A Systematic Review of the Application of Functional Near-Infrared Spectroscopy to the Study of Cerebral Hemodynamics in Healthy Aging

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Abstract

Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies have shown that healthy aging is associated with functional brain deterioration that preferentially affects the prefrontal cortex. This article reviews the application of an alternative method, functional near-infrared spectroscopy (fNIRS), to the study of age-related changes in cerebral hemodynamics and factors that influence cerebral hemodynamics in the elderly population. We conducted literature searches in PudMed and PsycINFO, and selected only English original research articles that used fNIRS to study healthy individuals with a mean age of ≥ 55 years. All articles were published in peer-reviewed journals between 1977 and May 2019. We synthesized 114 fNIRS studies examining hemodynamic changes that occurred in the resting state and during the tasks of sensation and perception, motor control, semantic processing, word retrieval, attentional shifting, inhibitory control, memory, and emotion and motivation in healthy older adults. This review, which was not registered in a registry, reveals an age-related reduction in resting-state cerebral oxygenation and connectivity in the prefrontal cortex. It also shows that aging is associated with a reduction in functional hemispheric asymmetry and increased compensatory activity in the frontal lobe across multiple task domains. In addition, this article describes the beneficial effects of healthy lifestyles and the detrimental effects of cardiovascular disease risk factors on brain functioning among nondemented older adults. Limitations of this review include exclusion of gray and non-English literature and lack of meta-analysis. Altogether, the fNIRS literature provides some support for various neurocognitive aging theories derived from task-based PET and fMRI studies. Because fNIRS is relatively motion-tolerant and environmentally unconstrained, it is a promising tool for fostering the development of aging biomarkers and antiaging interventions.

Keywords: near-infrared spectroscopy, NIRS, aging, older adults, brain, hemodynamics

1. Introduction

The world's population is aging at an unprecedented rate, with the number of people aged 60 years and over growing at a rate of 3% per year (United Nations, 2017). Aging is associated with deficits in sensory functioning (Baloh, Ying, & Jacobson, 2003), balance and gait (Seidler et al., 2010), handgrip strength and chewing ability (Locker, 2002; Massy-Westropp, Gill, Taylor, Bohannon, & Hill, 2011), and executive function (Andrés & Van der Linden, 2000; MacPherson, Phillips, & Della Sala, 2002; Park & Reuter-Lorenz, 2009; Tombaugh, Kozak, & Rees, 1999). Longitudinal studies have shown that impairments in vision and hearing (Freeman, Munoz, Rubin, & West, 2007; Reuben, Mui, Damesyn, Moore, & Greendale, 1999), balance and gait (Dumurgier et al., 2016; Verghese et al., 2002; Verghese, Holtzer, Lipton, & Wang, 2009; Wennie Huang, Perera, VanSwearingen, & Studenski, 2010), and executive function (Buracchio et al., 2011; Ewers et al., 2014; Herman, Mirelman, Giladi, Schweiger, & Hausdorff, 2010; Mirelman et al., 2012; Rapp & Reischies, 2005) predict functional disability, future falls, or the onset of dementia among nondemented older adults. Because immobility and dementia place a heavy financial burden on the families of older adults and society (Hurd, Martorell, Delavande, Mullen, & Langa, 2013; Stevens, Corso, Finkelstein, & Miller, 2006), understanding age-related changes in brain functioning might provide insights into the mechanisms underlying age-related functional declines, fostering the development of interventions aimed at improving the sensory, motor, and cognitive functions of older people.

Aging is associated with different kinds of functional abnormalities that follow an anterior-to-posterior gradient in the brain. In the resting state, positron emission tomography (PET) studies have identified decreases in regional cerebral blood flow and glucose metabolism with increasing age. These age-related decreases are most pronounced in the frontal lobe, including the anterior cingulate cortex, and least pronounced in the occipital lobe (Bentourkia et al., 2000; Kalpouzos et al., 2009). Similarly, functional magnetic resonance imaging (fMRI) studies have reported an age-related reduction in resting-state brain activity or functional connectivity in the default mode network comprising the medial frontal, posterior cingulate, and lateral parietal cortices (Damoiseaux et al., 2007; Koch et al., 2010; Mowinckel, Espeseth, & Westlye, 2012). In addition, large-scale meta-analytic studies of task-based fMRI studies have reported hyperactivation in the frontoparietal and default mode networks comprising the middle frontal gyrus, medial frontal gyrus, and precentral gyrus and hypoactivation in the visual network comprising the parahippocampal gyrus, fusiform gyrus, and lingual gyrus in healthy older adults across multiple cognitive domains (Li et al., 2015; Spreng, Wojtowicz, & Grady, 2010). These meta-analyses have also identified

a link between frontoparietal hyperactivation and improved behavioral performance, suggesting a role for the frontoparietal network in successful compensation among older adults.

