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Age-related differences in cortical functional connectivity during du al-task walking: a cross-sectional fNIRS study

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Abstract

Background

Aging is associated with alterations in gait and cognitive-motor function. This study employed functional near-infrared spectroscopy (fNIRS) and a dual-task paradigm to investigate differences in cortical functional connectivity (FC) during walking-related tasks between healthy older and younger adults.

Methods

A total of 58 healthy participants were included, comprising 30 older adults (median age, 67 years [IQR, 63.75–69.25]) and 28 younger adults (median age, 24 years [IQR, 24–25]). Using fNIRS, we compared FC across three conditions: single-task walking, a single cognitive task, and dual-task walking. Associations between FC measures and behavioral parameters were subsequently examined. Between-group and within-group FC differences were assessed using independent-samples and paired-samples t tests, respectively, with false discovery rate correction, and Spearman correlation analyses were used to examine associations between FC and behavioral measures.

Results

After false discovery rate (FDR) correction, no significant differences in FC were observed between single-task walking and dual-task walking in the younger group. In contrast, the older group showed significantly reduced FC in the right premotor cortex and supplementary motor area (PMC&SMA) during dual-task walking compared with single-task walking ($p < 0.05$). No significant between-group differences in FC were observed during either single-task condition. During dual-task walking, the older group generated fewer correct words ($p < 0.001$) and exhibited lower FC in the right prefrontal cortex (PFC) and right PMC&SMA, together with stronger PFC–supramarginal gyrus (SMG) connectivity, compared with the younger group (all $p < 0.05$). FC measures from these regions were also associated with several cognitive and gait-related parameters.

Conclusions

Older and younger adults exhibited distinct cortical FC patterns during dual-task walking. Reduced FC in the right PFC and PMC&SMA, together with increased PFC–SMG connectivity in older adults, may reflect age-related alterations in cortical network organization during dual-task walking.

Background

Human gait undergoes characteristic changes with advancing age, including reductions in gait speed and stride length and increases in gait variability [1, 2]. These changes may become more pronounced

when walking is performed concurrently with a cognitive task, reflecting age-related alterations in cognitive-motor integration. Gait alterations in older adults are closely associated with mobility limitations and cognitive function [3–5].

The cognitive contribution to gait becomes particularly evident under dual-task conditions, in which walking and a cognitive task must be performed simultaneously. With advancing age, cognitive involvement in gait control increases, and older adults may become more vulnerable to cognitive-motor interference when cognitive and motor demands must be managed concurrently [6, 7]. Neuroimaging studies have further shown that dual-task gait is associated with age-related alterations in cortical recruitment, particularly within frontal and motor-related regions. Accordingly, dual-task paradigms may reveal age-related differences in cognitive-motor control that are less apparent during single-task performance [4, 8].

Functional near-infrared spectroscopy (fNIRS) provides a non-invasive means of monitoring cortical hemodynamic responses during active movement and is particularly suitable for investigating brain activity during standing and walking [9, 10]. Many previous fNIRS studies of gait and dual-task performance have focused on regional cortical activation, particularly within the prefrontal cortex (PFC) [10]. Reviews of the available evidence indicate that dual-task walking frequently alters PFC activation in older adults, although the magnitude and direction of these responses vary according to task characteristics, cognitive demand, baseline condition, and cortical region examined [11–13]. Importantly, multi-region fNIRS studies have also demonstrated dual-task-related changes in premotor, supplementary motor, and primary motor cortices, suggesting that cognitive-motor interference involves distributed cortical systems rather than the PFC alone [14].

Regional activation, however, provides limited information about how distributed cortical regions interact as a functional network [15–17]. Recent fNIRS studies have therefore begun to examine functional connectivity (FC) and network-level organization during complex cognitive-motor tasks. In older adults, enhanced PFC connectivity has been reported during dual-task obstacle negotiation [18]. In healthy adults, dual-task performance has also been associated with changes in cortical network efficiency across multiple brain regions [19]. More recently, age-related differences in cortical activation and FC have been demonstrated during dual-task turning, with older and younger adults exhibiting distinct patterns of network modulation [20]. These findings highlight the importance of examining network-level interactions during cognitive-motor performance. Nevertheless, many recent fNIRS studies of gait and aging have continued to characterize regional prefrontal hemodynamic responses during single- and dual-task walking rather than distributed cortical functional connectivity [21, 22]. Although FC has begun to be examined during dual-task walking, existing work has also focused on specific populations, such as older adults with different cognitive status, and on manipulations of dual-task difficulty [23]. Recent studies have examined age-related cortical activation during straight-path dual-task walking and age-related FC during other motor-cognitive paradigms; however, evidence remains limited regarding age-group differences in distributed cortical FC across frontal, motor, somatosensory, and parietal regions during conventional straight-path dual-task walking [24, 25].

Therefore, the present cross-sectional study aimed to characterize age-group differences in cortical FC between healthy older and younger adults during single-task walking, a single cognitive task, and dual-task walking using fNIRS. We examined FC within and between cortical regions encompassing prefrontal, premotor, motor, somatosensory, and parietal areas and further explored associations between FC measures and cognitive and gait-related assessments. By comparing the three task conditions, we sought to determine whether age-group differences in cortical network organization were more apparent during dual-task walking than during either single-task condition.

Methods

Participants

Between June 2023 and October 2024, healthy older and younger adults were recruited from the First Affiliated Hospital of Dalian Medical University and surrounding communities. This cross-sectional study compared cortical functional connectivity between healthy older and younger adults during single-task walking, a single cognitive task, and dual-task walking. Participants were categorized as younger or older according to prespecified age criteria.

The inclusion criteria were as follows: (1) age 20–40 years for the younger group or 60–80 years for the older group; (2) ability to understand and complete all experimental procedures; and (3) provision of written informed consent. The exclusion criteria were: (1) musculoskeletal or neurological disorders affecting gait, such as spinal lesions or lower-limb fractures; (2) speech or language impairments that could interfere with task performance; (3) a history of severe brain injury, neurosurgery, or major neurological disorders; (4) diagnosed psychiatric disorders; (5) significant uncontrolled medical conditions; (6) uncorrected visual impairment; and (7) inability to read or illiteracy.

This study was approved by the Ethics Committee of the First Affiliated Hospital of Dalian Medical University (Approval No. PJ-KS-KY-2023-04 (X)). All procedures involving human participants were performed in accordance with the Declaration of Helsinki and relevant guidelines and regulations. Written informed consent was obtained from all participants before study participation.

