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Review article

The prefrontal cortex hemodynamic responses to dual-task paradigms in older adults: A systematic review and meta-analysis

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ABSTRACT

Background: Functional near-infrared spectroscopy (fNIRS) is a method to measure cerebral hemodynamics. Determining the changes in prefrontal cortex (PFC) hemodynamics during dual-task paradigms is essential in explaining alterations in physical activities, especially in older adults.
Aims: To systematically review and meta-analyze the effects of dual-task paradigms on PFC hemodynamics in older adults.
Methods: The search was conducted in PubMed, Scopus, and Web of Science from inception until March 2023 to identify studies on the effects of dual-task paradigms on PFC hemodynamics. The meta-analysis included variables of cerebral hemodynamics, such as oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HbR). The heterogeneity of the included studies was determined using the I^2 statistic. Additionally, subgroup analysis was conducted to compare the effects of different types of cognitive tasks.
Results: A total of 37 studies were included in the systematic review, 25 studies comprising 2224 older adults were included in the meta-analysis. Our findings showed that inhibitory control and working memory tasks significantly increased HbO_2 in the PFC by 0.53 ($p < 0.01$, 95% CI = 0.37 to 0.70) and 0.13 ($p < 0.01$, 95% CI = 0.08 to 0.18) μmol/L, respectively. Overall, HbO_2 was significantly increased during dual-task paradigms by 0.36 μmol/L ($P < 0.01$, 95% CI = 0.27 to 0.45). Moreover, dual-task paradigms also decreased HbR in the PFC by 0.04 ($P < 0.01$, 95% CI = −0.07 to −0.01). Specifically, HbR decreased by 0.08 during inhibitory control tasks ($p < 0.01$, 95% CI = −0.13 to −0.02), but did not change during working memory tasks.

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Conclusion: Cognitive tasks related to inhibitory control required greater cognitive demands, indicating higher pfc activation during dual-task paradigms in older adults. for clinical implications, the increase in pfc oxygenated hemoglobin and decrease in pfc deoxygenated hemoglobin may help explain why older adults are more likely to fall during daily activities.

1. Introduction

Aging causes deterioration in brain structure and function, which leads to a gradual decline in cognitive function [1–6]. Therefore, older adults show a decline in cognitive performance relative to younger adults [1,2,6]. The significance of cognitive performance in older persons, particularly in terms of walking performance, is well-established [7]. Walking is a motor task that has been suggested to be a coordinated movement mediated by cognitive function and motor control mechanisms [7–11]. Higher cognitive demands (e.g., simultaneous walking and talking) are associated with slower walking speeds [4,12,13]. In addition, the difficulty to maintain a conversation while walking (i.e., stopping walking when talking) is predictive of future falls in older persons [14–16]. This suggests that cognitive function plays an important role when performing motor tasks in conjunction with cognitive tasks, especially in older adults.

Dual-task is defined as the simultaneous execution of two distinct tasks [2]. For example, in daily life, it is common to encounter situations in which a motor task (e.g., standing or walking) is performed along with a cognitive task (e.g., thinking, or talking) [13,15,17]. Reduced ability to perform dual-task is the leading cause of postural instability, alterations in walking patterns, and increased risk of falling in older adults [18,19]. In older adults, falls are directly associated with bone fractures, resulting in substantial complications such as increased risk of disability, lower quality of life, and higher mortality [20]. Furthermore, older adults are more likely to fall when undertaking dual-tasking while walking compared to walking alone [17]. Therefore, understanding the mechanism that underpin dual-task paradigms in older adults is crucial.

The prefrontal cortex (PFC) is the cerebral cortex located in the front part of the brain, which is primarily responsible for executive function, including inhibitory control, working memory, and cognitive flexibility [21]. The executive function is associated with processing and selecting attention for responding when performing cognitive tasks [7,22]. Higher PFC activity is an indication of increased neural activity to complete tasks, and may be indicative of limited cognitive capacity [23]. Prefrontal regions relevant to cognitive tasks include the dorsolateral PFC [22,24,25], superior frontal gyrus, middle frontal gyrus [26], orbitofrontal cortex, and frontopolar cortex [27]. Thus, in terms of cortical activity, the PFC is the most common brain area to measure executive function when performing cognitive tasks [6,22,25,26,28–42].

Functional Near-Infrared Spectroscopy (fNIRS) is a non-invasive brain imaging method that uses the theory of neurovascular coupling [43–45]. Near-infrared light can penetrate tissues, several centimeters deep, making fNIRS a useful tool for non-invasive monitoring of brain tissue oxygenation and hemodynamics [45]. fNIRS uses relative changes in oxygenated hemoglobin (HbO_2) and deoxygenated hemoglobin (HbR) to infer neural activity and investigate neurovascular coupling in the brain associated with cognitive and motor tasks [43–45]. Because of its portability and no restriction on motion, fNIRS is a suitable technique for determining cerebral hemodynamics during any physical activity [44–46]. Therefore, fNIRS is commonly used to examine cortical activity during physical activities in the hemodynamic response manner [23,46].

Recently, fNIRS has been extensively used to investigate the cerebral hemodynamics of PFC in older adults [6,22,25,26,28–40]. However, previous studies have reported discrepancies in PFC hemodynamic results, with some showing an increase, decrease, or no change in PFC activity during dual-task performance [26,36,37,39,47–49]. Because of these discrepancies, there is no consensus on how dual-tasks may affect cerebral hemodynamics of the PFC in fNIRS studies. Therefore, this study aimed to systematically determine the effect of dual-task paradigms on the change of cerebral hemodynamics in the PFC (including HbO_2 and HbR) in older adults.

2. Materials and methods

This study was conducted according to the guidelines in the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) statement [50].

2.1. Data sources and search strategy

The search was conducted in the PubMed, Scopus, and Web of Science databases from inception until March 2023. A search strategy was implemented to find the study that investigated the effect of dual-task on PFC hemodynamics in healthy older adults. The following keywords were entered into each database: (elderly OR older) AND (cognit* OR dual*) AND (fNIRS OR hemodynamic). Further information about search strategies, we provide it in the supplementary materials.

2.2. Eligibility criteria

The inclusion criteria for this study were as follows: (a) population: older adults (aged 50 or older) [51]; (b) intervention: any dual-task that combined a cognitive task with a motor task; (c) comparison: any single-task that involved a motor task related to the lower limbs; (d) outcome: cerebral hemodynamics in the PFC. We excluded studies in which the population had cognitive impairment

Table 1
Summary of the included study characteristics.

Study	Population			Intervention		Outcome		
	N	Age	Cognitive function	Single-task	Dual-task	Device detail	Brain area	Cerebral hemodynamic
Beurskens 2014	10	71.0 ± 3.8	N/A	Walking	Walking with alternate letters of the alphabet	Device: DYNOT Imaging System, NIRx Medical Technologies, LLC Wavelength: 760 and 830 nm Channel: 14 channels Sampling rate: 1.81 Hz	- Bilateral middle frontal gyrus - Bilateral superior frontal gyrus	HbO_2 no difference HbR no difference
Chaparro 2017	12	63.1 ± 4.4	RBANS = 105.6 ± 11.3	Walking	Walking with alternate letters of the alphabet	Device: fNIR Imager 1000, fNIR Devices LLC, Potomac, MD Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Chen 2017	90	78.1 ± 5.5	RBANS = 93.5 ± 12.8	Walking	Walking with alternate letters of the alphabet	Device: fNIR Imager1000, (fNIR Devices LLC, Potomac, MD) Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Chen 2022	28	68.6 ± 4.1	MMSE ≥24.0	Walking	Walking with serial subtraction	Device: fNIR imaging system (LIGHTNIRS, Shimadzu Corp., Kyoto, Japan) Wavelength: 780, 805, and 830 nm Channel: 22 channels Sampling rate: 13.3 Hz	- Bilateral dlPFC (BA 46) - Bilateral OFC (BA 11) - Bilateral FPC (BA 10)	↑HbO_2
George 2019	221	76.0 ± 6.6	RBANS = 90.4 ± 11.9	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIRS Devices, LLC, Potomac, MD) Wavelength: 730, 805, and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Germain 2023	36	69.9 ± 4.9	MMSE = 28.7 ± 1.4	Walking	Walking with random generation of numbers	Device: Oxymon MKIII, Artinis Medical Systems Wavelength: 765 and 855 nm Channel: 2 channels Sampling rate: 10 Hz	- Left dlPFC (BA 10) - anterior PFC	↑HbO_2 ↓HbR
Hassan 2020	20	69.1 ± 6.9	MoCA = 26.1 ± 2.9	Walking	Walking with backwards spelling	Device: FNIR100W-1, BIOPAC Wavelength: 730 and 850 nm Sampling rate: 4 Hz	- Overall PFC	↑HbO_2
Hassan 2022	17	71.2 ± 4.9	MoCA = 25.6 ± 2.9	Walking	Walking with backwards spelling	Device: FNIR100W-1, BIOPAC Wavelength: 730 and 850 nm Sampling rate: 4 Hz	- Overall PFC	↑HbO_2
Hawkins 2018	15	77.2 ± 5.6	MMSE = 27.4 ± 1.7	Walking	Walking with verbal fluency task	Device: Niro 200NX, Hamatsu Phtonics Japan Wavelength: 735 and 810 nm Channel: 2 channels Sampling rate: 2 Hz	- Bilateral anterior PFC (BA 10)	↑HbO_2 HbR no difference
Hernandez 2016	8	61.0 ± 4.0	RBANS = 110.0 ± 12.0	Walking	Walking with alternate letters of the alphabet	Device: Imager 1000, 16 channels, fNIRS Devices LLC Wavelength: 730, 805 and 850 nm Sampling rate: 2 Hz	- Overall PFC	↑HbO_2 ↑HbR
Hernandez 2020	17	66.7 ± 5.4	3MS = 94.2 + 8.9	Walking	Walking with object discrimination	Device: Portalite, Artinis Medical Systems Inc. Wavelength: 760 and 810 nm Sampling rate: 10 Hz	- Left PFC (BA 10)	↑HbO_2 HbR no difference