While PET and fMRI have generated insights into age-related changes in brain oxygenation and activity, with both techniques heralded as the gold-standard for brain imaging, these methods are not without their limitations. First, PET involves the injection of radioactive compounds, exposing the patient to ionizing radiation. In addition, fMRI requires that the patient remain immobilized in a closed space and in a noisy environment during an MRI scan. These characteristics make fMRI an unappealing option for people who have claustrophobia or who are sensitive to noise. Neither is fMRI applicable for individuals with in situ metallic implants. Furthermore, fMRI is susceptible to motion artifacts and is therefore not ideal, if not contraindicated, for measuring brain activity during locomotion tasks or other tasks that involve head movements, such as walking or overt word production. Moreover, both PET and fMRI are relatively expensive in terms of purchase and running costs. The aim of this article, therefore, is to synthesize the literature regarding the application of functional near-infrared spectroscopy (fNIRS), which is an alternative brain imaging method, for the study of healthy aging.

Taking advantage of the relative transparency of biological tissue to near-infrared lights at wavelengths of 700–1000 nm, fNIRS non-invasively monitors the hemodynamic responses evoked by neuronal activity (Villringer & Chance, 1997). Due to neurovascular coupling (Girouard & Iadecola, 2006; Thompson, Peterson, & Freeman, 2003), neuronal activity leads to an increase in the concentration of oxyhemoglobin ([oxy-Hb]), and a decrease in the concentration of deoxyhemoglobin ([deoxy-Hb]) in the nearby bloodstream. An fNIRS device makes use of near-infrared light of two different wavelengths, one below and one above the isosbestic point of hemoglobin (805 nm), and consists of at least one pair of light-emitting and light-receiving diodes, which are usually placed over the frontal scalp region according to the international 10–20 system (Cutini et al., 2011; Tsuzuki et al., 2007). When the light is emitted to the scalp, a fraction of photons propagate through the scalp, the skull, the cerebrospinal fluid, and the surface of the cerebral cortex in a banana-shaped trajectory. As the photons leave the cortical surface and return to the scalp, they are detected by an optical receiver. The received signals can then be used to calculate the levels or changes in [oxy-Hb] and [deoxy-Hb] (Delpy et al., 1988). The validity (Cui, Bray, Bryant, Glover, & Reiss, 2011; Sato et al., 2013; Strangman, Culver, Thompson, & Boas, 2002) and reliability (Kakimoto et al., 2009; Plichta et al., 2006; Schecklmann, Ehlis, Plichta, & Fallgatter, 2008) of fNIRS signals have been supported by studies with younger adults. Finally, there are three methods of fNIRS (Ferrari & Quaresima, 2012; Scholkmann et al., 2014); while continuous-wave fNIRS can only measure the relative [oxy-

Hb] and [deoxy-Hb], frequency-domain and time-resolved fNIRS can quantify the absolute [oxy-Hb] and [deoxy-Hb] in the resting state.

It is increasingly recognized that fNIRS is a relatively cost-effective, environmentally unconstrained, noise-free, and motion-tolerant neuroimaging modality (Pinti et al., 2018). However, no studies to date have systematically reviewed the fNIRS literature on healthy aging, so the contributions of this technique to efforts aimed at understanding the mechanisms underlying brain aging remain unclear. Thus, the aim of this article is to review the literature with respect to studies employing this method for the study of age-related changes in brain activity in resting and task states. This review uses a narrative synthesis approach as opposed to meta-analysis due to differences in fNIRS systems and variations in the methods of statistical analysis across studies. The two objectives of this study are: (a) to characterize the pattern of age-related changes in resting-state cerebral oxygenation and task-evoked hemodynamic changes across multiple task domains, and (b) to identify moderating factors that might account for the variability of cerebral oxygenation seen among healthy older adults.