Clinical and behavioral assessments

Demographic characteristics, including age, sex, and years of education, were recorded. Neuropsychological assessments included the Montreal Cognitive Assessment (MoCA) and the Chinese version of the Mini-Mental State Examination (CMMS) for global cognitive function [26, 27]; the Shape Trail Test (STT) and Stroop Color Word Test (SCWT) for executive function; the Digit Span Test (DST) for memory function; the Boston Naming Test (BNT) for language function; the Clock Drawing Test (CDT) and Judgment of Line Orientation (JLO) for visuospatial function; and the Hamilton Depression Scale (HAMD) and Hamilton Anxiety Scale (HAMA) for mood and anxiety symptoms. The Activities of Daily

Living Scale (ADL) was used to assess activities of daily living, and the Overactive Bladder Symptom Score (OABSS) was also administered.

Gait and balance function were assessed using the Tinetti Balance and Gait Evaluation and the 3-m Timed Up and Go Test (TUG). Each participant completed three consecutive TUG trials, and the mean completion time was used for subsequent analysis.

fNIRS acquisition

fNIRS system and cortical regions

Cortical hemodynamic signals were recorded using a portable multichannel fNIRS system (NirSmart; Danyang Huichuang Medical Equipment Co. Ltd., China). The system used light-emitting diodes operating at wavelengths of 730 and 850 nm and avalanche photodiode detectors. A total of 23 source optodes and 15 detector optodes formed 47 measurement channels, with an average source–detector distance of approximately 3 cm. Changes in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) concentrations were continuously recorded during task performance.

The full-channel sampling rate was 11 Hz, corresponding to a temporal resolution of approximately 0.1 s. Optodes were positioned over the prefrontal, motor, somatosensory, and parietal cortical regions according to the International 10–20 system. Three-dimensional coordinates of the measurement channels were registered to Montreal Neurological Institute (MNI) standard space using the spatial registration tool in NirSpace software (Danyang Huichuang Medical Equipment Co. Ltd., China).

The measurement channels were assigned to the following cortical regions: dorsolateral prefrontal cortex (DLPFC; left: channels 13, 14, and 21; right: channels 7, 9, and 16); other prefrontal cortex regions (PFC; left: channels 4–6, 10, 12, 15, 19, and 20; right: channels 1–3, 8, 11, and 17); premotor cortex and supplementary motor area (PMC&SMA; left: channels 24, 32, 33, and 35; right: channels 22, 26, 29, and 30); primary motor cortex (M1; channels 28, 31, and 34); primary somatosensory cortex (S1; left: channels 36, 37, and 41–43; right: channels 27, 39, and 40); supramarginal gyrus (SMG; left: channel 47; right: channel 38); and somatosensory association cortex (S2; channels 44–46), as shown in Fig. 1.

Experimental paradigm

All fNIRS measurements were performed in a quiet room under natural lighting conditions. Before data acquisition, the fNIRS cap was adjusted to ensure adequate signal quality. Standardized verbal instructions and a demonstration of the experimental procedures were provided before testing. During task performance, participants were instructed to minimize unnecessary head and upper-body movements while completing the required tasks.

Single-task walking. The single-task walking condition lasted 100 s and consisted of three consecutive periods. During the 20-s pre-task baseline, participants stood quietly and were instructed to avoid unnecessary mental or physical activity. During the 60-s task period, participants walked at a self-selected comfortable pace along a straight path without performing an additional cognitive task. During the 20-s post-task baseline, participants resumed quiet standing until the end of the recording.

Single cognitive task. The single cognitive task lasted 100 s and consisted of a 20-s pre-task baseline, a 60-s cognitive task period, and a 20-s post-task baseline. During the pre-task baseline, participants remained seated and repeatedly articulated the sequence “1, 2, 3, 4, 5” at a natural pace and volume. During the task period, participants were instructed to generate as many words or idioms as possible containing each of three specified Chinese characters—“□” (river), “□” (home), and “□” (big)—with 20 s allocated to each character. Participants remained seated and responded verbally at a natural pace and volume. During the post-task baseline, participants again repeated the sequence “1, 2, 3, 4, 5” under the same verbal conditions.

Dual-task walking. The dual-task walking condition lasted 100 s and consisted of a 20-s pre-task baseline, a 60-s dual-task period, and a 20-s post-task baseline. During the pre-task baseline, participants stood quietly while repeatedly articulating the sequence “1, 2, 3, 4, 5” at a natural pace and volume. During the dual-task period, participants walked at a self-selected comfortable pace along a straight path while simultaneously generating as many words or idioms as possible containing each of three Chinese characters—“□” (sea), “□” (sun), and “□” (up)—with 20 s allocated to each character. During the post-task baseline, participants resumed standing and again repeated the sequence “1, 2, 3, 4, 5” under the same verbal conditions.

Statistical analysis

Normally distributed continuous variables were compared between groups using independent-samples t tests, whereas non-normally distributed continuous variables were compared using the Mann–Whitney U test. Categorical variables were compared using the chi-square (χ^2) test. All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant.

Between-group differences in FC were assessed using independent-samples t tests, whereas differences in FC between task conditions within the same group were assessed using paired-samples t tests. False discovery rate (FDR) correction was applied to the FC comparisons, with statistical significance defined as FDR-corrected $p < 0.05$.

Across all participants, Spearman correlation analyses were performed to examine associations between FC measures showing significant between-group differences during dual-task walking and cognitive and gait-related measures. Correlation analyses were exploratory, and p values were not adjusted for multiple comparisons. Correlation results were visualized using heatmaps.

fNIRS data preprocessing and functional connectivity analysis

Raw fNIRS data were preprocessed and analyzed using NirSpark software (Danyang Huichuang Medical Equipment Co. Ltd., China) running in MATLAB (MathWorks, USA). Preprocessing was performed using the Preprocess module in NirSpark. Motion artifacts caused by relative displacement between the scalp and optodes were corrected using a motion standard deviation algorithm combined with spline interpolation (SDThresh = 6; AMPThresh = 0.5). A band-pass filter of 0.01–0.08 Hz was applied to attenuate physiological noise and other irrelevant low- and high-frequency components. The filtered optical density signals were subsequently converted into concentration changes in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) using the modified Beer–Lambert law. Based on previous evidence indicating that task-evoked HbO signals show good correspondence with fMRI signals [28] and a favorable signal-to-noise ratio [29], the present FC analyses focused on HbO.

In NirSpark, the Network module was used to define regions of interest (ROIs) and calculate Pearson correlation coefficients between HbO time series for subsequent FC analyses [30, 31]. Within-ROI connectivity was defined as the mean Pearson correlation coefficient among different channels within each ROI, whereas between-ROI connectivity was defined using Pearson correlation coefficients between different ROIs.