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Table 1 (*continued*)

Study	Population			Intervention		Outcome		
	N	Age	Cognitive function	Single-task	Dual-task	Device detail	Brain area	Cerebral hemodynamic
Hoang 2022	25	72 ± 5	MoCA ≥26	Walking	Walking with serial subtraction	Device: NIRSport, NIRx Medical Technologies Wavelengths: 760 and 850 nm Channel: 18 channels Sampling rate: 7.81 Hz	- Bilateral dlPFC	↑HbO_2 ↓HbR
Holtzer 2011	11	69–88	MMSE = 27.2 ± 1.8	Walking	Walking with alternate letters of the alphabet	Device: Drexel Biomedical Engineering laboratory Wavelength: 730 and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Holtzer 2018	272	76.7 ± 6.7	RBANS = 91.2 ± 11.9	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730 and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Holtzer 2019a	56	76.7 ± 6.3	RBANS = 94.9 ± 11.6	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730 and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Holtzer 2019b	83	78.0 ± 6.3	RBANS = 93.72 ± 12.37	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730, 805, and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Holtzer 2020a	289	76.2 ± 6.5	RBANS = 97.1 ± 8.1	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730 and 850 nm Channel: 16 channels Sampling rate: 2Hz	- Overall PFC	↑HbO_2
Holtzer 2020b	71	76.8 ± 6.2	RBANS = 95.5 ± 11.0	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730, 805, and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2
Holtzer 2022	55	74.8 ± 4.9	N/A	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730, 805, and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO2
Izzetoglu 2020	83	78.0 ± 6.3	N/A	Walking	Walking with alternate letters of the alphabet	Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730, 805, and 850 nm Channel: 16 channels Sampling rate: 2 Hz	- Overall PFC	↑HbO_2 ↓HbR
Maidan 2016	38	70.4 ± 0.9	MMSE = 28.8 ± 0.2	Walking	Walking with serial subtraction	Device: PortaLite fNIRS system, (Artinis Medical Systems, Elst, the Netherlands) Wavelength: 760 and 850 nm	- Overall PFC	↑HbO_2

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Table 1 (*continued*)

Study	Population			Intervention		Outcome		
	N	Age	Cognitive function	Single-task	Dual-task	Device detail	Brain area	Cerebral hemodynamic
Marusic 2019	10	72.3 ± 3.2	MoCA = 28.0 ± 1.2	Tandem stance	Tandem stance with serial subtraction	Channel: 2 channels Sampling rate: 10 Hz Device: fNIRS (Oxymon, Artinis, The Netherlands). Wavelength: 780 and 850 nm	- Left dlPFC	HbO_2 no difference HbR no difference
Maruya 2021	27	76.5 ± 4.8	MMSE = 26.4 ± 2.0	Walking	Walking with serial subtraction	Channel: 2 channels Device: fNIRS (HOT-2000; NeU Co., Ltd., Tokyo, Japan) Wavelength: 800 nm	- Overall PFC	↓HbO_2
Mirelman 2017	20	69.7 ± 5.8	MoCA = 27.5 ± 2.1	Walking	Walking with serial subtraction	Channel: 2 channels Sampling rate: 10 Hz Device: PortaLite™ fNIRS system (Artinis Medical Systems, Elst, the Netherlands) Wavelength: 760 and 850 nm	- Overall PFC	↑HbO_2
Pakray 2021	383	76.0 ± 6.7	RBANS = 91.0 ± 11.8	Walking	Walking with alternate letters of the alphabet	Channel: 6 channels Sampling rate: 10 Hz Device: fNIRS Imager 1100 (fNIR Devices, LLC, Potomac, Maryland) Wavelength: 830, 805, and 850 nm Channel: 16 channels	- Overall PFC	↑HbO_2
Ross 2021	55	74.8 ± 4.9	RBANS = 92.7 ± 11.2	Walking	Walking with alternate letters of the alphabet	Sampling rate: 2 Hz Device: fNIRS Imager 1000 (fNIR Devices, LLC, Potomac, MD) Wavelength: 730, 805, and 850 nm Channel: 16 channels	- Overall PFC	↑HbO_2
Rosso 2017	10	74.0 ± 5.0	RBANS = 66.0 ± 28.0	Standing	Standing with auditory choice reaction time	Sampling rate: 2 Hz Device: fNIRS instrument (CW6 Real-time; TechEn Inc) Wavelength: 690 and 830 nm	- dlPFC - SMG - STG	↓HbO_2 ↓HbR
Salzman 2021	20	71.8 ± 6.4	MoCA = 27.2 ± 1.2	Walking	Walking with cognitive-auditory tasks	Device: OctaMon fNIRS device (Octamon, Artinis, The Netherlands) Wavelength: 690 and 830 nm Channel: 8 channels	- Overall PFC	↓HbO_2 ↓HbR
Salzman 2021	20	72.7 ± 6.9	MoCA = 27.3 ± 1.4	Stair climbing	Stair climbing with cognitive-auditory tasks	Device: OctaMon fNIRS device (Octamon, Artinis, The Netherlands) Wavelength: 760 and 850 nm Sampling rate: 10 Hz	- Overall PFC	↑HbO_2
St George 2021	26	70.6 ± 7.1	MoCA = 26.0 ± 3.0	Standing	Standing with serial subtraction	The NIRSport (NIRx Medizintechnik GmbH, Berlin) system Wavelength: 760 and 850 nm Channel: 22 channels Sampling rate: 7.8125 Hz	- Overall PFC	↓HbO_2
St George 2022	26	70.3 ± 7	MoCA = 26.0 ± 1.8	Walking	- Walking with alternate letters of the alphabet - Walking with serial subtraction	The NIRSport (NIRx Medizintechnik GmbH, Berlin) system Wavelength: 760 and 850 nm Channel: 22 channels Sampling rate: 7.8125 Hz	- Overall PFC	↑HbO_2 (alternate letters of the alphabet and serial subtraction task) ↓HbR (alternate letters of the alphabet and serial subtraction task)

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Table 1 (*continued*)

Study	Population			Intervention		Outcome		
	N	Age	Cognitive function	Single-task	Dual-task	Device detail	Brain area	Cerebral hemodynamic
Stojan 2023	49	68.62 ± 3.92	MMSE = 29.23 ± 0.98	Walking	- Walking with serial subtraction - Walking with Stroop task	Device: NIRSport systems (NIRx Medical Technologies, Glen Head, NY, USA) Wavelength: 760 and 850 nm Channel: 38 channels	- Bilateral dlPFC (BA 9 and 46) - Bilateral vlPFC (BA 44 and 45) - Superior parietal lobe (BA 5 and 7) - Inferior parietal lobe (BA 39 and 40)	↑HbO_2 (serial subtraction and Stroop task) ↓HbR (serial subtraction) HbR no difference (Stroop task)
Stuart 2019	18	72.6 ± 8.0	MoCA = 28.1 ± 1.5	Walking	Walking with digit vigilance task	Device: fNIRS optical imaging system (LABNIRS; Shimadzu, Kyoto, Japan) Wavelength: 780, 805 and 830 nm Sampling rate: 23.8 Hz	- PFC - PMC - SMA - M1	↓HbO_2
Talamonti 2022a	24	67.91 ± 5.42	MoCA = 27.79 ± 1.32	Walking	Walking with n-back task	Device: Portable fNIRS in-house prototype Wavelength: 735 and 850 nm Sampling rate: 20 Hz	- PMC - OFC - Rostral medial PFC - Caudal dorsal PFC - Rostral dorsal PFC - Ventromedial PFC	↑HbO_2
Talamonti 2022b	24	66.7 ± 5.4	MMSE = 28.3 ± 1.1	Walking	Walking with n-back task	Device: Portable inhouse built fNIRS system Wavelength: 735 and 860 nm Channel: 256 channels Sampling rate: 20 Hz	- PMC - OFC - Rostral medial PFC - Caudal dorsal PFC - Rostral dorsal PFC	HbO_2 no difference HbR no difference
Teo 2021	26	71.1 ± 4.2	MoCA = 28.1 ± 1.6	Walking	Walking with serial subtraction	Single channel fNIRS device (Portalite, Artinis Medical Systems, The Netherlands) Wavelength: 760 and 850 nm	- Left PFC	↑HbO_2 ↑HbR
Wagshul 2019	55	74.8 ± 5.0	RBANS = 92.5 ± 11.4	Walking	Walking with alternate letters of the alphabet	fNIRS Imager 1100 was used (fNIRS Devices, LLC, Potomac, MD). Wavelength: 730 and 850 nm 16 channels.	- Overall PFC	↑HbO_2

