed effects models (LMEM) determined significance of absolute HbO_2 changes ($normHbO_2$) from control to experimental task during the different blocks of testing within each of the ROI. Specifically, LMEM were created with group (young vs old) as a between subject factor and task (walk and dual, or stand and cognitive task or walk) and trial (1, 2, 3, 4, 5) as repeated within-subject factors, with treadmill speed as a covariate. All interactions between these features were considered within the models. Bonferroni correction for multiple comparisons (p-value / number of comparisons) was applied during the post hoc analyses. To clearly present our data, graphs of the relative changes across trials ($diffHbO_2$) (i.e. dual-task – walking, or walking – standing or cognitive-task - standing) were also created using the same LMEM, without the task factor. Spearman's correlations explored relationships between demographic, gait and cognitive characteristics with relative cortical activity levels ($diffHbO_2$ averaged values across trials). The level of statistical significance was set at $p<0.05$.

Sample size calculation ($\alpha=0.05$, $1-\beta=0.8$): The study sample size was based upon preliminary pilot data from our healthy young and older adults, and previous fNIRS dual-task studies (30, 36), which have generally used sample sizes of $n<20$ for young and older adult groups. For

our primary aim, we derived an effect size from previous research by Beurskens et al. (2014) who tested PFC activity using fNIRS in 15 young and 10 older adults while walking (on a treadmill) under single and dual-task conditions. Based on their Age x Condition (single or dual-task) findings (F=5.57, $p<0.05$) with an effect size of 0.96 (Cohens d), a minimum of 30 subjects (15 per group) was required to detect differences in fNIRS dual-task walking data between young and older adults. Pilot data from our cohort demonstrated that this sample size would be sufficient to identify changes of 4.3% in cortical activity from single to dual-task with a power of 0.8.

3. Results

3.1.1. Participants

Table 1 displays the demographics, cognitive and visual characteristics of the participants. Young and older adults were significantly different in age ($p<.001$) and education ($p=.012$), with older adults having fewer years of formal education. Older adults had significantly reduced attention, executive function and visuo-spatial ability. Older adults walked at a slower preferred treadmill speed than younger adults (2.7±0.8km/hr vs 3.9±0.7km/hr, $p<.001$). However, gait characteristics while walking on the treadmill did not differ between tasks (walking vs dual-task walking) or the groups.

<<Insert Table 1 here>>

3.1.2. Changes in cortical activity

3.1.2.1. Dual-task

Table 2 shows the cortical activity (normHbO_2) results for the conditions and interaction effects with trial and group with a dual-task. Our results demonstrated that both young and older adults respond in a similar manner to a dual-task. Cortical activity (normHbO_2) significantly increased within all motor ROIs (PMC, SMA, M1) in both groups when performing a dual-task (Table 2). Interestingly, PFC (left and right) activation did not significantly change under dual-task conditions for both groups (left: F=.16, $p=.693$; right: F=1.14, $p=.287$, Table 2). Across trials cortical activation was greatest within the first and/or second trial (Supplementary Tables 1 and 2), and a two-way interaction effect (Task*Trial, normHbO_2, Table 2) indicated that increased activation attenuated over consecutive trials in both groups (Figure 3).

There were very few group differences in cortical activation (normHbO_2 levels) between young and older adults when performing a dual-task, with only left SMA activation being significantly different (Group*Task, Table 2). This indicated that older adults had less left SMA activation under dual-task walking conditions compared to young adults (Supplementary Table 1).

<<Insert Table 2 here>>

3.1.2.2. Independent cognitive and motor tasks

In contrast to dual-task conditions, independent performance of the cognitive task led to significantly increased cortical activity across all ROIs in both groups, with similar attenuation across trials (Supplementary Figure 1). Older adults had greater left PFC (F=6.2, *p*=.013) and PMC (F=4.3, *p*=.040) activation during the cognitive task compared to young adults.

The largest increases in cortical activity (normHbO_2) across all assessed ROIs occurred when independently performing a motor task (walking) in both groups (Supplementary Figure 2). Supplementary Figure 2 also demonstrated that cortical response to walking appeared more consistent than response to a dual-task or independent cognitive task (i.e. similar levels activation over each trial with no trend to increase or decrease over time); however, there appeared to be a greater response within the PFC and M1 for older adults.

<<Insert Figure 3 here>>

3.1.2.3. Demographic, cognitive and gait correlates of cortical activity

There were few significant relationships between the obtained demographic and cognitive or gait measures (reported in Table 1) with relative cortical activity (diffHbO_2). The only consistent finding was that better executive function (CLOX1) related to greater increase in activity within the majority of ROI with a dual-task in both young and older adults (Table 3).

To our knowledge, this is the first study to explore and compare cortical activity (HbO_2) across cognitive and motor regions in response to a dual-task in young and older adults. The study also examined the relationship between cortical activity dual-task response and cognitive characteristics. Results contrasted with our hypotheses. Findings indicated that both young and older adults respond in the same manner to a dual-task, with significantly increased cortical activity in motor regions (PMC, SMA, M1) and no significant difference in cognitive regions (PFC). We also found that cortical activity increased in response to a dual-task primarily within initial task exposure (Trials 1 and/or 2) and response attenuated with consecutive trials. Dual-task cortical activation related to executive function across both groups.

4.1.1. Cortical activity response to dual-task

Bilateral cortical activity increased in motor cortical ROIs in both young and older adults under dual-task, which was most prominent during the initial dual-task exposure (Trials 1 and 2). Holtzer, Mahoney (64) found similar attenuation of cortical activity response to walking and dual-task following the first two trials, although attenuation to their spoken dual-task was less

evident than the present study. Our results also agree with previous imaging work that has shown that internally and externally driven tasks increase cortical activation in multiple motor cortical regions (65, 66). However, PFC activity did not significantly increase under dual-task and there was no significant difference in PFC activity between the groups. Our findings agree with some previous reports (18, 35), but also contrast with several previous studies that have identified PFC activation group differences between young and older adults under dual-task (36, 37). Similarly, previous studies have reported significantly increased PFC activity under dual-task in both young and older adults (35-37). However, examination of multiple ROIs allowed our study to identify reduction in left SMA activation under dual-task in older adults compared to young adults. Reduced activation in older adults may relate to degradation or breakdown in SMA communication with the basal ganglia (BG) and M1 for normal automatic gait control (67). Furthermore, evidence demonstrates that the left SMA is involved in language processing and speech (68-70), and therefore age-related SMA deficits may impact both gait and cognitive task performance with implications for falls risk. Further age-related comparison is limited as the majority of previous studies have only involved separate investigation of young or older adults (46), or static seated dual-task paradigms (71). Methodological protocol or dual-task differences between studies may also have affected previous results and comparisons, and the following section discusses these factors.