Results

Demographic, clinical, and behavioral characteristics

A total of 58 healthy participants were included, comprising 30 older adults (age, 67 [63.75, 69.25] years) and 28 younger adults (age, 24 [24, 25] years). There was no significant difference in sex distribution between the two groups ($p = 0.737$). Older adults had fewer years of education ($p < 0.001$).

Compared with the younger group, older adults had lower CMMS, MoCA, BNT, DST, and JLO scores and longer STT and SCWT completion times (all $p < 0.001$). No significant between-group difference was observed in CDT scores ($p = 0.168$). Older adults also had higher HAMA, HAMD, OABSS, and ADL scores than the younger adults (all $p < 0.05$).

For gait-related measures, older adults had a longer TUG completion time than younger adults (8.85 ± 1.17 vs. 6.96 ± 1.07 s, $p < 0.001$), whereas no significant between-group difference was observed in Tinetti scores ($p = 0.168$). During dual-task walking, older adults generated fewer correct words than the younger adults (11.40 ± 3.87 vs. 16.04 ± 4.40, $p < 0.001$). Participant characteristics and behavioral measures are summarized in Table 1.

Table 1
Demographic, clinical, cognitive, and gait-related characteristics of the younger and older groups.

Age (years)	**Younger adults (n = 28)**	**Older adults (n = 30)**	**$t/\chi^2/Z$**	***p***
	24 (24, 25)	**67 (63.75,69.25)**	**-6.592[c]**	**< 0.001**
Sex (male/female)	10/18	12/18	0.113[b]	0.737
Education (years)	17 (12,18)	9 (9,15)	5.075[c]	< 0.001
CMMS	30 (29,30)	29 (28,30)	3.955[c]	< 0.001
MoCA	28 (28,30)	26 (25,27)	5.687[c]	< 0.001
BNT	29 (29,30)	27 (25.5,28)	5.579[c]	< 0.001
DST	27.78 ± 3.37	17.73 ± 4.45	9.528[a]	< 0.001
STT-A	22 (21,24.5)	53 (41.5,71.5)	-6.311[c]	< 0.001
STT-B	59 (57,70.25)	125 (100.5,155)	-6.278[c]	< 0.001
SCWT-A	21.70 ± 3.63	26.48 ± 3.85	-4.497[a]	< 0.001
SCWT-B	28.46 (24.41,33.23)	35.47 (33.13,40.19)	-4.127[c]	< 0.001
SCWT-C	52.73 ± 10.59	70.95 ± 13.50	-5.222[a]	< 0.001
CDT	10 (10,10)	10 (10,10)	1.378[c]	0.168
JLO	29 (28,30)	23 (22.5,25)	5.833[c]	< 0.001
HAMA	1.5 (1,4)	5 (4,7.5)	-3.101[c]	0.002
HAMD	0 (0,2.25)	4 (3,7)	-4.598[c]	< 0.001
OABSS	0 (0,0)	1 (1,2)	-6.076[c]	< 0.001
ADL	20 (20,20)	20 (20,20)	2.238[c]	0.025

Note: Data are presented as mean ± standard deviation or median (interquartile range), as appropriate. ^a t value; ^b χ^2 value; ^c Z value. CMMS, Chinese version of the Mini-Mental State Examination; MoCA, Montreal Cognitive Assessment; BNT, Boston Naming Test; DST, Digit Span Test; STT-A, Shape Trail Test A; STT-B, Shape Trail Test B; SCWT-A, Stroop Color Word Test A; SCWT-B, Stroop Color Word Test B; SCWT-C, Stroop Color Word Test C; CDT, Clock Drawing Test; JLO, Judgment of Line Orientation; HAMA, Hamilton Anxiety Scale; HAMD, Hamilton Depression Scale; OABSS, Overactive Bladder Symptom Score; ADL, Activities of Daily Living Scale; TUG, Timed Up and Go Test; Tinetti, Tinetti Balance and Gait Evaluation.

Age (years)	**Younger adults (n = 28)**	**Older adults (n = 30)**	**$t/\chi^2/Z$**	***p***
	24 (24, 25)	**67 (63.75,69.25)**	**-6.592[c]**	**< 0.001**
TUG (s)	6.96 ± 1.07	8.85 ± 1.17	-6.271[a]	< 0.001
Tinetti	28 (28,28)	28 (28,28)	1.378[c]	0.168
Correct words during dual-task walking	16.04 ± 4.40	11.40 ± 3.87	4.269	< 0.001

Note: Data are presented as mean ± standard deviation or median (interquartile range), as appropriate. ^a t value; ^b χ^2 value; ^c Z value. CMMS, Chinese version of the Mini-Mental State Examination; MoCA, Montreal Cognitive Assessment; BNT, Boston Naming Test; DST, Digit Span Test; STT-A, Shape Trail Test A; STT-B, Shape Trail Test B; SCWT-A, Stroop Color Word Test A; SCWT-B, Stroop Color Word Test B; SCWT-C, Stroop Color Word Test C; CDT, Clock Drawing Test; JLO, Judgment of Line Orientation; HAMA, Hamilton Anxiety Scale; HAMD, Hamilton Depression Scale; OABSS, Overactive Bladder Symptom Score; ADL, Activities of Daily Living Scale; TUG, Timed Up and Go Test; Tinetti, Tinetti Balance and Gait Evaluation.

fNIRS functional connectivity results

Functional connectivity patterns for younger and older adults under single-task walking, the single cognitive task, and dual-task walking are shown in Fig. 2.

In the younger adults, no significant differences in within-ROI or between-ROI connectivity were observed between single-task and dual-task walking after FDR correction. The corresponding within-group comparisons are shown in Fig. 3a.

In the older group, within-ROI connectivity in the right PMC&SMA was significantly lower during dual-task walking than during single-task walking (FDR-corrected $p < 0.05$). No significant task-related differences were observed in within-ROI connectivity in the other ROIs after FDR correction. No significant differences in between-ROI connectivity were observed between the two walking conditions in the older group after FDR correction. The corresponding results for the older group are shown in Fig. 3b.

During single-task walking, no significant between-group differences were observed in either within-ROI or between-ROI connectivity after FDR correction (Fig. 4a). Similarly, no significant between-group differences were observed during the single cognitive task after FDR correction (Fig. 4b).

During dual-task walking, the older group showed significantly lower within-ROI connectivity in the right PFC and right PMC&SMA than the younger group (both FDR-corrected $p < 0.05$). In contrast, between-ROI PFC–SMG connectivity was significantly stronger in the older adults than in the younger group (FDR-corrected $p < 0.05$; Fig. 4c).

Correlation analysis

Across all participants, Spearman correlation analyses were performed to examine associations between selected FC measures and cognitive and gait-related assessments. The FC measures selected for correlation analysis were those showing significant between-group differences during dual-task walking, including between-ROI PFC–SMG connectivity and within-ROI connectivity in the right PFC and right PMC&SMA.