HbO_2: Oxygenated Hemoglobin; HbR: Deoxygenated Hemoglobin; PFC: Prefrontal Cortex; RBANS: Repeatable Battery for the Assessment of Neuropsychological Status; MoCA: Montreal Cognitive Assessment; 3MS: Modified Mini-Mental State Exam; MMSE: Mini-mental State Examination; dlPFC: Dorsolateral Prefrontal Cortex; FPC: Frontopolar Cortex; OFC: Orbitofrontal Cortex; SMG: Supra-Marginal Gyrus; STG: Superior-Temporal Gyrus; PMC: Premotor Cortex; SMA: Supplementary Motor Area; M1: Primary Motor Cortex.

(e.g., dementia and Alzheimer's) or motor deficits (e.g., stroke and Parkinson's Disease). Intervention studies with more than two task integrations were excluded. We also excluded non-English language or non-original research studies.

2.3. Study selection

All included studies were imported into Endnote 20 (Clarivate Analytics, Boston, USA) to remove the duplicates. After the removal of duplicate studies, two independent reviewers (KL and PK) reviewed the remaining studies in accordance with the eligibility criteria on the titles and abstracts. Disagreements between the two independent reviewers (KL and PK) about study selection were resolved by discussion with the third independent reviewer (GN).

2.4. Data extraction

Data from all included studies were extracted and summarized in the table (see Table 1) by two independent reviewers (KL and PK).

Two independent reviewers (KL and PK) retrieved the following data from each included study: (a) first author and year of publication; (b) sample size, age, and cognitive function; (c) task descriptions (including sing-task and dual-task); (d) device details; (e) brain areas; and (f) results of cerebral hemodynamics. In case the data were unclear or incomplete, we contacted the first or corresponding author of the study by email. If we did not receive a response by email, the data was estimated by using a program custom-written in the MATLAB R2020a software (MathWorks, Natrick, MA, USA) [52,53]. When the two independent reviewers (KL and PK) disagreed on data extraction, the third independent reviewer (GN) was invited to a meeting to find an agreement on adjudication.

2.5. Risk of bias assessment

Two independent reviewers (KL and PK) assessed the risk of bias of the included studies according to the Risk of Bias In Non-Randomized Studies-of Interventions (ROBINS-I) [54]. ROBINS-I consists of the following domains: (a) bias due to confounding; (b) bias in selection of participants; (c) bias in classification of interventions; (d) bias due to deviations from intended interventions; (e) bias due to missing data; (f) bias in measurement of outcomes; and (g) bias in selection of the reported result. The judgments for each domain were low risk of bias, unclear risk of bias, and high risk of bias. Disagreements between the two independent reviewers (KL and PK) about the risk of bias were also resolved by discussion with the third independent reviewer (GN).

2.6. Synthesis of results

The Review Manager v.5.3 (RevMan, The Nordic Cochrane Centre, Cochrane Collaboration, Copenhagen, Denmark) was used to determine cerebral hemodynamics in the PFC between single-task and dual-task. Data synthesis was conducted when the included studies reported a similar primary outcome in mean ± SD for at least 3 studies [50]. Subgroup analysis was conducted to compare the effects of different types of cognitive tasks. The cognitive tasks were categorized in accordance with their respective executive functions [21]: a) inhibitory control tasks: the tasks that suppress or countermand before response; b) working memory tasks: the tasks that provide the starting information and require the information to be manipulated based on conditions; and c) cognitive flexibility tasks: the tasks that allow to choose between two (or more than two) different responses. This meta-analysis used weighted mean differences (WMD) with 95% confidence intervals (95% CI) because the outcome was presented in the same units [50]. The I^2 value was used to define the heterogeneity of the outcome [50]. I^2 values of more than 50% were used to indicate heterogeneity. The alpha

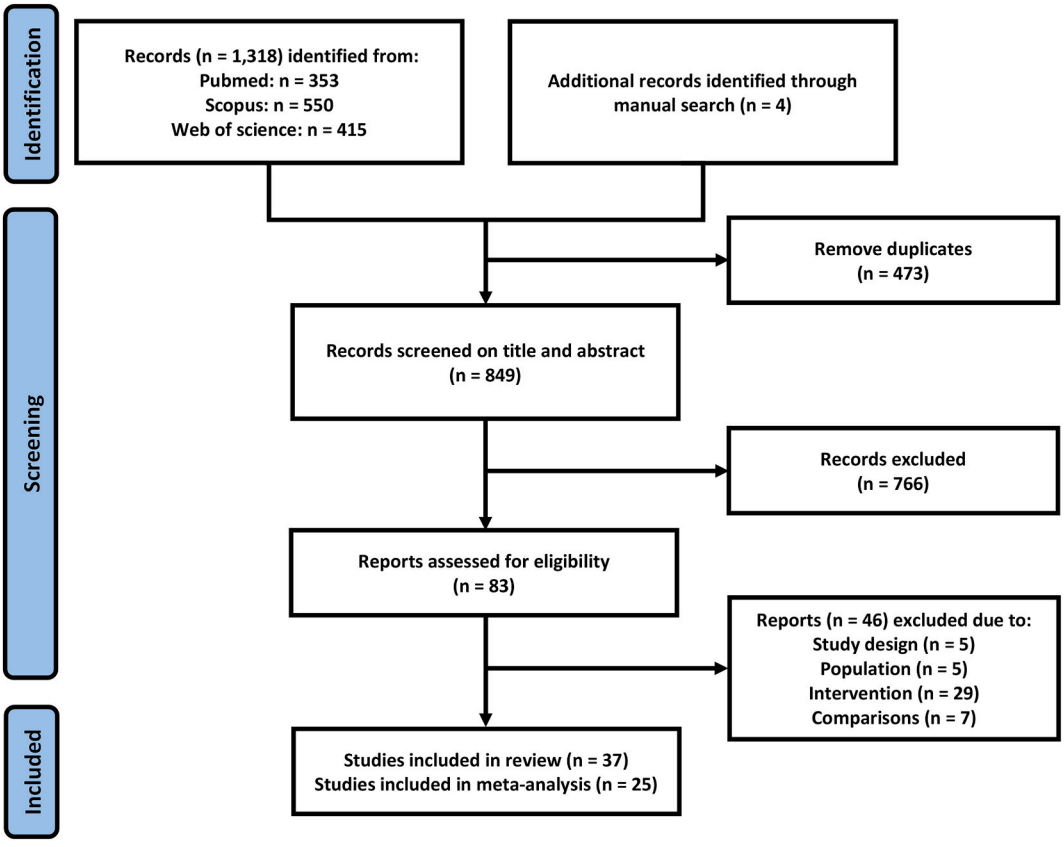

Fig. 1. PRISMA flow diagram summarizing study screening and selection for review.