4.1.2. The role of protocol and nature of dual-task in cortical activation

Use of a motor task (i.e. single-task walking) as a baseline condition may have limited the capacity to find further increases in cortical activity (HbO_2 levels) under dual-task. Previous studies have used static baseline conditions of standing (35-37) or sitting (18), which may have inflated findings. Indeed, when using standing as a baseline condition, we found large increases in HbO_2 ($normHbO_2$ and $diffHbO_2$) levels across all ROI when independently performing a motor task (i.e. walking) in both young and older adults, with greater response in PFC and M1 for older adults. Furthermore, such increases with walking may be due to an increase in general perfusion or motion artefact, as well as increased cortical activity (72). Therefore, static baseline comparison may not be appropriate and could explain previous significant PFC activity changes.

Previous age comparison studies have primarily investigated dual-task cortical activity response during over-ground walking. In contrast, due to the exploratory nature of this study and the use of a multi-channel tethered fNIRS system, we used a treadmill set to each participants' preferred walking speed. Cortical activity during treadmill walking differs compared to over-ground walking (56), likely due to increased attention to gait with the external prompt of the treadmill particularly in those who are unaccustomed to them. The treadmill required participants to continue at a set speed and therefore they could not slow

their walking under dual-task (Table 1), which occurs when walking over-ground (73). Motor regions (i.e. SMA and M1) are associated with gait speed while treadmill walking (74), therefore increased motor region activation (increased effort) may have been caused by participants having to walk at a faster speed than preferred under dual-task. Indeed, several previous studies have demonstrated an increase in cortical activity with faster walking speed (75-77).

The nature of the cognitive task may affect findings. Our cognitive task involved a vigilance-based attention task that entailed a heard speech paradigm to reduce the risk of artefact influencing the HbO_2 level recordings (78). In contrast, previous dual-task studies have involved continuous or intermittent talking while walking (35, 36, 64). Spoken and inner (speaking without vocalisation) speech can influence HbO_2 and HHb levels within the cortex (79-81), with speaking having the largest effect (80). Increases related to speaking do not represent neurovascular coupling alone, hence may not represent greater cortical activation (72). Therefore, previous studies may have reported an inflated dual-task response due to increased HbO_2 levels because of speaking rather than actual cortical activity.

A key factor to consider when interpreting these and other previous dual-task fNIRS findings is the limited understanding of the underlying neural activity involved with different dual-tasks, which has been highlighted within a recent systematic review (82). Currently studies report that dual tasking involves the PFC (83) and other cortical regions are not often considered. However, other regions such as the temporal lobe, which is involved in memory, may also be involved in dual-task performance (84) and involvement of cortical regions may differ between individuals. For example, even during standing our cognitive task increased cortical activation in various regions, with group differences in the left PFC and PMC, which are involved in language encoding and word retrieval (85, 86). However, when walking with the same cognitive task group differences were not evident. These findings highlight the complexity of the underlying mechanisms involved in dual-task performance and the need for further understanding.

4.1.3. Cortical activation relationship with executive function

We found a consistent relationship between increased cortical activity ($diffHbO_2$) and higher executive function across the groups. Findings are consistent with theories that link the PFC and other frontal lobe regions (i.e. PMC) (87) to the monitoring and control of executive (and attentional) resources to competing task demands (16, 88). Previous studies have demonstrated robust relationships between executive function and gait, which relate to the underlying cortical activity involved (19). Motor and cognitive processes are functionally related with the M1, SMA and PMC regions influenced by the PFC (89), as the conception,

initiation and on-going control of movement relate to activation of these regions (90). Participants with better executive function likely had greater capacity to increase their cortical activation with a dual-task to enable them to maintain their gait and perform the secondary task simultaneously.

4.1.4. Limitations

The present study has several limitations. Although we have adequately justified our sample size it is still relatively small. Similarly, all of the young participants were university students with a significantly different education level compared to older adults, which may impact cognition and by-proxy gait findings due to the known influence of education on cognition (91). This study did not involve a comprehensive cognitive battery which future studies may use to uncover further cognitive relationships with cortical activity. Walking was completed on a treadmill with a tethered fNIRS device which may not be truly representative of over-ground walking and associated cortical outcomes. However, this study assessed multiple cortical regions to provide a greater understanding of the contribution of the front lobe to walking and dual tasking. Future work may benefit from a full cap system that would allow data capture from temporal, parietal and other regions. Future work could examine cortical activity when walking in response to a graded secondary cognitive task, which would allow for quantifying varying task difficulty. As such there is a need to develop standardised dual-task paradigms, which may be used with fNIRS methodologies.

5. Conclusions

This study found that both young and older adults respond in a similar manner to dual-task conditions. Using a robust methodological approach, we found dual-tasking increased cortical activity in multiple motor ROIs in both groups, but older adults do not increase SMA activation to the same level as young adults. Overall, changes in cortical activity with a dual-task related to executive function. Methodological factors require consideration within future work and progression to more natural over-ground walking tasks is required.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Statement

All data presented within the current study can be obtained from the corresponding author.