Between-ROI PFC–SMG connectivity was negatively correlated with DST scores ($\rho = -0.33$, $p < 0.05$). Within-ROI connectivity in the right PFC was negatively correlated with TUG, SCWT-A, STT-A, STT-B, HAMD, and OABSS scores and positively correlated with MoCA, DST, BNT, and JLO scores (all $p < 0.05$). Within-ROI connectivity in the right PMC&SMA was negatively correlated with SCWT-A, STT-B, and OABSS scores and positively correlated with CMMS, MoCA, DST, BNT, and JLO scores (all $p < 0.05$). The complete correlation results are shown in Fig. 5.

Discussion

This study compared cortical FC between healthy older and younger adults during single-task walking, a single cognitive task, and dual-task walking using fNIRS. Three main findings emerged. First, in older adults, within-ROI connectivity in the right PMC&SMA was lower during dual-task walking than during single-task walking, whereas no significant task-related FC changes were observed in younger adults. Second, during dual-task walking, older adults showed lower within-ROI connectivity in the right PFC and right PMC&SMA but stronger between-ROI PFC–SMG connectivity than younger adults; no significant between-group FC differences were observed during either single-task condition. Older adults also generated fewer correct words during dual-task walking. Third, the FC measures that differed between groups were associated with several cognitive and gait-related measures, suggesting that these network-level differences may be related to individual variation in cognitive-motor function.

Within the older group, within-ROI connectivity in the right PMC&SMA was reduced during dual-task walking compared with single-task walking. This finding may reflect reduced local functional integration within motor-related cortical regions when cognitive and motor demands must be managed simultaneously. Previous fNIRS studies have shown that dual-task walking modulates activity in premotor, supplementary motor, and primary motor regions, and older adults may exhibit attenuated SMA responses compared with younger adults under dual-task conditions [14]. More recent network-level studies have also shown that increasing dual-task demands can alter cortical network organization and reduce network efficiency [19]. Thus, the reduced right PMC&SMA connectivity observed in the present study may represent an age-related difficulty in the maintenance of local motor-network integration under increased cognitive-motor demands. However, the present data do not establish whether this pattern reflects neural inefficiency, compensatory reorganization, or another form of task-related network adaptation.

No significant difference in within-ROI PFC connectivity was observed between single-task and dual-task walking in the older group. Previous fNIRS studies have reported heterogeneous PFC responses during

dual-task walking, with the magnitude and direction of task-related changes varying across study designs and task demands [12, 13, 32]. Importantly, regional activation and functional connectivity represent different aspects of cortical function and should not be directly equated [33]. Therefore, the absence of a significant task-related change in PFC connectivity in the present study does not necessarily indicate an absence of PFC involvement during dual-task walking. Differences in cognitive load, baseline condition, task structure, cortical coverage, and analytical approach may contribute to variability across studies [11].

In contrast, the younger group showed no significant differences in FC between single-task and dual-task walking. One possible explanation is that the cognitive-motor demands imposed by the present paradigm may have been insufficient to elicit detectable changes in cortical connectivity in younger adults. Previous fNIRS studies have shown that cortical activation and network-level responses during dual-task performance vary according to task complexity and the executive demands of the concurrent cognitive task [11, 19, 34]. Nevertheless, the present study did not directly assess neural reserve or compensatory recruitment, and these constructs generally require explicit operationalization using neural and behavioral measures [35, 36]. Therefore, the absence of significant FC changes in younger adults should be interpreted as relative stability of the measured cortical connectivity under the current experimental conditions rather than as direct evidence of greater neural efficiency [35, 36].

Similarly, no significant between-group differences in FC were observed during either single-task walking or the single cognitive task. These findings may indicate that age-group differences in the cortical networks examined here became more apparent when cognitive and motor demands were combined [37]. However, the absence of significant differences during the single-task conditions should not be interpreted as evidence that cortical network organization was identical between younger and older adults [38]. fNIRS measurements are restricted to the sampled superficial cortical regions, and the observed signals and connectivity estimates may also depend on optode coverage, task design, preprocessing procedures, and analytical choices [11].

During dual-task walking, older adults showed lower within-ROI connectivity in the right PFC and right PMC&SMA than younger adults. This pattern suggests that age-group differences in local cortical network organization become more evident when cognitive and motor demands are imposed simultaneously. Recent fNIRS evidence similarly demonstrates age-related differences in cortical network modulation during complex dual-task walking. In a study comparing younger and older adults during dual-task turning, the two age groups exhibited distinct patterns of cortical activation and functional connectivity [20]. Together with the present findings, these observations suggest that aging may be associated with altered recruitment and integration of cortical networks under cognitively demanding walking conditions [39].

In contrast, between-ROI PFC–SMG connectivity was stronger in older adults than in younger adults during dual-task walking. This finding may be consistent with age-related alterations in frontal and parietal cortical recruitment under increased dual-task demands [40]. Previous fNIRS studies have

reported enhanced functional connectivity during complex dual-task walking in older adults. For example, enhanced PFC connectivity has been observed during dual-task obstacle negotiation, while more recent work has demonstrated increased connectivity between the primary somatosensory cortex and other cortical regions during dual-task turning in older adults [18, 20]. Therefore, stronger PFC–SMG connectivity in the present study may represent one component of broader age-related network reorganization under dual-task conditions [41, 42]. Whether this increase represents successful compensation, inefficient recruitment, or another adaptive response cannot be determined from the present cross-sectional data.

Behaviorally, older adults also generated fewer correct words during dual-task walking than younger adults. This finding indicates poorer performance on the concurrent cognitive task in older adults under the present dual-task condition. Previous fNIRS studies comparing younger and older adults have similarly reported age-related differences in both cognitive and gait performance during dual-task walking [32]. However, because task-specific gait parameters were not quantified during the dual-task condition in the present study, it is not possible to determine whether a cognitive-motor trade-off occurred or whether poorer cognitive performance was accompanied by deterioration in gait performance. Dual-task interference is commonly quantified by comparing gait performance between single- and dual-task conditions, and gait-related dual-task cost has been widely used to characterize cognitive-motor interference [43].

Exploratory correlation analyses further showed that between-ROI PFC–SMG connectivity was negatively associated with DST scores, whereas within-ROI connectivity in the right PFC and right PMC&SMA was associated with several cognitive, clinical, and gait-related measures. These findings suggest that individual variation in cortical FC during dual-task walking may be related to differences in cognitive-motor function [44]. However, the correlation analyses were exploratory and p values were not adjusted for multiple comparisons; therefore, these associations should be interpreted cautiously and regarded as hypothesis-generating. In addition, the cross-sectional and correlational nature of the analyses precludes conclusions regarding directionality or causality.