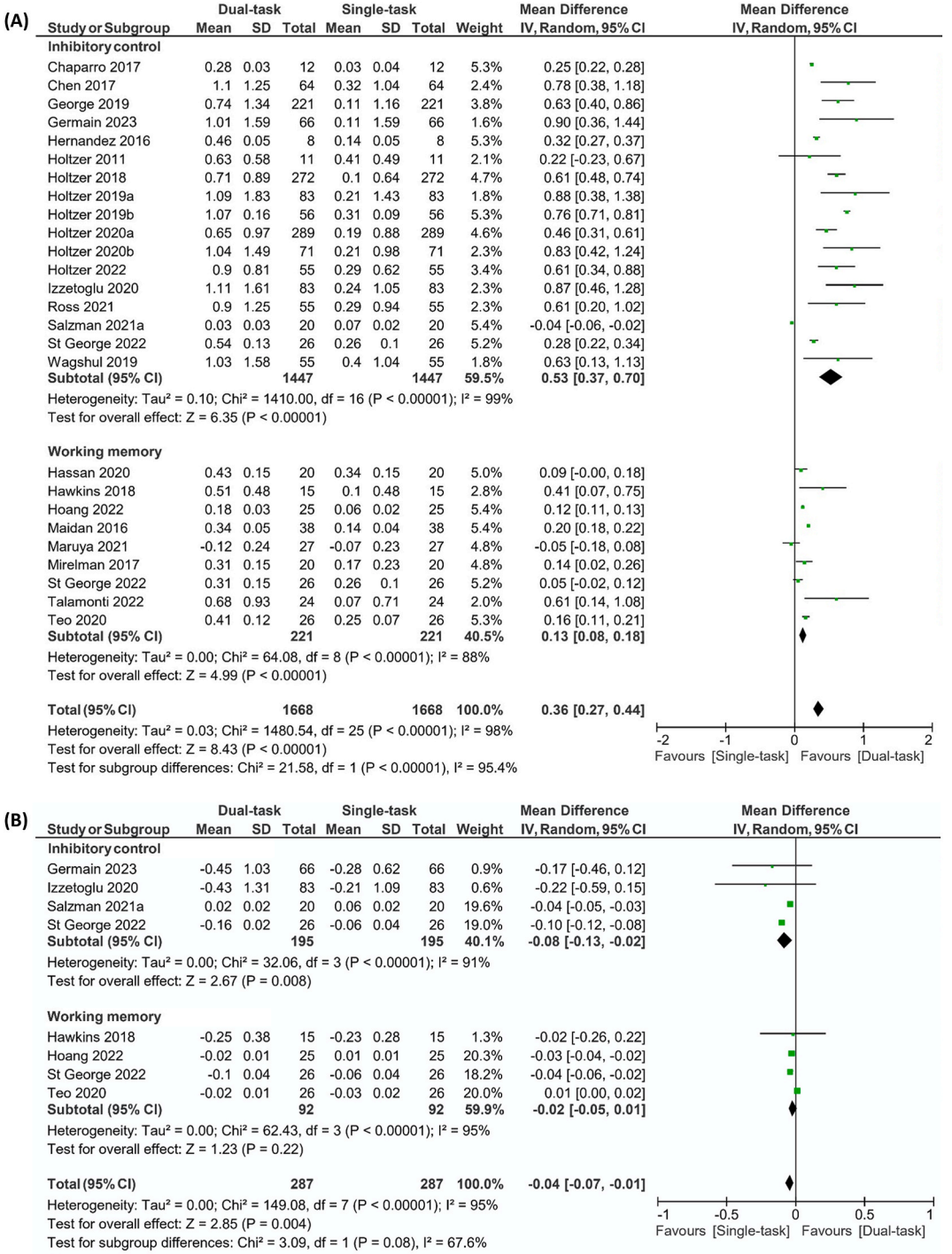

Fig. 2. Forest plots showing weighted mean differences with 95% CI in the influence of dual-task paradigms on: **(A)** Oxygenated Hemoglobin and **(B)** Deoxygenated Hemoglobin.

level was set at 0.05 for statistical significance.

3. Results

3.1. Search results

The PRISMA flowchart shows a summary of the study selection process, as illustrated in Fig. 1. The initial search identified a total of 1322 studies after searching three databases, four of which was an additional study from a manual search [24,30,55,56]. 849 studies remained after the removal of duplicates. The remaining studies were then screened by title and abstract. After the screening, 83 studies were assessed by full-text reviews. We excluded a total of 46 studies for the following reasons: non-original research studies (n = 5), individuals with cognitive impairment (n = 5), interventions involving more than two tasks (n = 29), not comparing with physical single tasks (n = 7), and single motor task was not involved lower extremities task (n = 1). Finally, 37 eligible studies [6,22,24–28,30–40,47–49,55–70] were included in the systematic review. However, because of limitations in data extraction, 25 studies [6,22,25–40,47–49,55–66,68–70] were included in the quantitative synthesis. Of these, data from four studies were extracted using MATLAB [33,56,57,59].

3.2. Study characteristics

The included studies were published between 2011 and 2023. The characteristics of the included studies are summarized in Table 1. A total of 2224 older adults were recruited from 37 studies [6,22,24–28,30–40,47–49,55–70], with 1642 older adults from 25 studies of them included in the meta-analysis. The age of participants ranged from 61 to 78 years old (mean 74.92 ± 6.04 years). Most of the included studies clearly stated that the older adults had no cognitive impairment, except for 3 studies [26,36,47] that did not report. For single-task paradigm, all of the included studies used a motor task including walking in 33 studies [6,24,26–28,30–40,47–49,55,57–64,66–70], standing in 3 studies [22,25,56], and stair climbing in 1 study [65]. For dual-task paradigms, cognitive tasks were performed as follows: 22 studies [6,22,26,28,34–36,38,39,47,55,57–62,64–67,70] used inhibitory control tasks (i.e., alternate letters of alphabet, auditory task, random generation of numbers, and Stroop task), 17 studies [24,25,27,30–33,37,40,48,49,56,63,66–69] used working memory tasks (i.e., backward spelling, serial subtraction, n-back, object discrimination, and verbal fluency task). Two studies used both inhibitory control and working memory as cognitive tasks [66,67]. None of the included studies used cognitive flexibility tasks as cognitive task.

3.3. The effect of dual-task paradigms on oxygenated hemoglobin (HbO_2)

All of the data synthesis used walking as a single-task (100%), while the dual-task paradigms were inhibitory control tasks (65%) and working memory (35%). For subgroup analysis, in inhibitory control task, the majority of studies favor dual-task paradigm, but 2 study [63,65] favor single-task paradigm. A total of 17 studies [6,28,34–36,38,39,47,55–62,65,66,70] involving 1447 older adults were analyzed in order to determine the effect of inhibitory control task on HbO_2. The data synthesis revealed that inhibitory control tasks significantly increased HbO_2 in the PFC by 0.53 μmol/L ($Z = 6.35$, $p < 0.01$, 95% CI = 0.37 to 0.70, $I^2 = 99\%$). Meanwhile, in working memory task, a total of 9 studies [30,31,33,37,40,48,63,66,69] involving 221 older adults were analyzed in order to determine the effect of working memory task on HbO_2. The data synthesis revealed that working memory tasks significantly also increased HbO_2 in the PFC by 0.13 μmol/L ($Z = 4.99$, $p < 0.01$, 95% CI = 0.08 to 0.18, $I^2 = 88\%$). Therefore, a total of 25 studies [6,28,30,31,33–40,47,48,55,57–63,66,69,70] involving 1642 older adults were analyzed in order to determine the overall effect of dual-task paradigms on HbO_2. Meta-analysis revealed that dual-task paradigms significantly increased HbO_2 concentration in the PFC by 0.36 μmol/L ($Z = 8.43$, $P < 0.01$, 95% CI = 0.27 to 0.44, $I^2 = 99\%$). Fig. 2A shows a forest plot displaying the effects of the dual-task paradigms on HbO_2.

3.4. The effect of dual-task paradigms on deoxygenated hemoglobin (HbR)

All data synthesis used walking as a single-task (100%), while the dual-task paradigms were inhibitory control tasks (50%) and working memory (50%). A total of 7 studies [31,33,39,40,47,55,66] involving 261 older adults were analyzed in order to determine the overall effect of dual-task paradigms on HbR. Meta-analysis revealed that dual-task paradigms significantly decreased HbR concentration in the PFC by 0.04 μmol/L ($Z = 2.85$, $P < 0.01$, 95% CI = −0.07 to −0.01, $I^2 = 95\%$). The majority of studies favor single-task paradigm, but 1 study [40] favor dual-task paradigm. In the subgroup analysis on inhibitory control task, a total of 4 studies [39,47,55,66] involving 195 older adults were analyzed in order to determine the effect of inhibitory control task on HbR. The data synthesis revealed that inhibitory control tasks significantly decreased HbR in the PFC by 0.08 μmol/L ($Z = 2.67$, $p < 0.01$, 95% CI = −0.13 to −0.02, $I^2 = 91\%$). However, a total of 4 studies [31,33,40,66] involving 92 older adults revealed that working memory task did not change HbR in the PFC (WMD = −0.02, $Z = 1.23$, $p = 0.22$, 95% CI = −0.05 to 0.01, $I^2 = 95\%$). Fig. 2B shows a forest plot displaying the effects of the dual-task paradigms on HbR.