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Figure Captions:

Figure 1 - Experimental design for the separate conditions

Figure 2 – Montreal Neurological Institute (MNI) co-ordinates for fNIRS emitter and detector optodes exported from NIRS-SPM software

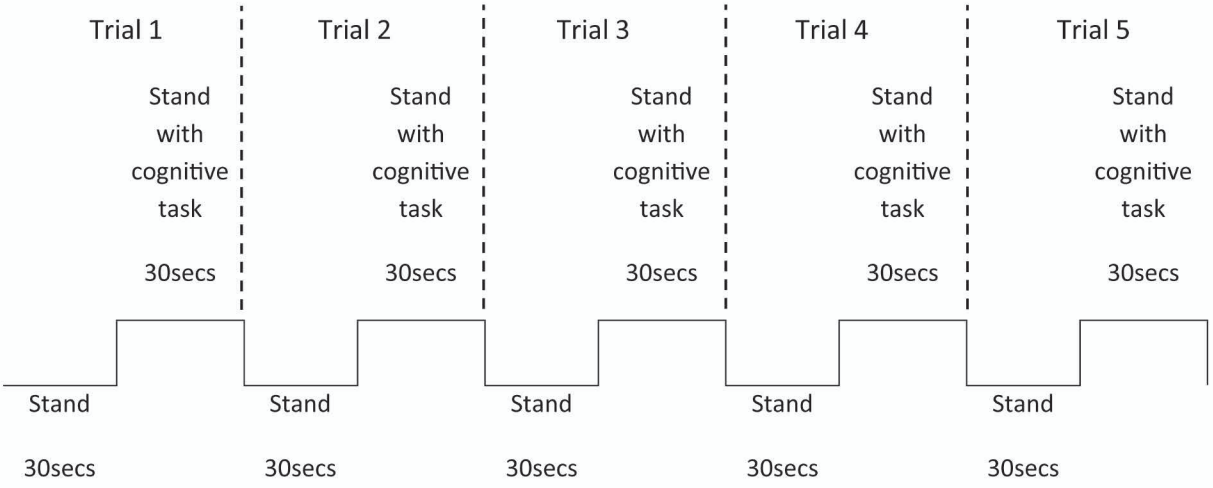
Figure 3 – Difference in cortical activity (mean ± SE) with a dual-task *[*significance level p<0.05 between group difference in the specified trial; significant difference between trials are displayed within square brackets, PFC = prefrontal cortex; PMC = premotor cortex; SMA = supplementary motor area; M1 = primary motor cortex]*

Supplementary Figure 1 – Difference in cortical activity (mean ± SE) with a cognitive task *[*significance level p<0.05 between group difference in the specified trial; significant difference between trials are displayed within square brackets, PFC = prefrontal cortex; PMC = premotor cortex; SMA = supplementary motor area; M1 = primary motor cortex]*

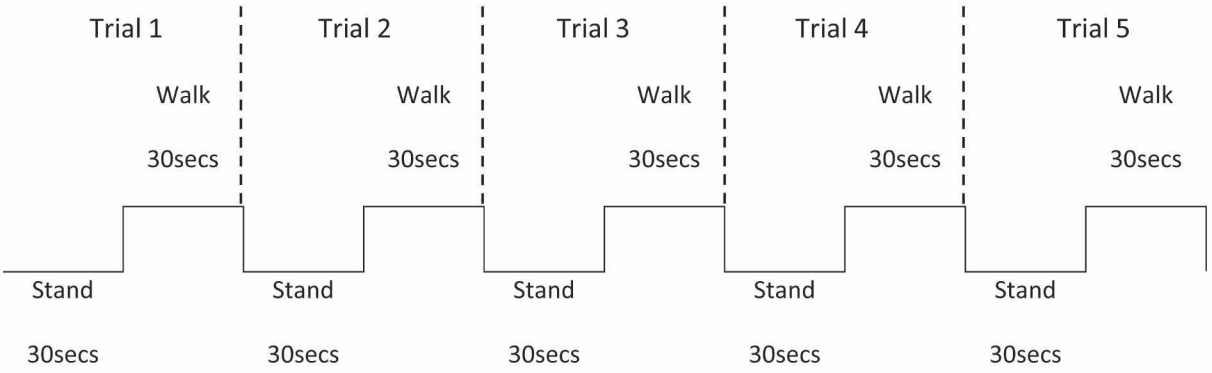
Supplementary Figure 2 – Difference in cortical activity (mean ± SE) with a motor task *[*significance level p<0.05 between group difference in the specified trial; significant difference between trials are displayed within square brackets, PFC = prefrontal cortex; PMC = premotor cortex; SMA = supplementary motor area; M1 = primary motor cortex]*