Limitations

Several limitations should be considered. First, the sample size was relatively small, which may limit the generalizability of the findings. In addition, the older and younger groups differed substantially in years of education. Because education was not adjusted for in the present analyses, residual confounding cannot be excluded, particularly for cognitive and cognitive-motor outcomes [45]. Moreover, the cross-sectional design precludes assessment of longitudinal changes in cortical network organization with aging. Future studies with larger samples and longitudinal designs are needed to further characterize age-related differences in cortical network organization during walking.

Second, the limited penetration depth of fNIRS restricts measurements primarily to superficial cortical regions and does not permit direct assessment of deeper brain structures [12]. In addition, the optode

configuration used in the present study provided limited cortical coverage. These characteristics should be considered when interpreting the observed connectivity patterns, because fNIRS findings are inherently restricted to the cortical regions sampled by the optode array [11, 46]. Future studies combining broader or high-density fNIRS coverage with complementary neuroimaging techniques such as fMRI may provide a more comprehensive characterization of cortical and subcortical network interactions during walking.

Third, the experimental paradigm included task characteristics that were not fully controlled. The single cognitive task was performed while seated, whereas the cognitive component of the dual-task condition was performed during walking. In addition, different sets of Chinese characters were used in the single cognitive and dual-task conditions, and their difficulty was not formally matched. These differences may have contributed to variation in cognitive demand across conditions because dual-task performance is influenced by the type and difficulty of the concurrent cognitive task as well as by methodological differences in task protocols [11, 47]. Moreover, task-specific gait parameters were not quantified during dual-task walking, precluding calculation of dual-task gait costs and limiting assessment of potential cognitive-motor trade-offs. Previous studies have quantified dual-task interference by simultaneously assessing cognitive and gait performance under single- and dual-task conditions, allowing cognitive and motor dual-task costs to be calculated [19, 47]. Future studies should use more closely matched cognitive stimuli and simultaneously quantify task-specific cognitive and gait performance.

Fourth, the 60-s task periods provided relatively short time series for FC estimation. Previous work has shown that the performance and reliability of fNIRS connectivity measures can be sensitive to the length of the available time series [48]. Therefore, the relatively short recording duration should be considered when interpreting the present FC findings. Longer task periods or repeated task blocks may improve the stability of connectivity estimates, although this must be balanced against participant burden and fatigue, particularly in older adults [49].

Finally, the correlation analyses were exploratory and were conducted across the entire sample, and p values were not adjusted for multiple comparisons. Because the younger and older groups differed in several demographic, cognitive, and FC measures, some observed associations may partly reflect between-group differences rather than purely within-group relationships. Given the number of associations examined and the relatively small sample size, the possibility of false-positive findings cannot be excluded [50]. Accordingly, the observed correlations should be considered hypothesis-generating and require confirmation in larger independent samples [51].

Conclusions

This study identified distinct cortical FC patterns between older and younger adults during dual-task walking using fNIRS. During dual-task walking, older adults showed lower **within-ROI connectivity** in the right PFC and right PMC&SMA but stronger between-ROI PFC–SMG connectivity than younger adults. These findings suggest age-group differences in cortical network organization under increased

cognitive-motor demands and support the potential value of dual-task paradigms for characterizing age-related differences in cognitive-motor network function.

Abbreviations

ADL
Activities of Daily Living Scale
BNT
Boston Naming Test
CDT
Clock Drawing Test
DLPFC
dorsolateral prefrontal cortex
DST
Digit Span Test
FC
functional connectivity
FDR
false discovery rate
fMRI
functional magnetic resonance imaging
fNIRS
functional near-infrared spectroscopy
HAMA
Hamilton Anxiety Scale
HAMD
Hamilton Depression Scale
HbO
oxygenated hemoglobin
HbR
deoxygenated hemoglobin
JLO
Judgment of Line Orientation
M1
primary motor cortex
MNI
Montreal Neurological Institute
CMMS
Chinese version of the Mini-Mental State Examination
MoCA

Montreal Cognitive Assessment
OABSS
Overactive Bladder Symptom Score
PFC
prefrontal cortex
PMC
premotor cortex
ROI
region of interest
S1
primary somatosensory cortex
S2
somatosensory association cortex
SCWT
Stroop Color Word Test
SMA
supplementary motor area
SMG
supramarginal gyrus
STT
Shape Trail Test
TUG
Timed Up and Go Test.

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of the First Affiliated Hospital of Dalian Medical University (Approval No. PJ-KS-KY-2023-04 (X)). All procedures involving human participants were performed in accordance with the Declaration of Helsinki and relevant guidelines and regulations. Written informed consent was obtained from all participants before study participation.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

X-Y Zhang contributed to conceptualization, methodology, investigation, data curation, software, formal analysis, visualization, writing—original draft, and writing—review and editing. X-Y Zhao contributed to investigation, data acquisition, data curation, visualization, and writing—review and editing. J-J Tian contributed to data acquisition, data curation, visualization, and writing—review and editing. B-C Wang contributed to investigation, data curation, and writing—review and editing. S-Y Wang contributed to investigation, data curation, and writing—review and editing. B-Y Guan contributed to investigation, data curation, and writing—review and editing. C-L Song contributed to review and editing. L Zhang contributed to writing—review and editing. B-W Zhang contributed to supervision, project administration, formal analysis, funding acquisition, and writing—review and editing. All authors read and approved the final manuscript.

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Clinical trial number

Not applicable.