3.5. Risk of bias

4 studies [26,36,47,62] out of the 37 studies (10%) demonstrated an unclear risk in the domain of confounding. 5 studies (13%)

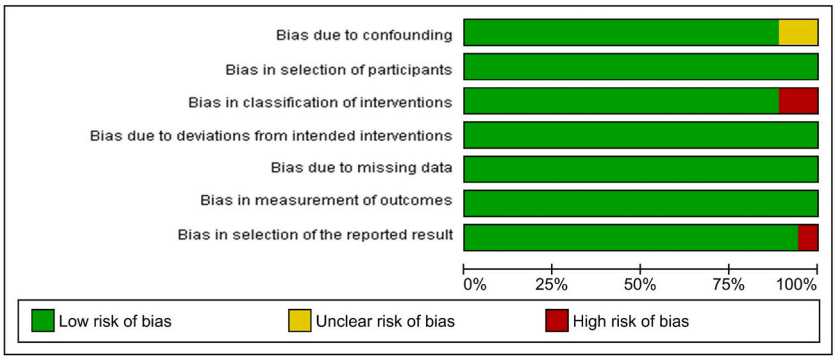

Fig. 3. Summary risk of bias for all included studies.

showed a high risk of bias in the classification of interventions [22,25,29,56,65]. 2 studies (5%) showed a high risk of bias in selection of the reported results [22,40]. However, all the included studies had a low risk of bias in the remaining domains (i.e., selection of participants, deviations from intended interventions, missing data, and measurement of outcomes). The risk of bias for all included studies is summarized in Fig. 3. The detailed risk of bias for each study regarding the seven domains is illustrated in Fig. 4.

4. Discussion

This study is the first to systematically review and meta-analyze all research studies on changes in cerebral hemodynamics in the PFC due to dual-task paradigms in older adults. Most of the included studies demonstrated a low risk of bias, indicating that only studies with good-quality evidence were included in the data synthesis. According to the data synthesis, dual-task paradigms (both inhibitory control and working memory tasks) increase the concentration of HbO_2, but have no effect on HbR in comparison to single-task in older adults. Specifically, inhibitory control tasks were more likely to increase HbO_2 and decrease HbR than working memory tasks. Therefore, we suggest that cognitive tasks related to inhibitory control require greater cognitive demands, resulting in higher HbO_2 and lower HbR in the PFC during dual-task walking.

4.1. The effect of dual-task paradigms on oxygenated hemoglobin (HbO_2)

Dual-task paradigms resulted in a higher concentration of HbO_2 in the PFC of older adults when compared with single-task paradigms. In single-task paradigms, older adults also increased levels of PFC activation during walking [66]. This is consistent with previous findings that the human brain utilizes approximately 20% of the total oxygen consumption at rest [71]. During multitasking, the brain requires substantially more oxygen to maintain optimal oxygen levels [25,63,72]. For this reason, adequate oxygenation is necessary for normal brain function during dual-tasking [25]. In our data synthesis, older adults also exhibited higher HbO_2 levels in the PFC, suggesting a greater reliance on executive functions when performing dual-tasking.

4.1.1. Differential effects of cognitive tasks on HbO_2 in the PFC

The cognitive tasks in the included studies were used as dual-tasks to increase cognitive demands during walking. The most commonly used cognitive tasks were inhibitory control tasks (such as alternate letters of the alphabet and auditory choice reaction) and working memory tasks (such as serial subtraction, verbal fluency, and backwards spelling). Previous studies have reported that the underlying mechanism of inhibitory control is associated with an increase in HbO_2 concentration in the right PFC [25,30]. Additionally, previous studies have shown that the concentration of HbO_2 in the left PFC increases when performing cognitive tasks that require working memory [73,74]. Although the included studies did not independently report the HbO_2 concentration in the left or right lobes of the PFC, we found that inhibitory control tasks have a greater effect on HbO_2 as compared to working memory tasks. It is possible that the cognitive tasks related to right PFC activity (i.e., inhibitory control tasks) require more HbO_2 concentration during walking.

Most of the included studies showed an increase in HbO_2 concentration during dual-task walking. However, some of the included studies showed a decrease in HbO_2 when walking with cognitive tasks (such as the auditory choice reaction time task [22], visual task [26], alternating letters of the alphabet [47] or cognitive-auditory task [39]). The cognitive information processing hypothesis can explain these discrepancies [9]. According to this theory, cognitive tasks might be recognized in long-term memory, which has an advantageous effect in minimizing interference from dual-tasks [75]. Hence, executive functions may be constrained and reorganized in accordance with long-term memory. Moreover, a number of studies have demonstrated that the decrease in PFC activation is associated with automatic tasks [76,77]. Nevertheless, this study does not provide a consensus regarding the decrease in HbO_2 in older adults under dual-tasking.

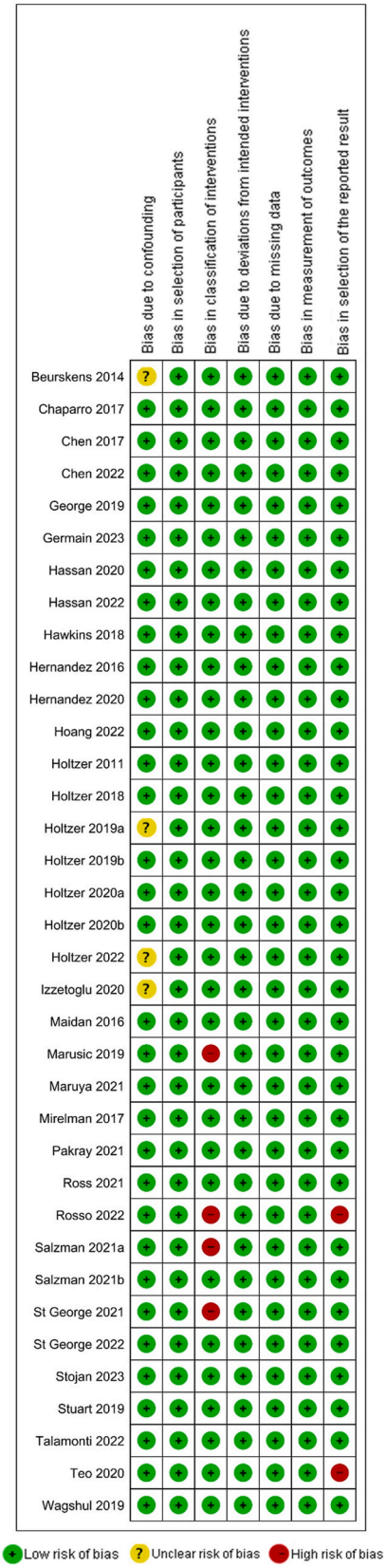

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Fig. 4. Detailed risk of bias for each study.

4.2. The effect of dual-task paradigms on deoxygenated hemoglobin (HbR)

Our findings suggest that dual-task paradigms reduced the HbR concentration in the PFC of older adults. Normally, a decrease in HbR concentration coincides with an increase in HbO_2 concentration. Previous studies have reported that older adults show a reduction in HbR concentration and an increase in HbO_2 concentration during dual-task walking, which indicates an increase in PFC activation [31,33,39,47]. Similar to our study, dual-task paradigms that included both inhibitory control and working memory tasks were found to decrease HbR levels in the PFC.

4.2.1. Differential effects of cognitive tasks on HbR in the PFC

Our findings revealed that inhibitory control tasks reduced HbR in the PFC, however working memory tasks did not have the same effect. The decrease in HbR in the PFC has been associated with the increased in HbO_2 level, which consistent with the previous dual-task studies [33,47,55,66,67]. The decrease in HbR is usually observed during difficult tasks, which in this case is the inhibitory control task [66]. In contrast, working memory tasks do not require the same level of cognitive demand as inhibitory control tasks, resulting in less demand for increased PFC activity and oxygen consumption [55,66]. A previous study has suggested that inhibitory control tasks were more disruptive to behavioral performance than the working memory tasks [66]. Therefore, our findings suggest that inhibitory control tasks and working memory tasks may involve different neural mechanisms, with inhibitory control tasks being associated with increased neural activity and decreased HbR in the PFC.

4.3. Clinical implications

Utilizing brain hemodynamics, particularly under dual-task paradigms, may provide an early detection approach for screening risk of falling in older adults. Early detection of alterations in cortical hemodynamics may also provide a significant chance to design an appropriate intervention, thereby minimizing the risk of falling among older adults.

4.4. Study limitations

Several limitations of the present study must be taken into account when interpreting the findings. First, this meta-analysis study did not restrict the types of cognitive tasks that were included in order to analyze the differential effects of complexity of dual-tasking. Future studies and reviews should elucidate the influence of these factors on cerebral hemodynamic. Second, some of the cognitive tasks used in the included studies involved speaking, such as counting backwards and verbal fluency, which require muscles located near the PFC [78]. Such muscle activities and different facial expressions may affect fNIRS signal quality [79]. Third, although our study only included healthy older adults, there was still some variation in their cognitive function, and some studies did not specifically report on cognitive functions. This factor should be considered when interpreting our findings. Fourth, the presence of physiology-based systemic interferences in the signal (e.g., cardiac pulsation and respiration) are a major concern with fNIRS measurements [80,81]. Such systemic interferences exist in both the cerebral and superficial layers of the head reducing the accuracy of fNIRS for identifying brain activation. Recommended approaches for reducing systemic interference in fNIRS signals are low pass filtering and low frequency oscillations [82,83]. Lastly, our conclusions cannot be generalized to patients with cognitive impairment (e.g., dementia, Alzheimer's disease) or motor deficits (e.g., post-stroke, Parkinson's disease). Therefore, future studies examining the influences of dual-task paradigms on cerebral hemodynamics in patient populations should be conducted.