Supplementary Table 1 - Relative concentrations of HbO2 during dual-task

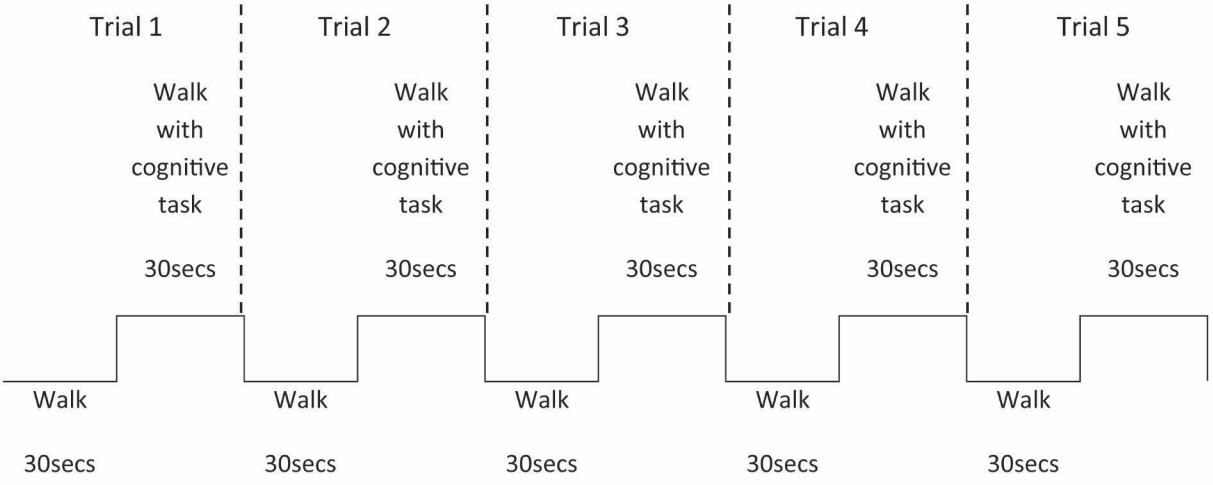
Cognitive task



Motor task

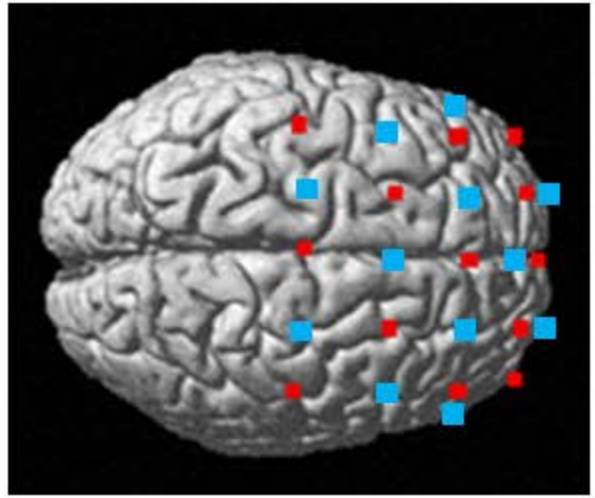


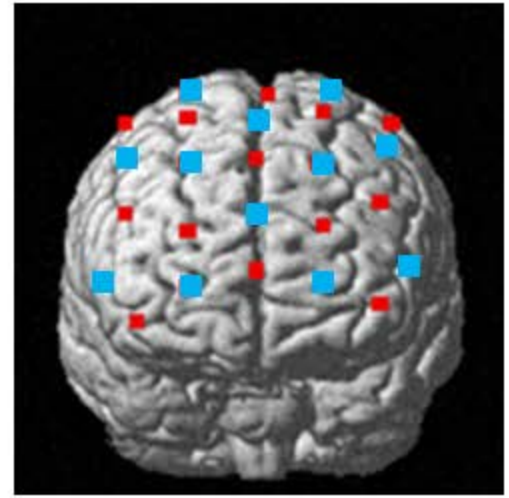
Dual-task



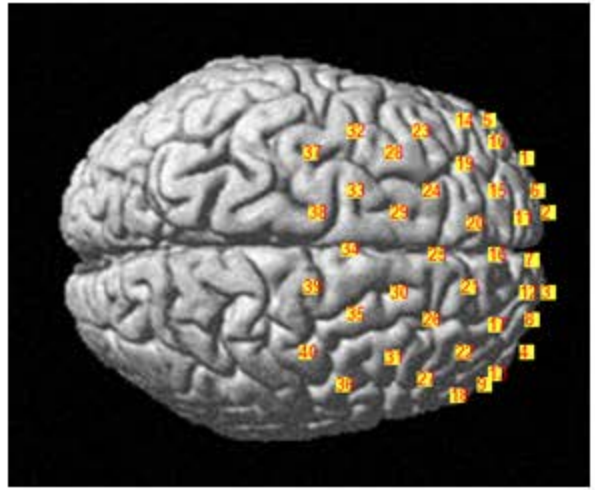
MNI co-ordinates over brain regions of interest

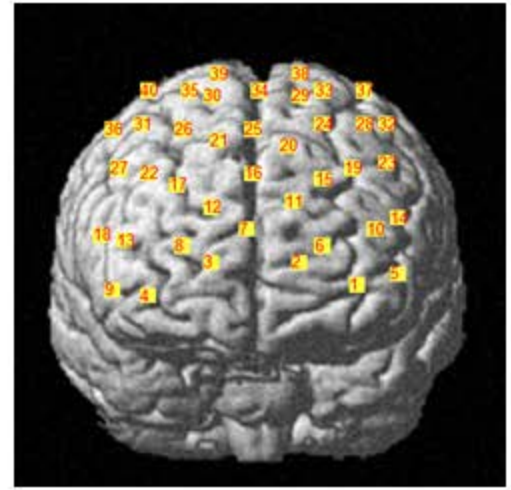
Emitter (red) and Detector (blue) locations