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Figures

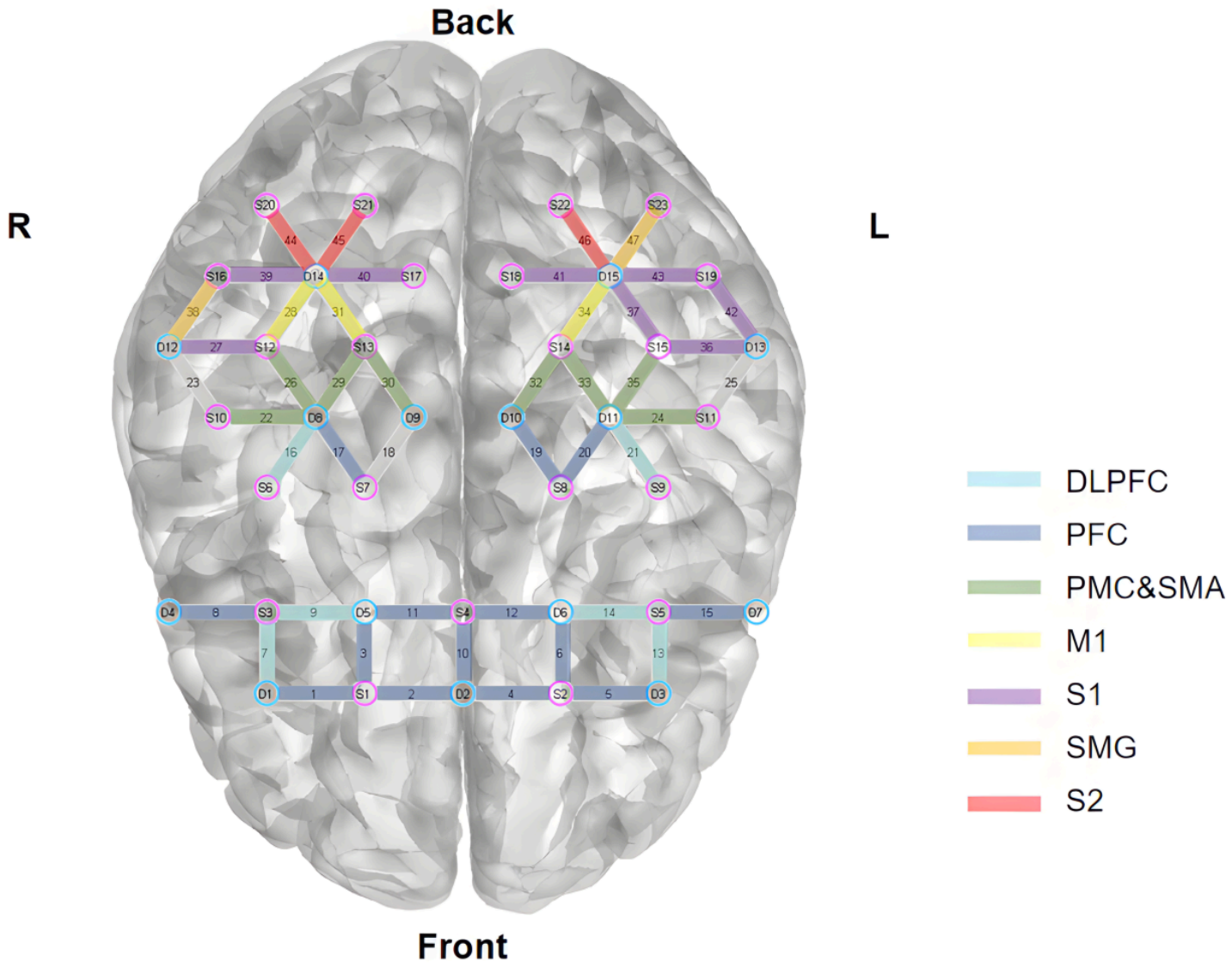

Figure 1

Distribution of fNIRS measurement channels. Pink circles indicate source optodes, blue circles indicate detector optodes, and the numbers between source and detector optodes represent the measurement channels.

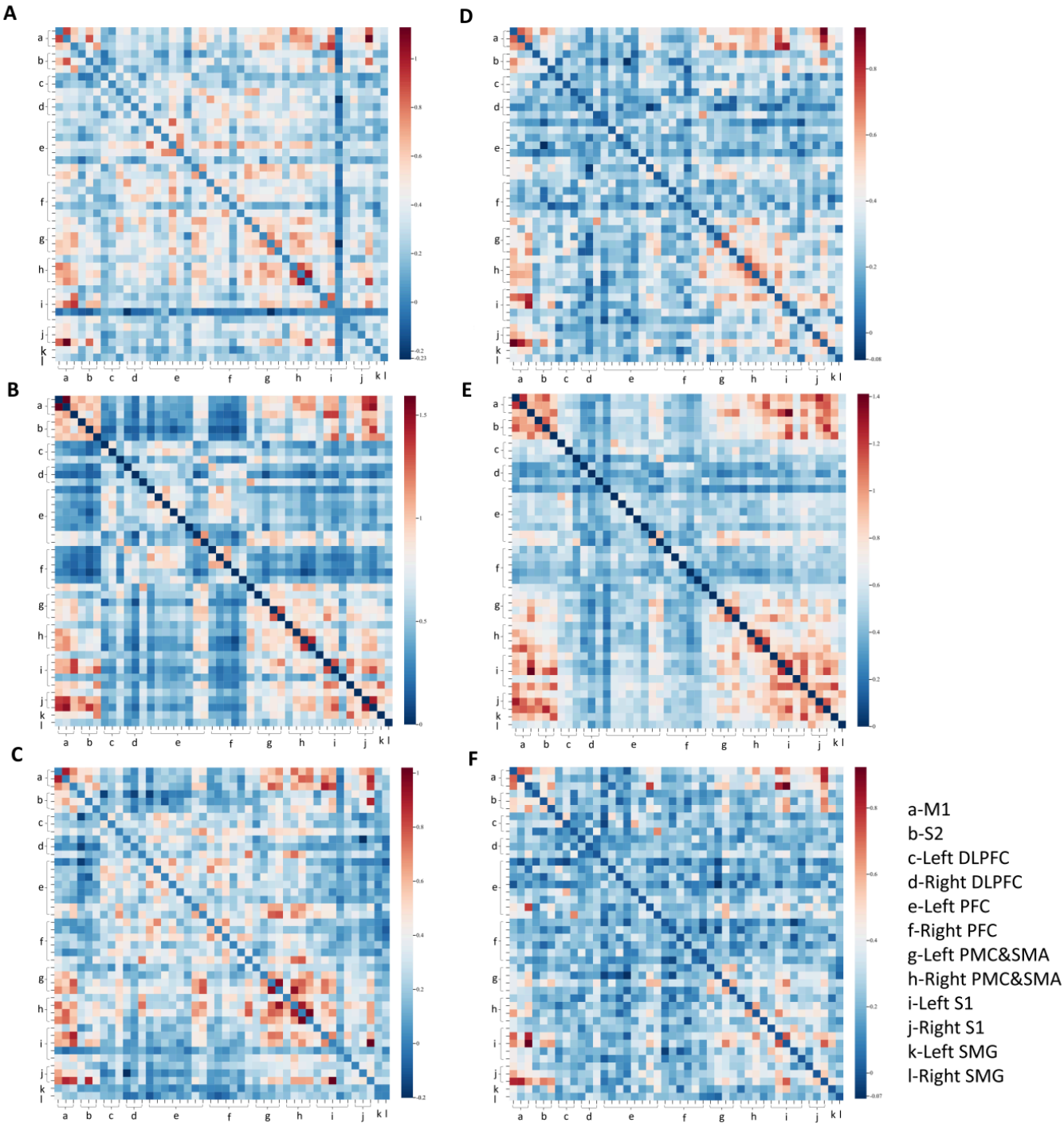

Figure 2

Functional connectivity patterns under the three task conditions. (A) Younger adults during single-task walking; (B) younger adults during the single cognitive task; (C) younger adults during dual-task walking; (D) older adults during single-task walking; (E) older adults during the single cognitive task; and (F) older adults during dual-task walking.