2. Method

2.1. Search Strategy and Study Selection

This study, which was not registered in a registry, conformed to standard methodological guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (Moher, Liberati, Tetzlaff, & Altman, 2009). To identify fNIRS studies in healthy older adults, we conducted a literature search using PubMed on June 6, 2019. An additional search using PsycINFO was performed on January 12, 2020 to improve the comprehensiveness of this review. The keywords we used were “older adult” or “elder*” or “aging” or “age*” and “functional near-infrared spectroscopy” or “fnirs” or “nirs”. Publication date was set as a limit, and only articles that were published between January 1, 1977 and May 31, 2019 were selected. The first author performed the literature search. After the initial search, the titles and abstracts of the studies were screened.

A study was included if it met all three following criteria: (a) applied fNIRS to study brain function, (b) included at least one sample group with a mean age of at least 55 years, and (c) an original research article written in English. In addition, articles were excluded if they met any of the following criteria: (a) examined pathological aging populations, such as mild cognitive impairment and dementia, (b) examined individuals with psychiatric or neurological disorders, such as depression or Parkinson’s disease, (c) included patients with traumatic brain injury, cardiovascular disease (e.g., stroke), sleep disorder, organ dysfunction, or deafness, (d) monitored brain activity

during surgery or anesthesia, or (e) not being published in a peer-reviewed journal. These exclusion criteria were established to ensure that healthy or cognitively normal older adults were recruited in the selected studies, and that fNIRS was applied to study brain function in the resting and task states. We selected only articles that were published in peer-reviewed journals to make sure that all the studies reviewed were of high quality.

Two independent reviewers (MKY, ASC) coded each article based on the inclusion and exclusion criteria. After screening the titles and abstracts, the full texts of the screened articles were retrieved for eligibility assessment. The initial agreement between the two reviewers on study inclusion was 98.6%. Cohen's Kappa was 0.85, suggesting almost perfect agreement (Landis & Koch, 1977). Disagreements between reviewers were resolved by consensus.

Data Extraction

We extracted the following information related to data collection and study results from each of the identified articles, entering this data into a predesigned table: author name(s), year of publication, study type, sample characteristics (i.e., sample size, gender composition, and years of age), fNIRS parameters (i.e., source-receiver separation distance, sampling rate, channel location, and fNIRS system), activation task, and fNIRS findings (see supplementary tables). The summary measures were age differences in the levels and changes in [oxy-Hb] or [deoxy-Hb] in the resting and task states, as well as the relationships between non-age factors and the resting levels or task-evoked changes in [oxy-Hb] or [deoxy-Hb] among older adults.

All studies were classified into one of the following ten categories: (a) resting state, (b) sensation and perception, (c) gross motor skills, (d) fine motor skills, (e) semantic processing, (f) word retrieval, (g) attentional shifting, (h) inhibitory control, (i) memory, and (j) emotion and motivation. The first author extracted and tabulated the data from each selected study, and the second author checked the extracted data. We did not contact any study authors for additional information. For each category, we reported the number and percentage of studies reporting significant age effects and the number of studies examining the moderating effects of non-age factors on cerebral oxygenation among older adults. Meta-analysis was not performed because of the large variability in fNIRS systems and analytic methods used in the included studies.

2.2. Risk of Bias and Quality Control Assessment

We carried out risk of bias and quality control assessment for the selected studies. With respect to risk of bias within studies, given that underpowered studies and multichannel studies that fail to correct for multiple testing are prone to report false-positive findings (Forstmeier, Wagenmakers, & Parker, 2017), we examined whether *a priori* power analysis was conducted for all studies, and whether multiple comparison correction was applied for studies testing more than two regions or channels. Studies testing only two regions (e.g., left and right hemispheres) were not subject to this assessment because of the hemispheric specialization of functions. In addition, learning and age-related changes in brain and skull structures have been shown to influence brain function (Kelly & Garavan, 2005) and estimation of hemoglobin concentration (Duncan et al., 1996), respectively. As such, failure to match age groups on educational level and to correct the differential pathlength factor, which is used to estimate [oxy-Hb] and [deoxy-Hb], for age may lead to erroneous conclusions about age differences in hemoglobin concentration. These two aspects were therefore assessed for studies comparing different age groups.