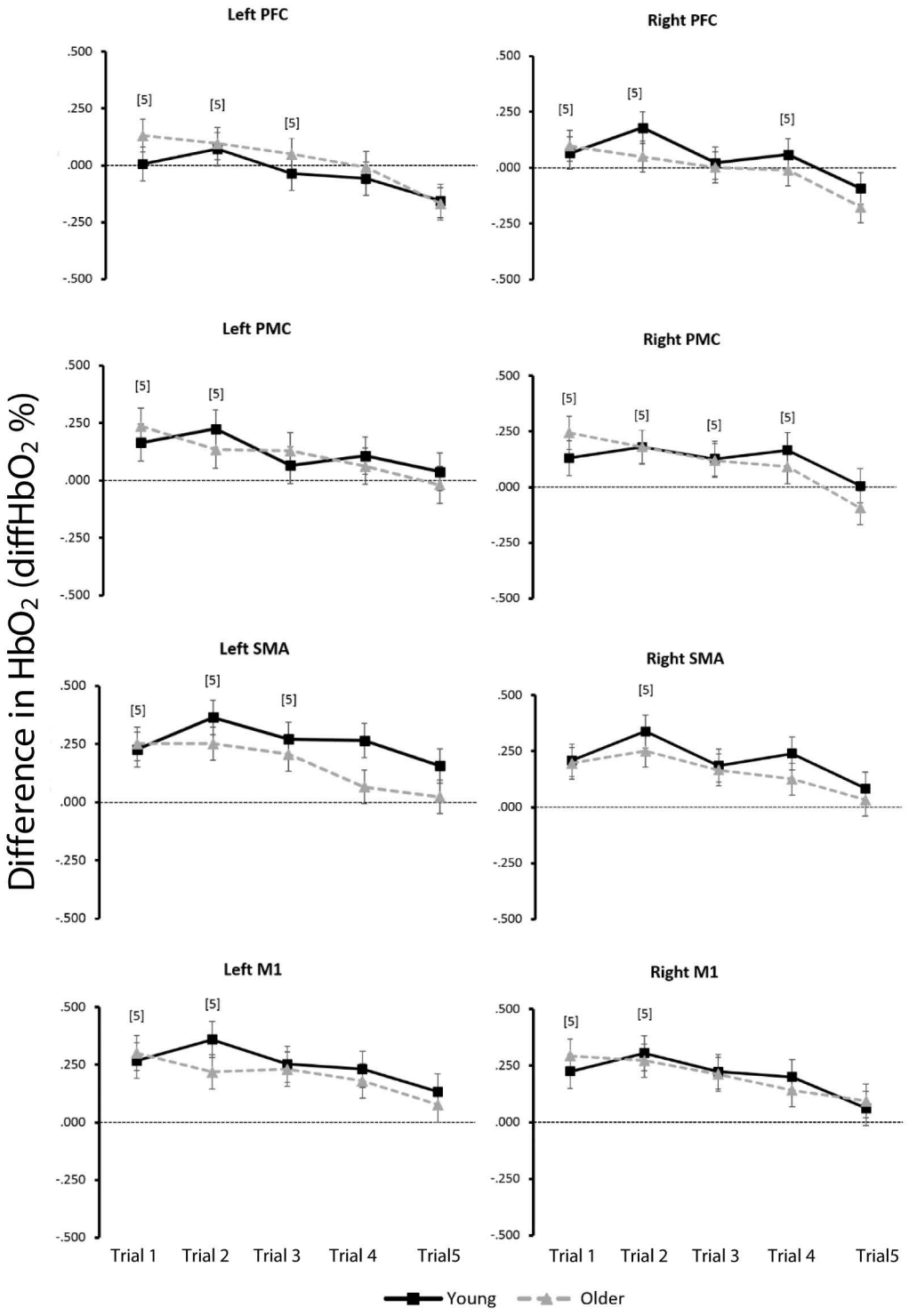


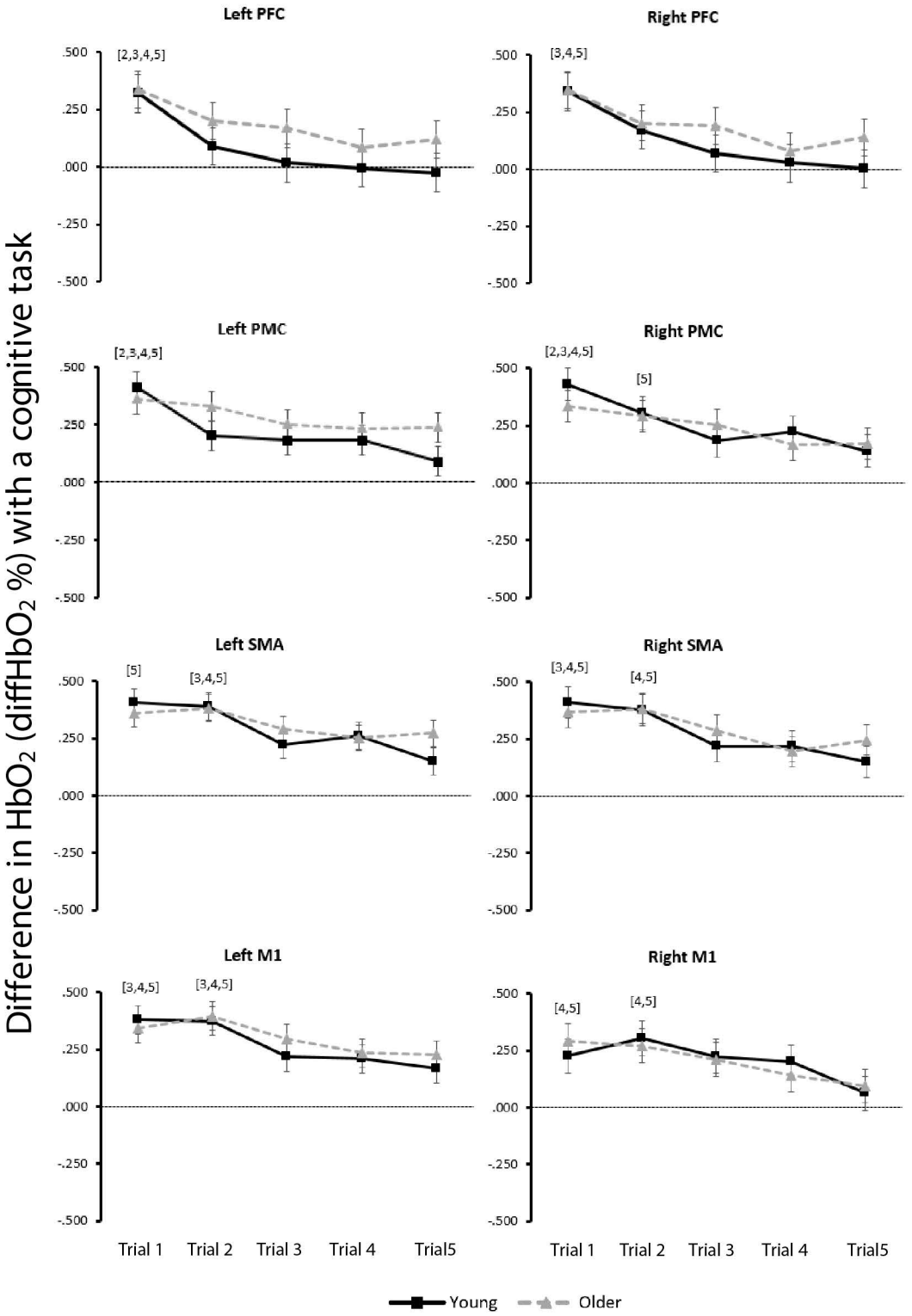


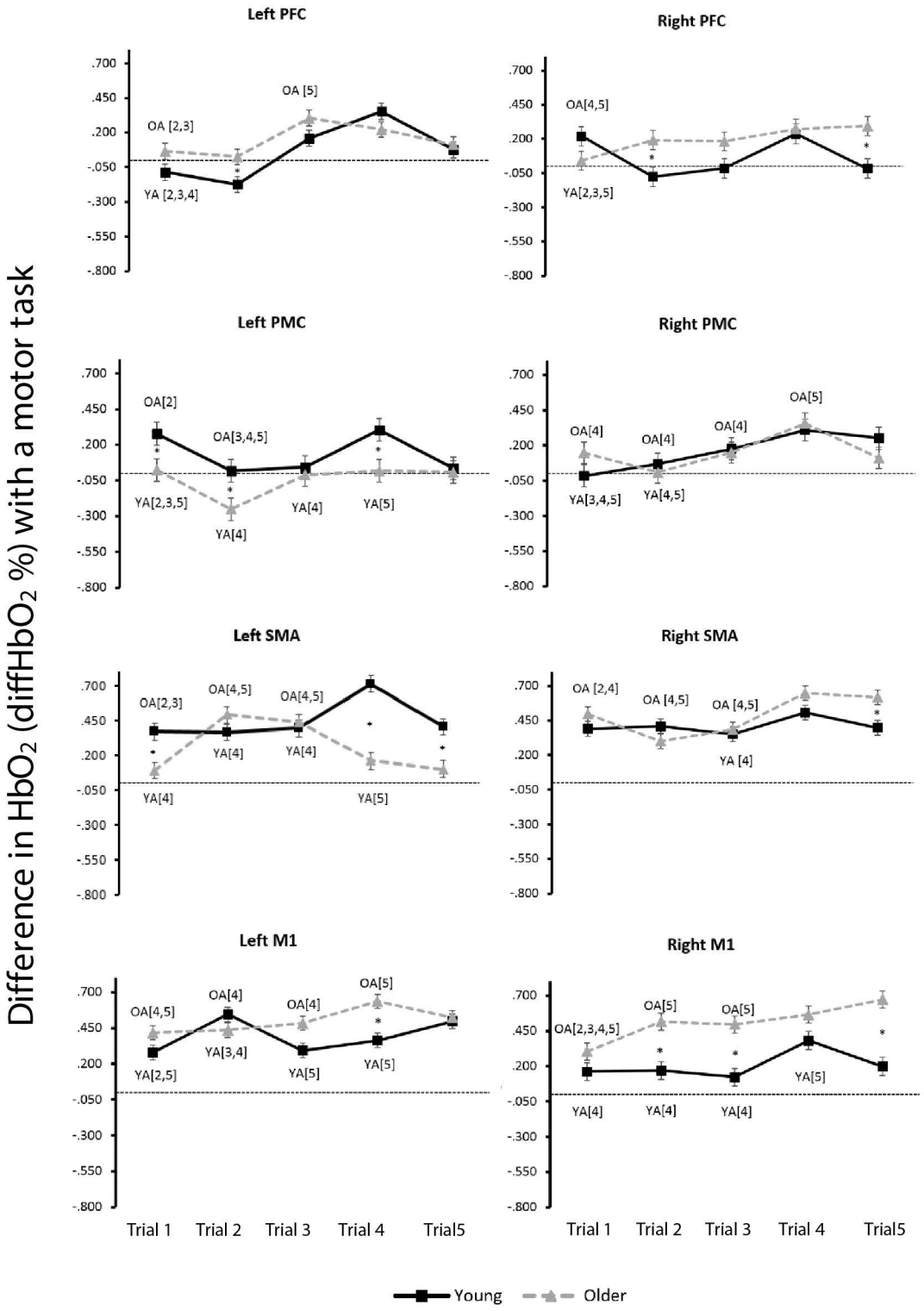
Channel locations






Left PFC
Right PFC
Left PMC
Right PMC
Left SMA
Right SMA
Left M1
Right M1
Difference in HbO2 (diffHbO2 %)
.500
.250
.000
-.250
-.500
[5]
Trial 1
Trial 2
Trial 3
Trial 4
Trial5
Young
Older


Left PFC
Right PFC
Left PMC
Right PMC
Left SMA
Right SMA
Left M1
Right M1
Difference in HbO2 (diffHbO2 %) with a cognitive task
.500
.250
.000
-.250
-.500
[2,3,4,5]
[3,4,5]
[5]
[4,5]
Trial 1
Trial 2
Trial 3
Trial 4
Trial5
Young
Older


Difference in HbO2 (diffHbO2 %) with a motor task
Left PFC
Right PFC
Left PMC
Right PMC
Left SMA
Right SMA
Left M1
Right M1
.700
.450
.200
-.050
-.300
-.550
-.800
OA [2,3]
YA [2,3,4]
OA [5]
OA[4,5]
YA[2,3,5]
OA[2]
OA[3,4,5]
YA[2,3,5]
YA[4]
YA[4]
YA[5]
OA[4]
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OA[5]
YA[3,4,5]
YA[4,5]
OA[2,3]
OA[4,5]
OA[4,5]
YA[4]
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OA [2,4]
OA [4,5]
OA [4,5]
YA [4]
OA[4,5]
YA[2,5]
OA[4]
YA[3,4]
OA[4]
YA[5]
OA[5]
YA[5]
OA[2,3,4,5]
YA[4]
OA[5]
YA[4]
OA[5]
YA[4]
YA[5]
Trial 1
Trial 2
Trial 3
Trial 4
Trial5
Young
Older