Within-group comparison between single-task and dual-task walking

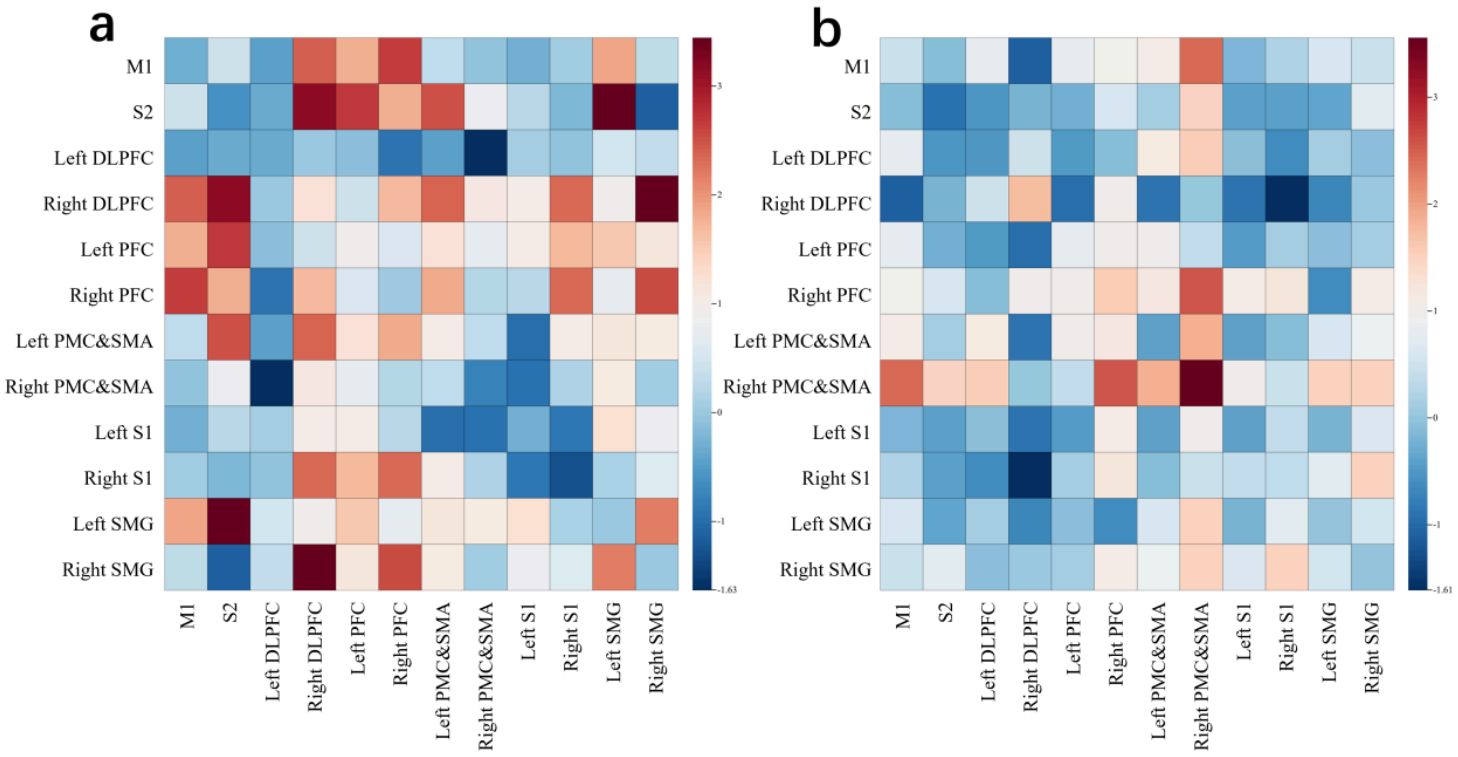

Figure 3

Within-group comparisons of functional connectivity between single-task and dual-task walking. (a) Younger group; (b) older group. Results are displayed as t-value matrices.