With respect to risk of bias between studies, we examined whether there was selective reporting of [oxy-Hb] and [deoxy-Hb] within studies. While it is common for fNIRS studies to analyze and report only [oxy-Hb] because this index has a higher signal-to-noise ratio than [deoxy-Hb] (Cui et al., 2011; Strangman et al., 2002), some researchers may choose to report only [oxy-Hb] because this index, but not [deoxy-Hb], yields significant results. Thus, reporting bias may be present in studies reporting only [oxy-Hb]. In addition, some researchers may choose to analyze and report [deoxy-Hb] as well because only this index yields significant results, reflecting another instance of reporting bias. Accordingly, we also examined whether the studies that have analyzed both indices reported significant results for [deoxy-Hb] but not for [oxy-Hb]. It is notable that the correlation between changes in [oxy-Hb] and [deoxy-Hb] provides information as to whether changes in [oxy-Hb] reflect functional activity or systemic or artifactual activity (Yamada, Umeyama, & Matsuda, 2012). Thus, presentation of both indices constitutes an important quality control step to verify that age differences in the levels or changes in hemoglobin concentration reflect age differences in neural activity.

We further assessed the quality control procedure employed by each study. Specifically, we examined whether screening tests were administered, and the cutoff scores were used to ensure that all the older adults recruited were cognitively healthy and not demented. In addition, we summarized the artifact correction methods applied in each study. To ensure that changes in fNIRS signals reflect changes in neural activity, corrections for cardiac and respiratory artifacts and high-frequency noise (e.g., low-pass and moving-average filtering), motion artifacts (e.g., spline interpolation, wavelet filtering, and correlation-based signal improvement), nonneuronal and systemic

changes (e.g., short-distance and common average reference corrections), slow drifts (e.g., discrete cosine transform-based high-pass filtering and wavelet minimum description length detrending), and temporal autocorrelation (e.g., precoloring and prewhitening) can be applied (see Scholkmann et al., 2014, for a review of artifact correction methods).

3. Results

3.1. Study Characteristics

Figure 1 presents the flow of the literature search. Initially, we identified 2223 articles in PubMed and 423 articles in PsycINFO. After removing 331 duplicates, 2315 records were screened. After screening the titles and abstracts based on the inclusion and exclusion criteria, 277 articles were retrieved for full-text review. We subsequently excluded a further 163 articles for various reasons: 146 studies did not include at least one sample group with a mean age of at least 55 years, 13 were published in sources other than peer-reviewed journals (i.e., conference proceedings, book chapters, or dissertations), two studies did not perform fNIRS analysis, and one study measured brain activity during anesthesia. Thus, 114 studies were included for review in the final stage. These studies were classified into two categories: (a) 64 studies compared younger and older adults to identify age-related changes in brain activity, and (b) 50 studies examined the role of non-age factors influencing brain activity among nondemented older adults. Of these latter studies, 20 studies manipulated variables to cause changes in brain activity, and 30 studies just observed the relationship between non-age factors and brain activity.

INSERT FIGURE 1 ABOUT HERE

Figure 2 shows the number of fNIRS articles focused on healthy aging published each year in peer-reviewed journals (i.e., published studies with at least one group of healthy individuals with a mean age of at least 55 years). The first article was published in 2001, and there were no more than two articles published every year between 2001 and 2011. There were, however, 10 such articles in 2012. Since then, the number of fNIRS articles published each year has remained stable, if not increased, over time. There were ten articles published between January and May 2019 (not shown in Figure 2). Additionally, there have been 28 studies published on gross motor skills, 23 on the resting state, 14 on memory, 13 on inhibitory control, 11 on attentional shifting, ten on sensation and perception, nine on word retrieval, eight on fine motor skills, four on semantic processing, and three on emotion and motivation (Figure 3). Some studies examined more than one domain. The following sections review fNIRS studies in relation to each domain (see Table 1 for summary).