Table 1 - Demographic, cognitive, visual and clinical characteristics

		Young Adults (n=17)	Older Adults (n=18)	*p*
Demographic	Age (years)	20.3 (1.2)	72.6 (8.0)	**<.001***
	Sex (m/f)	8m / 9f	9m / 9f	.862†
	Height (m)	1.73 (0.10)	1.69 (0.08)	.274
	Weight (kg)	65.5 (13.6)	74.1 (18.6)	.128
	Education (years)	15.7 (0.8)	13.6 (3.3)	**.012***
	Beck Depression Inventory (BDI)	3.0 (10.0)‡	3.5 (22.0)‡	.708⌈
	Falls efficacy scale (FES-I)	17.5 (1.4)	19.6 (5.5)	.129
Global cognition	Montreal Cognitive Assessment (MoCA)	28.2 (1.4)	28.1 (1.5)	.892
Attention	Simple reaction time (Mean)	315.9 (42.5)	372.2 (64.0)	**.004***
	Choice reaction time (Mean)	400.8 (38.7)	529.3 (48.1)	**<.001***
Executive function	Royals CLOX 1	13.8 (1.15)	12.8 (1.6)	.059
	SOC (Problems solved in minimum moves)	8.7 (1.7)	6.3 (2.4)	**.002***
Visuo-spatial ability	Royals CLOX 2	14.4 (0.8)	13.6 (1.2)	**.033***
Working memory	Max Digit Span Length (sitting)	6.3 (1.1)	6.0 (1.2)	.444
Visual function	Visual acuity (Snellen chart)	4.5 (0.7)	5.0 (1.9)	.354
Treadmill speed	Comfortable pace (km/hr)	3.9 (0.7)	2.7 (0.8)	**<.001***
Dual-task errors - (%)	Standing % (Min, Max)	0.0 (0.0, 11.1) ‡	0.0 (0.0, 7.4) ‡	.832⌈
	Walking % (Min, Max)	0.0 (0.0, 3.7) ‡	0.0 (0.0, 3.7) ‡	.590⌈
Single-task walking	Step Length (m)	0.50 (0.06)	0.47 (0.06)	.096
	Step Velocity (m/s)	0.85 (0.16)	0.80 (0.13)	.289
	Step Time (s)	0.60 (0.05)	0.58 (0.06)	.411
	Stance Time (s)	0.72 (0.04)	0.72 (0.06)	.796
	Swing Time (s)	0.48 (0.06)	0.47 (0.06)	.635
Dual-task walking	Step Length (m)	0.51 (0.06)	0.47 (0.06)	.051
	Step Velocity (m/s)	0.86 (0.16)	0.80 (0.12)	.208
	Step Time (s)	0.60 (0.05)	0.59 (0.06)	.536
	Stance Time (s)	0.72 (0.04)	0.72 (0.06)	.850
	Swing Time (s)	0.48 (0.06)	0.47 (0.07)	.764

[Mean and standard deviation presented unless otherwise stated, *significance level p<0.05, † = X^2, ‡ = Median and range, ⌈ = Man-Whitney-U test, SOC = stockings of Cambridge]

Table 2 – Linear Mixed Effects Model Fixed Effects for Cortical Activity (normHbO$_2$) during a dual-task

Cortical region	Task	Task*Trial	Group*Task
Left PFC	$F_{4,297}$ = 0.16	**$F_{4,297}$ = 5.35****	$F_{4,297}$ = 1.96
Right PFC	$F_{4,297}$ = 1.14	**$F_{4,297}$ = 5.45****	$F_{4,297}$ = 2.22
Left PMC	**$F_{4,297}$ = 30.26****	**$F_{4,297}$ = 2.84***	$F_{4,297}$ = 0.10
Right PMC	**$F_{4,297}$ = 35.11****	**$F_{4,297}$ = 4.66***	$F_{4,297}$ = 0.12
Left SMA	**$F_{4,297}$ = 123.40****	**$F_{4,297}$ = 3.97***	**$F_{4,297}$ = 6.68***
Right SMA	**$F_{4,297}$ = 98.88****	**$F_{4,297}$ = 4.20***	$F_{4,297}$ = 2.40
Left M1	**$F_{4,297}$ = 135.34****	**$F_{4,297}$ = 3.09***	$F_{4,297}$ = 1.48
Right M1	**$F_{4,297}$ = 113.16****	**$F_{4,297}$ = 3.74***	$F_{4,297}$ = 0.00

*[significance level *p<0.05 **p<.001, PFC = pre-frontal cortex, PMC = pre-motor cortex, SMA = supplementary motor area, M1 = primary motor cortex]*

Table 3 –Demographic and cognitive outcome relationship with relative cortical activity (diffHbO$_2$) under dual-task walking

Rho (p)	Executive Function (CLOX1)		
Cortical region	**YA**	**OA**	**All participants**
Left PFC	.383 (.129)	.257 (.304)	.285 (.097)
Right PFC	.346 (.174)	.176 (.484)	**.358 (.034*)**
Left PMC	.296 (.248)	.298 (.230)	**.334 (.050*)**
Right PMC	**.520 (.032*)**	.428 (.076)	**.436 (.009*)**
Left SMA	.235 (.363)	.449 (.062)	**.411 (.014*)**
Right SMA	-.034 (.896)	**.505 (.032*)**	.267 (.122)
Left M1	.232 (.371)	.125 (.622)	.256 (.137)
Right M1	.265 (.305)	.439 (.069)	**.357 (.035*)**

[*significance level p<0.05, Spearman's rho correlations presented, PFC = pre-frontal cortex, PMC = pre-motor cortex, SMA = supplementary motor area, M1 = primary motor area, CLOX1 = Royalls clock drawing]