5. Conclusions

Older adults exhibit an increase in oxygenated hemoglobin concentration and a decrease in deoxygenated hemoglobin in the PFC when performing the dual-task paradigms. The increase in PFC oxygenated hemoglobin and decrease in PFC deoxygenated hemoglobin might explain why older adults are more likely to fall while walking, walk slowly, or reduce physical activity. Although cognitive tasks (e.g., alternate letters, serial subtractions, and general conversation) are not particularly difficult, older adults spend considerable effort to accomplish tasks, particularly those requiring inhibitory control. Therefore, we propose that cognitive tasks associated with inhibitory control tasks are more likely to influence cerebral hemodynamics during dual-task, especially in walking.

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Institutional review board statement

This is a meta-analysis study. No ethical approval is required.

Informed consent statement

This is a meta-analysis study. The informed consent is not applicable.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data will be made available on request.

Additional information

Supplementary content related to this article has been publish online at [URL].

Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17812.

References

[1] K.Z. Li, U. Lindenberger, A.M. Freund, P.B. Baltes, Walking while memorizing: age-related differences in compensatory behavior, Psychol. Sci. 12 (3) (2001) 230–237, https://doi.org/10.1111/1467-9280.00341.
[2] U. Lindenberger, M. Marsiske, P.B. Baltes, Memorizing while walking: increase in dual-task costs from young adulthood to old age, Psychol. Aging 15 (3) (2000) 417–436, https://doi.org/10.1037//0882-7974.15.3.417.
[3] S.A. Fraser, K.Z.H. Li, N. Berryman, L. Desjardins-Crépeau, M. Lussier, K. Vadaga, L. Lehr, T.T.M. Vu, L. Bosquet, L. Bherer, Does combined physical and cognitive training improve dual-task balance and gait outcomes in sedentary older adults? Front. Hum. Neurosci. 10 (2017) 688, https://doi.org/10.3389/fnhum.2016.00688.
[4] R. Holtzer, J. Verghese, G. Allali, M. Izzetoglu, C. Wang, J.R. Mahoney, Neurological gait abnormalities moderate the functional brain signature of the posture first hypothesis, Brain Topogr. 29 (2) (2016) 334–343, https://doi.org/10.1007/s10548-015-0465-z.
[5] C.L. Grady, Functional brain imaging and age-related changes in cognition, Biol. Psychol. 54 (2000) 259–281, https://doi.org/10.1016/S0301-0511(00)00059-4.
[6] R. Holtzer, J.R. Mahoney, M. Izzetoglu, K. Izzetoglu, B. Onaral, J. Verghese, fNIRS study of walking and walking while talking in young and old individuals, J Gerontol A Biol Sci Med Sci 66 (8) (2011) 879–887, https://doi.org/10.1093/gerona/glr068.
[7] J. Verghese, H. Buschke, L. Viola, M. Katz, C. Hall, G. Kuslansky, R. Lipton, Validity of divided attention tasks in predicting falls in older individuals: a preliminary study, J. Am. Geriatr. Soc. 50 (9) (2002) 1572–1576, https://doi.org/10.1046/j.1532-5415.2002.50415.x.
[8] R.D. Abbott, L.R. White, G.W. Ross, K.H. Masaki, J.D. Curb, H. Petrovitch, Walking and dementia in physically capable elderly men, JAMA 292 (12) (2004) 1447–1453, https://doi.org/10.1001/jama.292.12.1447.
[9] H.H. Atkinson, C. Rosano, E.M. Simonsick, J.D. Williamson, C. Davis, W.T. Ambrosius, S.R. Rapp, M. Cesari, A.B. Newman, T.B. Harris, S.M. Rubin, K. Yaffe, S. Satterfield, S.B. Kritchevsky, Cognitive function, gait speed decline, and comorbidities: the health, aging and body composition study, J Gerontol A Biol Sci Med Sci 62 (8) (2007) 844–850, https://doi.org/10.1093/gerona/62.8.844.
[10] J. Verghese, C. Wang, R.B. Lipton, R. Holtzer, X. Xue, Quantitative gait dysfunction and risk of cognitive decline and dementia, J. Neurol. Neurosurg. Psychiatry 78 (9) (2007) 929–935, https://doi.org/10.1136/jnnp.2006.106914.
[11] J. Weuve, J.H. Kang, J.E. Manson, M.M. Breteler, J.H. Ware, F. Grodstein, Physical activity, including walking, and cognitive function in older women, JAMA 292 (12) (2004) 1454–1461, https://doi.org/10.1001/jama.292.12.1454.
[12] O. Beauchet, C. Annweiler, G. Allali, G. Berrut, F.R. Herrmann, V. Dubost, Recurrent falls and dual task-related decrease in walking speed: is there a relationship? J. Am. Geriatr. Soc. 56 (7) (2008) 1265–1269, https://doi.org/10.1111/j.1532-5415.2008.01766.x.
[13] A. Bootsma-van der Wiel, J. Gussekloo, A.J. de Craen, E. van Exel, B.R. Bloem, R.G. Westendorp, Walking and talking as predictors of falls in the general population: the Leiden 85-Plus Study, J. Am. Geriatr. Soc. 51 (10) (2003) 1466–1471, https://doi.org/10.1046/j.1532-5415.2003.51468.x.
[14] O. Beauchet, C. Annweiler, V. Dubost, G. Allali, R.W. Kressig, S. Bridenbaugh, G. Berrut, F. Assal, F.R. Herrmann, Stops walking when talking: a predictor of falls in older adults? Eur. J. Neurol. 16 (7) (2009) 786–795, https://doi.org/10.1111/j.1468-1331.2009.02612.x.
[15] E.W. de Hoon, J.H. Allum, M.G. Carpenter, C. Salis, B.R. Bloem, M. Conzelmann, H.A. Bischoff, Quantitative assessment of the stops walking while talking test in the elderly, Arch. Phys. Med. Rehabil. 84 (6) (2003) 838–842, https://doi.org/10.1016/s0003-9993(02)04951-1.
[16] W.R. Young, M. Olonilua, R.S. Masters, S. Dimitriadis, A. Mark Williams, Examining links between anxiety, reinvestment and walking when talking by older adults during adaptive gait, Exp. Brain Res. 234 (1) (2016) 161–172, https://doi.org/10.1007/s00221-015-4445-z.
[17] L. Lundin-Olsson, L. Nyberg, Y. Gustafson, "Stops walking when talking" as a predictor of falls in elderly people, Lancet 349 (9052) (1997) 617, https://doi.org/10.1016/s0140-6736(97)24009-2.
[18] C.D. Hall, L. Heusel-Gillig, R.J. Tusa, S.J. Herdman, Efficacy of gaze stability exercises in older adults with dizziness, J. Neurol. Phys. Ther. 34 (2) (2010) 64–69, https://doi.org/10.1097/NPT.0b013e3181dde6d8.
[19] J.M. Hausdorff, Gait variability: methods, modeling and meaning, J. NeuroEng. Rehabil. 2 (2005) 19, https://doi.org/10.1186/1743-0003-2-19.
[20] P. Kannus, M. Paavola, L. Józsa, Aging and degeneration of tendons, in: N. Maffulli, P. Renström, W.B. Leadbetter (Eds.), Tendon Injuries: Basic Science and Clinical Medicine, Springer London, London, 2005, pp. 25–31.
[21] A. Diamond, Executive functions, Annu. Rev. Psychol. 64 (2013) 135–168, https://doi.org/10.1146/annurev-psych-113011-143750.

[22] A.L. Rosso, M. Cenciarini, P.J. Sparto, P.J. Loughlin, J.M. Furman, T.J. Huppert, Neuroimaging of an attention demanding dual-task during dynamic postural control, Gait Posture 57 (2017) 193–198, https://doi.org/10.1016/j.gaitpost.2017.06.013.

[23] V. Quaresima, M. Ferrari, Functional near-infrared spectroscopy (fNIRS) for assessing cerebral cortex function during human behavior in natural/social situations: a concise review, Organ. Res. Methods 22 (1) (2019) 46–68, https://doi.org/10.1177/1094428116658959.

[24] S.A. Hassan, L.V. Bonetti, K.T. Kasawara, D.S. Beal, D. Rozenberg, W.D. Reid, Decreased automaticity contributes to dual task decrements in older compared to younger adults, Eur. J. Appl. Physiol. 122 (4) (2022) 965–974, https://doi.org/10.1007/s00421-022-04891-w.