Between-group comparisons between younger and older adults

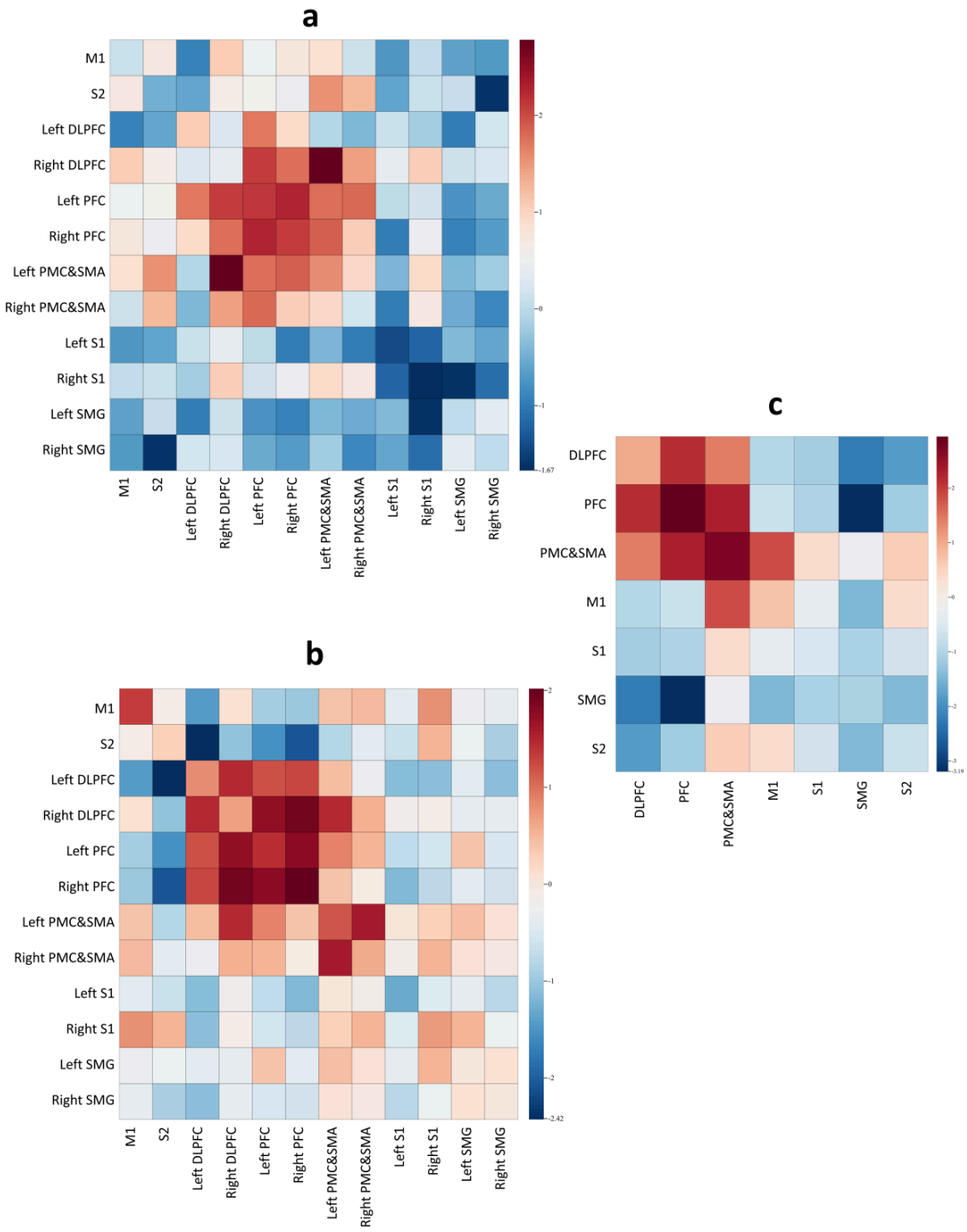

Figure 4

Between-group comparisons of functional connectivity under the three task conditions. (a) Single-task walking; (b) single cognitive task; and (c) dual-task walking. Results are displayed as t-value matrices.

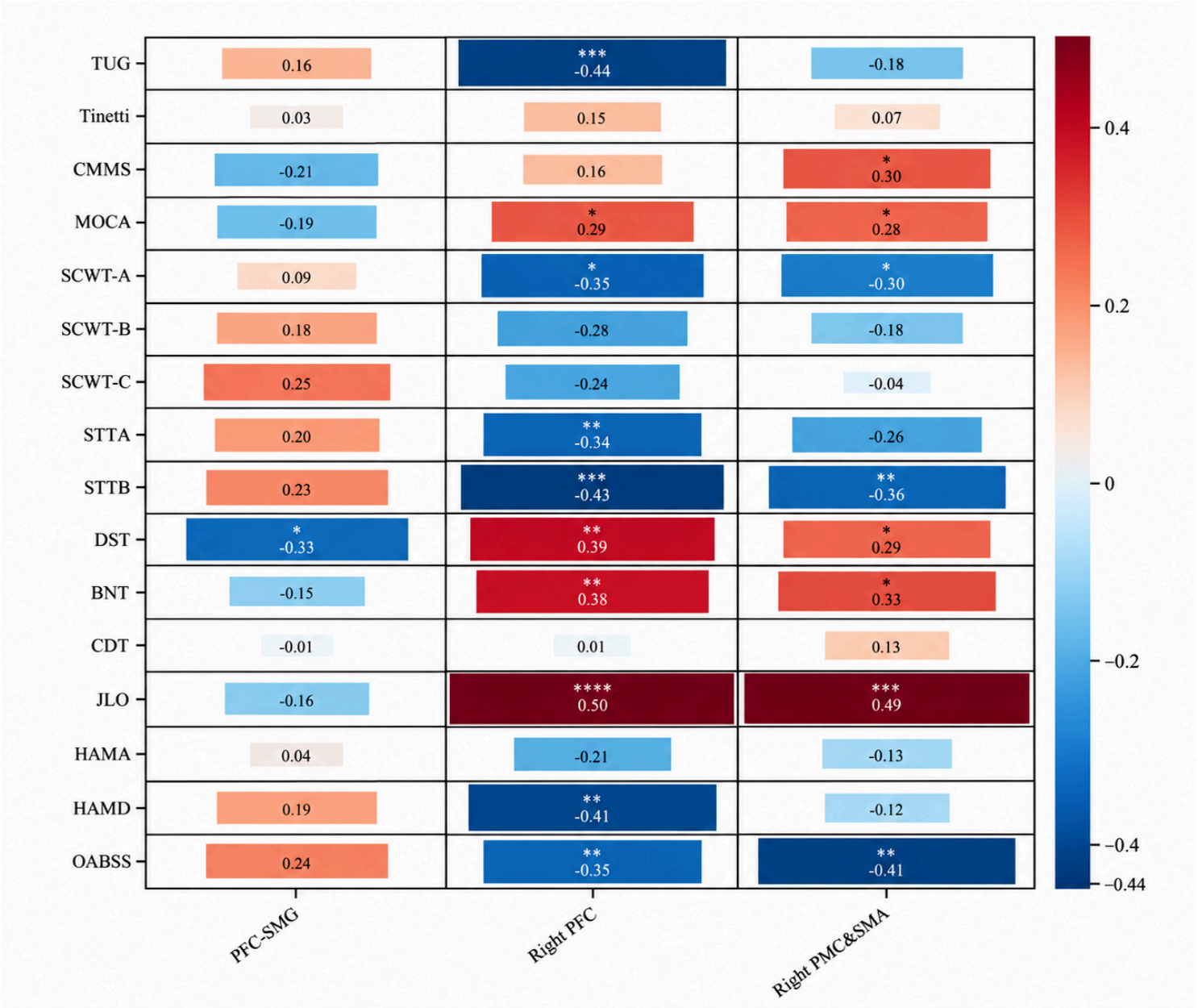

Figure 5

Heatmap of Spearman correlations between selected functional connectivity measures and clinical and behavioral assessments across all participants

Note: Color intensity and cell size represent the magnitude of Spearman's ρ. Numeric values indicate Spearman's correlation coefficients. *p < 0.05, **p < 0.01, ***p < 0.001, and ****p < 0.0001.

TUG, Timed Up and Go Test; Tinetti, Tinetti Balance and Gait Evaluation; CMMS, Chinese version of the Mini-Mental State Examination; MoCA, Montreal Cognitive Assessment; SCWT-A, Stroop Color Word Test A (color dots); SCWT-B, Stroop Color Word Test B (color words); SCWT-C, Stroop Color Word Test C (interfering color words); STT-A, Shape Trail Test A (numbers); STT-B, Shape Trail Test B (numbers and shapes); DST, Digit Span Test; BNT, Boston Naming Test; CDT, Clock Drawing Test; JLO, Judgment of Line

Orientation; HAMA, Hamilton Anxiety Scale; HAMD, Hamilton Depression Scale; OABSS, Overactive Bladder Symptom Score.