Supplementary Table 1 – Relative concentrations of HbO2 during dual-task

		Young Adult		Older Adult	
		Mean	**SE**	**Mean**	**SE**
LPFC	Trial 1	-0.086	0.059	0.065	0.057
	Trial 2	-0.174	0.059	0.025	0.057
	Trial 3	0.159	0.059	0.304	0.057
	Trial 4	0.354	0.059	0.222	0.057
	Trial 5	0.076	0.059	0.113	0.057
RPFC	Trial 1	0.221	0.071	0.04	0.069
	Trial 2	-0.076	0.071	0.192	0.069
	Trial 3	-0.015	0.071	0.182	0.069
	Trial 4	0.237	0.071	0.274	0.069
	Trial 5	-0.017	0.071	0.294	0.069
LPMC	Trial 1	0.276	0.081	0.024	0.079
	Trial 2	0.018	0.081	-0.25	0.079
	Trial 3	0.042	0.081	-0.011	0.079
	Trial 4	0.305	0.081	0.017	0.079
	Trial 5	0.035	0.081	0.008	0.079
RPMC	Trial 1	-0.017	0.078	0.148	0.076
	Trial 2	0.067	0.078	0.008	0.076
	Trial 3	0.176	0.078	0.149	0.076
	Trial 4	0.309	0.078	0.355	0.076
	Trial 5	0.252	0.078	0.111	0.076
LSMA	Trial 1	0.369	0.059	0.091	0.058
	Trial 2	0.363	0.059	0.49	0.058
	Trial 3	0.393	0.059	0.433	0.058
	Trial 4	0.715	0.059	0.159	0.058
	Trial 5	0.406	0.059	0.101	0.058
RSMA	Trial 1	0.391	0.054	0.496	0.053
	Trial 2	0.409	0.054	0.300	0.053
	Trial 3	0.351	0.054	0.385	0.053
	Trial 4	0.507	0.054	0.648	0.053
	Trial 5	0.398	0.054	0.618	0.053
LM1	Trial 1	0.279	0.051	0.416	0.049
	Trial 2	0.545	0.051	0.435	0.049
	Trial 3	0.293	0.051	0.483	0.049
	Trial 4	0.364	0.051	0.635	0.049
	Trial 5	0.496	0.051	0.524	0.049
RM1	Trial 1	0.162	0.063	0.304	0.061
	Trial 2	0.169	0.063	0.516	0.061
	Trial 3	0.123	0.063	0.496	0.061
	Trial 4	0.382	0.063	0.566	0.061
	Trial 5	0.198	0.063	0.673	0.061

[SE = standard error, L = left, R = right, PFC = prefrontal cortex, PMC = premotor cortex, SMA = supplementary motor area, M1 = primary motor area]

Supplementary Table 2 – Between trial differences in relative concentrations of HbO2 during dual-task

Trial (I)	Trial (J)	LPFC		RPFC		LPMC		RPMC		LSMA		RSMA		LM1		RM1	
		Diff	*p*	Diff	*p*	Diff	*p*	Diff	*p*	Diff	*p*	Diff	*p*	Diff	*p*	Diff	*p*
Trial 1	Trial 2	-0.015	0.81	-0.03	0.58	0.02	0.74	0.01	0.92	-0.07	0.21	-0.09	0.13	-0.01	0.13	-0.03	0.63
	Trial 3	0.062	0.33	0.07	0.24	0.10	**0.09**	0.06	0.32	0.00	0.99	0.03	0.64	0.04	0.64	0.04	0.50
	Trial 4	0.102	0.11	0.06	0.34	0.12	**0.06**	0.06	0.36	0.07	0.19	0.02	0.73	0.08	0.73	0.09	0.15
	Trial 5	0.231	**0.00**	0.22	**0.00**	0.19	**0.00**	0.23	**0.00**	0.15	**0.01**	0.15	**0.02**	0.18	**0.02**	0.18	**0.00**
Trial 2	Trial 1	0.015	0.81	0.03	0.58	-0.02	0.74	-0.01	0.92	0.07	0.21	0.09	0.13	0.01	0.13	0.03	0.63
	Trial 3	0.077	0.23	0.10	**0.09**	0.08	0.17	0.06	0.37	0.07	0.21	0.12	**0.05**	0.05	**0.05**	0.07	0.25
	Trial 4	0.117	**0.07**	0.09	0.13	0.10	0.12	0.05	0.42	0.14	**0.01**	0.11	**0.06**	0.08	0.06	0.12	**0.06**
	Trial 5	0.247	**0.00**	0.25	**0.00**	0.17	**0.01**	0.22	**0.00**	0.22	**0.00**	0.24	**0.00**	0.19	**0.00**	0.21	**0.00**
Trial 3	Trial 1	-0.062	0.33	-0.07	0.24	-0.10	**0.09**	-0.06	0.32	0.00	0.99	-0.03	0.64	-0.04	0.64	-0.04	0.50
	Trial 2	-0.077	0.23	-0.10	**0.09**	-0.08	0.17	-0.06	0.37	-0.07	0.21	-0.12	**0.05**	-0.05	**0.05**	-0.07	0.25
	Trial 4	0.04	0.53	-0.01	0.83	0.01	0.84	-0.01	0.94	0.07	0.19	-0.01	0.90	0.04	0.90	0.05	0.43
	Trial 5	0.169	**0.01**	0.15	**0.02**	0.09	0.14	0.17	**0.01**	0.15	**0.01**	0.12	**0.05**	0.14	**0.05**	0.14	**0.02**
Trial 4	Trial 1	-0.102	0.11	-0.06	0.34	-0.12	**0.06**	-0.06	0.36	-0.07	0.19	-0.02	0.73	-0.08	0.73	-0.09	0.15
	Trial 2	-0.117	**0.07**	-0.09	0.13	-0.10	0.12	-0.05	0.42	-0.14	**0.01**	-0.11	0.06	-0.08	0.06	-0.12	**0.06**
	Trial 3	-0.04	0.53	0.01	0.83	-0.01	0.84	0.01	0.94	-0.07	0.19	0.01	0.90	-0.04	0.90	-0.05	0.43
	Trial 5	0.129	**0.05**	0.16	**0.01**	0.08	0.21	0.17	**0.01**	0.08	0.17	0.13	**0.04**	0.10	**0.04**	0.09	0.13
Trial 5	Trial 1	-0.231	**0.00**	-0.22	**0.00**	-0.19	**0.00**	-0.23	**0.00**	-0.15	**0.01**	-0.15	**0.02**	-0.18	**0.02**	-0.18	**0.00**
	Trial 2	-0.247	**0.00**	-0.25	**0.00**	-0.17	**0.01**	-0.22	**0.00**	-0.22	**0.00**	-0.24	**0.00**	-0.19	**0.00**	-0.21	**0.00**
	Trial 3	-0.169	**0.01**	-0.15	**0.02**	-0.09	0.14	-0.17	**0.01**	-0.15	**0.01**	-0.12	**0.05**	-0.14	**0.05**	-0.14	**0.02**
	Trial 4	-0.129	**0.05**	-0.16	**0.01**	-0.08	0.21	-0.17	**0.01**	-0.08	0.17	-0.13	**0.04**	-0.10	**0.04**	-0.09	0.13

[Significant p<0.05 values are highlighted in bold. Diff = mean difference between trials (I-J)]