[25] U. Marusic, W. Taube, S.A. Morrison, L. Biasutti, B. Grassi, K. De Pauw, R. Meeusen, R. Pisot, J. Ruffieux, Aging effects on prefrontal cortex oxygenation in a posture-cognition dual-task: an fNIRS pilot study, Eur Rev Aging Phys Act 16 (2019) 2, https://doi.org/10.1186/s11556-018-0209-7.

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

[27] Y. Chen, Z. Cao, M. Mao, W. Sun, Q. Song, D. Mao, Increased cortical activation and enhanced functional connectivity in the prefrontal cortex ensure dynamic postural balance during dual-task obstacle negotiation in the older adults: a fNIRS study, Brain Cognit. 163 (2022), 105904, https://doi.org/10.1016/j.bandc.2022.105904.

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

[29] D.T. Corp, G.J. Youssef, R.A. Clark, J. Gomes-Osman, M.A. Yücel, S.J. Oldham, S. Aldraiwiesh, J. Rice, A. Pascual-Leone, M.A. Rogers, Reduced motor cortex inhibition and a 'cognitive-first' prioritisation strategy for older adults during dual-tasking, Exp. Gerontol. 113 (2018) 95–105, https://doi.org/10.1016/j.exger.2018.09.018.

[30] S.A. Hassan, M.A. Campos, K.T. Kasawara, L.V. Bonetti, K.K. Patterson, D.S. Beal, G.A.F. Fregonezi, M.B. Stanbrook, W.D. Reid, Changes in oxyhemoglobin concentration in the prefrontal cortex during cognitive-motor dual tasks in people with chronic obstructive pulmonary disease, COPD 17 (3) (2020) 289–296, https://doi.org/10.1080/15412555.2020.1767561.

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

[32] A.R. Hernandez, S.P. Winesett, Q.P. Federico, S.A. Williams, S.N. Burke, D.J. Clark, A cross-species model of dual-task walking in young and older humans and rats, Front. Aging Neurosci. 12 (2020) 276, https://doi.org/10.3389/fnagi.2020.00276.

[33] I. Hoang, L. Paire-Ficout, R. Derollepot, S. Perrey, H. Devos, M. Ranchet, Increased prefrontal activity during usual walking in aging, Int. J. Psychophysiol. 174 (2022) 9–16, https://doi.org/10.1016/j.ijpsycho.2022.01.011.

[34] R. Holtzer, M. Izzetoglu, Mild cognitive impairments attenuate prefrontal cortex activations during walking in older adults, Brain Sci. 10 (7) (2020) 415, https://doi.org/10.3390/brainsci10070415.

[35] R. Holtzer, D. Ross, M. Izzetoglu, Intraindividual variability in neural activity in the prefrontal cortex during active walking in older adults, Psychol. Aging 35 (8) (2020) 1201–1214, https://doi.org/10.1037/pag0000583.

[36] R. Holtzer, D. Ross, C. O'Brien, M. Izzetoglu, M.E. Wagshul, Cognitive reserve moderates the efficiency of prefrontal cortex activation patterns of gait in older adults, J Gerontol A Biol Sci Med Sci 77 (9) (2022) 1836–1844, https://doi.org/10.1093/gerona/glab288.

[37] I. Maidan, F. Nieuwhof, H. Bernad-Elazari, M.F. Reelick, B.R. Bloem, N. Giladi, J.E. Deutsch, J.M. Hausdorff, J.A. Claassen, A. Mirelman, The role of the frontal lobe in complex walking among patients with Parkinson's disease and healthy older adults: an fNIRS Study, Neurorehabilitation Neural Repair 30 (10) (2016) 963–971, https://doi.org/10.1177/1545968316650426.

[38] D. Ross, M.E. Wagshul, M. Izzetoglu, R. Holtzer, Prefrontal cortex activation during dual-task walking in older adults is moderated by thickness of several cortical regions, Geroscience 43 (4) (2021) 1959–1974, https://doi.org/10.1007/s11357-021-00379-1.

[39] T. Salzman, D. Tobón Vallejo, N. Polskaia, L. Michaud, G. St-Amant, Y. Lajoie, S. Fraser, Hemodynamic and behavioral changes in older adults during cognitively demanding dual tasks, Brain Behav 11 (3) (2021), e02021, https://doi.org/10.1002/brb3.2021.

[40] W.P. Teo, T. Rantalainen, N. Nuzum, L. Valente, H. Macpherson, Altered prefrontal cortex responses in older adults with subjective memory complaints and dementia during dual-task gait: an fNIRS study, Eur. J. Neurosci. 53 (4) (2021) 1324–1333, https://doi.org/10.1111/ejn.14989.

[41] E. Al-Yahya, H. Dawes, L. Smith, A. Dennis, K. Howells, J. Cockburn, Cognitive motor interference while walking: a systematic review and meta-analysis, Neurosci. Biobehav. Rev. 35 (3) (2011) 715–728, https://doi.org/10.1016/j.neubiorev.2010.08.008.

[42] P.H.S. Pelicioni, M. Tijsma, S.R. Lord, J. Menant, Prefrontal cortical activation measured by fNIRS during walking: effects of age, disease and secondary task, PeerJ 7 (2019), e6833, https://doi.org/10.7717/peerj.6833.

[43] S.C. Bunce, M. Izzetoglu, K. Izzetoglu, B. Onaral, K. Pourrezaei, Functional near-infrared spectroscopy, IEEE Eng. Med. Biol. Mag. 25 (4) (2006) 54–62, https://doi.org/10.1109/memb.2006.1657788.

[44] D.R. Leff, F. Orihuela-Espina, C.E. Elwell, T. Athanasiou, D.T. Delpy, A.W. Darzi, G.Z. Yang, Assessment of the cerebral cortex during motor task behaviours in adults: a systematic review of functional near infrared spectroscopy (fNIRS) studies, Neuroimage 54 (4) (2011) 2922–2936, https://doi.org/10.1016/j.neuroimage.2010.10.058.

[45] S. Perrey, Non-invasive NIR spectroscopy of human brain function during exercise, Methods 45 (4) (2008) 289–299, https://doi.org/10.1016/j.ymeth.2008.04.005.

[46] P. Pinti, I. Tachtsidis, A. Hamilton, J. Hirsch, C. Aichelburg, S. Gilbert, P.W. Burgess, The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience, Ann. N. Y. Acad. Sci. 1464 (1) (2020) 5–29, https://doi.org/10.1111/nyas.13948.

[47] M. Izzetoglu, R. Holtzer, Effects of processing methods on fNIRS signals assessed during active walking tasks in older adults, IEEE Trans. Neural Syst. Rehabil. Eng. 28 (3) (2020) 699–709, https://doi.org/10.1109/tnsre.2020.2970407.

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

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

[50] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. McDonald, L.A. McGuinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021) n71, https://doi.org/10.1136/bmj.n71.

[51] S. Sabharwal, H. Wilson, P. Reilly, C.M. Gupte, Heterogeneity of the definition of elderly age in current orthopaedic research, SpringerPlus 4 (2015) 516, https://doi.org/10.1186/s40064-015-1307-x.

[52] J. Shi, D. Luo, H. Weng, X.T. Zeng, L. Lin, H. Chu, T. Tong, Optimally estimating the sample standard deviation from the five-number summary, Res. Synth. Methods 11 (5) (2020) 641–654, https://doi.org/10.1002/jrsm.1429.

[53] D. Luo, X. Wan, J. Liu, T. Tong, Optimally estimating the sample mean from the sample size, median, mid-range, and/or mid-quartile range, Stat. Methods Med. Res. 27 (6) (2018) 1785–1805, https://doi.org/10.1177/0962280216669183.

[54] J.A. Sterne, M.A. Hernán, B.C. Reeves, J. Savović, N.D. Berkman, M. Viswanathan, D. Henry, D.G. Altman, M.T. Ansari, I. Boutron, J.R. Carpenter, A.W. Chan, R. Churchill, J.J. Deeks, A. Hróbjartsson, J. Kirkham, P. Jüni, Y.K. Loke, T.D. Pigott, C.R. Ramsay, D. Regidor, H.R. Rothstein, L. Sandhu, P.L. Santaguida, H. J. Schünemann, B. Shea, I. Shrier, P. Tugwell, L. Turner, J.C. Valentine, H. Waddington, E. Waters, G.A. Wells, P.F. Whiting, J.P. Higgins, ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions, BMJ 355 (2016) i4919, https://doi.org/10.1136/bmj.i4919.

[55] C. Germain, A. Perrot, C. Tomasino, J. Bonnal, C. Ozsancak, P. Auzou, F. Prieur, Effect of the level of physical activity on prefrontal cortex hemodynamics in older adults during single- and dual-task walking, J. Aging Phys. Activ 31 (1) (2023) 96–104, https://doi.org/10.1123/japa.2021-0410.

[56] R.J. St George, M.R. Hinder, R. Puri, E. Walker, M.L. Callisaya, Functional near-infrared spectroscopy reveals the compensatory potential of pre-frontal cortical activity for standing balance in young and older adults, Neuroscience 452 (2021) 208–218, https://doi.org/10.1016/j.neuroscience.2020.10.027.
[57] G. Chaparro, J.M. Balto, B.M. Sandroff, R. Holtzer, M. Izzetoglu, R.W. Motl, M.E. Hernandez, Frontal brain activation changes due to dual-tasking under partial body weight support conditions in older adults with multiple sclerosis, J. NeuroEng. Rehabil. 14 (1) (2017) 65, https://doi.org/10.1186/s12984-017-0280-8.
[58] C.J. George, J. Verghese, M. Izzetoglu, C. Wang, R. Holtzer, The effect of polypharmacy on prefrontal cortex activation during single and dual task walking in community dwelling older adults, Pharmacol. Res. 139 (2019) 113–119, https://doi.org/10.1016/j.phrs.2018.11.007.
[59] M.E. Hernandez, R. Holtzer, G. Chaparro, K. Jean, J.M. Balto, B.M. Sandroff, M. Izzetoglu, R.W. Motl, Brain activation changes during locomotion in middle-aged to older adults with multiple sclerosis, J. Neurol. Sci. 370 (2016) 277–283, https://doi.org/10.1016/j.jns.2016.10.002.
[60] R. Holtzer, C.J. George, M. Izzetoglu, C. Wang, The effect of diabetes on prefrontal cortex activation patterns during active walking in older adults, Brain Cognit. 125 (2018) 14–22, https://doi.org/10.1016/j.bandc.2018.03.002.
[61] R. Holtzer, M. Izzetoglu, M. Chen, C. Wang, Distinct fNIRS-derived HbO2 trajectories during the course and over repeated walking trials under single-and dual-task conditions: implications for within session learning and prefrontal cortex efficiency in older adults, J Gerontol A Biol Sci Med Sci 74 (7) (2019) 1076–1083, https://doi.org/10.1093/gerona/gly181.
[62] R. Holtzer, R. Kraut, M. Izzetoglu, K. Ye, The effect of fear of falling on prefrontal cortex activation and efficiency during walking in older adults, Geroscience 41 (1) (2019) 89–100, https://doi.org/10.1007/s11357-019-00056-4.
[63] K. Maruya, T. Arai, H. Fujita, Brain activity in the prefrontal cortex during cognitive tasks and dual tasks in community-dwelling elderly people with pre-frailty: a pilot study for early detection of cognitive decline, Healthcare (Basel). 9 (10) (2021) 1250, https://doi.org/10.3390/healthcare9101250.
[64] H. Pakray, E. Seng, M. Izzetoglu, R. Holtzer, The effects of perceived pain in the past month on prefrontal cortex activation patterns assessed during cognitive and motor performances in older adults, Pain Med. 22 (2) (2021) 303–314, https://doi.org/10.1093/pm/pnaa404.
[65] T. Salzman, A. Aboualmagd, H. Badawi, D. Tobón-Vallejo, H. Kim, L. Dahroug, F. Laamarti, A. El Saddik, S. Fraser, Prefrontal cortex involvement during dual-task stair climbing in healthy older adults: an fNIRS study, Brain Sci. 11 (1) (2021) 71, https://doi.org/10.3390/brainsci11010071.
[66] R.J. St George, O. Jayakody, R. Healey, M. Breslin, M.R. Hinder, M.L. Callisaya, Cognitive inhibition tasks interfere with dual-task walking and increase prefrontal cortical activity more than working memory tasks in young and older adults, Gait Posture 95 (2022) 186–191, https://doi.org/10.1016/j.gaitpost.2022.04.021.
[67] R. Stojan, M. Mack, O. Bock, C. Voelcker-Rehage, Inefficient frontal and parietal brain activation during dual-task walking in a virtual environment in older adults, Neuroimage (2023), 120070, https://doi.org/10.1016/j.neuroimage.2023.120070.
[68] D. Talamonti, E.G. Dupuy, S. Boudaa, T. Vincent, S. Fraser, A. Nigam, F. Lesage, S. Belleville, C. Gagnon, L. Bherer, Prefrontal hyperactivation during dual-task walking related to apathy symptoms in older individuals, PLoS One 17 (4) (2022), e0266553, https://doi.org/10.1371/journal.pone.0266553.
[69] D. Talamonti, C. Gagnon, T. Vincent, A. Nigam, F. Lesage, L. Bherer, S. Fraser, Exploring cognitive and brain oxygenation changes over a 1-year period in physically active individuals with mild cognitive impairment: a longitudinal fNIRS pilot study, BMC Geriatr. 22 (1) (2022) 648, https://doi.org/10.1186/s12877-022-03306-x.
[70] M.E. Wagshul, M. Lucas, K. Ye, M. Izzetoglu, R. Holtzer, Multi-modal neuroimaging of dual-task walking: structural MRI and fNIRS analysis reveals prefrontal grey matter volume moderation of brain activation in older adults, Neuroimage 189 (2019) 745–754, https://doi.org/10.1016/j.neuroimage.2019.01.045.
[71] D. Talamonti, T. Vincent, S. Fraser, A. Nigam, F. Lesage, L. Bherer, The benefits of physical activity in individuals with cardiovascular risk factors: a longitudinal investigation using fNIRS and dual-task walking, J. Clin. Med. 10 (4) (2021) 579, https://doi.org/10.3390/jcm10040579.
[72] M. Mihara, I. Miyai, M. Hatakenaka, K. Kubota, S. Sakoda, Role of the prefrontal cortex in human balance control, Neuroimage 43 (2) (2008) 329–336, https://doi.org/10.1016/j.neuroimage.2008.07.029.
[73] R. Cabeza, L. Nyberg, Imaging cognition II: an empirical review of 275 PET and fMRI studies, J. Cognit. Neurosci. 12 (1) (2000) 1–47, https://doi.org/10.1162/08989290051137585.
[74] J.D. Gabrieli, R.A. Poldrack, J.E. Desmond, The role of left prefrontal cortex in language and memory, Proc. Natl. Acad. Sci. U. S. A. 95 (3) (1998) 906–913, https://doi.org/10.1073/pnas.95.3.906.
[75] D.E. Callan, J.A. Jones, A. Callan, Multisensory and modality specific processing of visual speech in different regions of the premotor cortex, Front. Psychol. 5 (2014) 389, https://doi.org/10.3389/fpsyg.2014.00389.
[76] A. Dietrich, M. Audiffren, The reticular-activating hypofrontality (RAH) model of acute exercise, Neurosci. Biobehav. Rev. 35 (6) (2011) 1305–1325, https://doi.org/10.1016/j.neubiorev.2011.02.001.
[77] T. Wu, K. Kansaku, M. Hallett, How self-initiated memorized movements become automatic: a functional MRI study, J. Neurophysiol. 91 (4) (2004) 1690–1698, https://doi.org/10.1152/jn.01052.2003.
[78] G.A. Zimeo Morais, J.B. Balardin, J.R. Sato, fNIRS Optodes' Location Decider (fOLD): a toolbox for probe arrangement guided by brain regions-of-interest, Sci. Rep. 8 (1) (2018) 3341, https://doi.org/10.1038/s41598-018-21716-z.
[79] J.B. Balardin, G.A. Zimeo Morais, R.A. Furucho, L. Trambaiolli, P. Vanzella, C. Biazoli, J.R. Sato, Imaging brain function with functional near-infrared spectroscopy in unconstrained environments, Front. Hum. Neurosci. 11 (2017) 258, https://doi.org/10.3389/fnhum.2017.00258.
[80] H. Obrig, M. Neufang, R. Wenzel, M. Kohl, J. Steinbrink, K. Einhäupl, A. Villringer, Spontaneous low frequency oscillations of cerebral hemodynamics and metabolism in human adults, Neuroimage 12 (6) (2000) 623–639, https://doi.org/10.1006/nimg.2000.0657.
[81] S.J. Payne, J. Selb, D.A. Boas, Effects of autoregulation and CO2 reactivity on cerebral oxygen transport, Ann. Biomed. Eng. 37 (11) (2009) 2288–2298, https://doi.org/10.1007/s10439-009-9763-5.
[82] M.A. Franceschini, S. Fantini, J.H. Thompson, J.P. Culver, D.A. Boas, Hemodynamic evoked response of the sensorimotor cortex measured noninvasively with near-infrared optical imaging, Psychophysiology 40 (4) (2003) 548–560, https://doi.org/10.1111/1469-8986.00057.
[83] G. Jasdzewski, G. Strangman, J. Wagner, K.K. Kwong, R.A. Poldrack, D.A. Boas, Differences in the hemodynamic response to event-related motor and visual paradigms as measured by near-infrared spectroscopy, Neuroimage 20 (1) (2003) 479–488, https://doi.org/10.1016/s1053-8119(03)00311-2.