INSERT FIGURE 2 ABOUT HERE

INSERT FIGURE 3 ABOUT HERE

3.2. Resting (Sitting, Standing, Lying, and Postural Change)

Twenty-three fNIRS studies have examined changes in the oxygenation of cerebral blood in resting older adults (see Supplementary Table 1). Five of these studies show that, compared to younger adults, older adults have lower resting prefrontal cortex (PFC) oxygenation, which was a highly reproducible finding regardless of source-detector distance or frequency bands (i.e., oscillations related to cardiac, myogenic, and endothelial activities; Shiogai, Stefanovska, & McClintock, 2010) (Amiri et al., 2014; Hallacoglu et al., 2012; Harada, Nashihara, Morozumi, Ota, & Hatakeyama, 2007; Li, Zhang, Xin, Luo, Cui et al., 2013; Tan et al., 2016; see also Claassen, Colier & Jansen, 2006, for the reproducibility of fNIRS measurements in older adults under hypoxia). No studies have reported an increase in resting PFC oxygenation in older adults. Additionally, four studies have shown that aging is associated with reduced connectivity between the left and right PFC, increased connectivity between the PFC and sensorimotor cortex (i.e., increased influence from the motor cortex to the PFC), and an overall decline in global and local efficiency as well as small-worldness that preferentially affects frontal networks while sitting or standing, or in response to postural change (Huo et al., 2018; Tan et al., 2016; Wang et al., 2016; also see Mehagnoul-Schipper, Colier, & Jansen, 2001). Furthermore, two of these studies have shown that older adults have lower connectivity of blood flow oscillations, specifically in the 0.052–0.145 Hz interval (i.e., oscillations related to myogenic activity; Shiogai et al., 2010), between the PFC and sensorimotor cortex than younger adults, suggesting the presence of frequency-dependent changes in connectivity between the PFC and the sensorimotor cortex (Tan et al., 2016; Wang et al., 2016).

Apart from PFC oxygenation levels and connectivity between brain regions, five studies have reported an age-related change in the coupling of PFC activity and arterial blood pressure (Cui et al., 2014; Gao et al., 2015), the age-related attenuation of neurovascular coupling (Mukli, Nagy, Racz, Herman, & Eke, 2018), and blood flow oscillations within the PFC (Schroeter, Schmiedel, & von Cramon, 2004; Zeller et al., 2019) while sitting or in response to postural change. Taken together, these findings suggest an age-related reduction in the inherent ability of endothelial cells to maintain stable cerebral blood flow during cerebral autoregulation. The PFC of older adults may also be less adequately protected against the effects of rapid blood flow changes (due to postural changes) than younger adults.

Although aging is associated with changes in resting cerebral hemodynamics in general, there is considerable variability among older adults. First, two studies have shown that physical exercise and sleep quality are two lifestyle habits that exert a moderating effect over resting cerebral oxygenation among nondemented older adults. While the amount of weekly physical exercise is associated with higher resting oxygenation in the dorsolateral PFC (dlPFC; Suhr & Chelberg, 2013), sleep quality is associated with lower resting oxygenation in the PFC and occipital cortex, as well as higher connectivity between the left and right PFC, and between the PFC, motor, and occipital cortex (Bu, Wang et al., 2018). The opposing effect of physical exercise and sleep quality on PFC oxygenation suggests that optimal brain functioning might rely on an optimal level of cerebral blood oxygenation in older adults. In addition, four studies have shown that cardiovascular disease risk factors, including hypertension (Bu, Huo et al., 2018; Li et al., 2014), increased arterial flow velocity (Li et al. 2012), and diabetes (Suhr & Chelberg, 2013), are associated with reduced resting PFC oxygenation or connectivity between the left and right PFC or among prefrontal, motor, and occipital regions among older adults. Rhee and Mehta (2018) have also showed a link between obesity and greater variability in functional connectivity among frontal and sensorimotor regions at rest among older adults. Nevertheless, one study has reported higher PFC oxygenation in hypertensive older adults with increased arterial flow velocity than in normotensive older adults and hypertensive older adults without increased arterial flow velocity (Li, Zhang, Xin, Luo, Zhou et al., 2013). As such, there may be an interaction between hypertension and arterial flow velocity on PFC oxygenation in older adults. Finally, one study has reported a positive correlation between the right lateralization of [oxy-Hb] changes and the level of state anxiety in both younger and older adults, who did not differ in the strength of the relationship (Ishikawa et al., 2014).

3.3. Sensation and Perception (Visual Perception, Auditory Perception, and Vestibular Function)

There have been ten studies that have examined sensation and perception, including visual processing (n = 4), auditory processing (n = 1), and vestibular function (n = 5), in older adults. Regarding visual processing, there have been three studies on checkerboard stimulation and one on motion coherence perception. Two out of three (67%) studies have reported an age-related reduction in occipital cortex activation in response to visual stimulation with full-field alternating checkboards (Fabiani et al., 2014; Schroeter et al., 2004; Ward, Aitchison, Tawse, Simmers, & Shahani, 2015). Speed of visual stimulation and aerobic fitness may be two moderating factors. In other words, older adults have less occipital activation than younger adults in response to fast (7.5 Hz alternating checkerboard; Ward et al., 2015) but not slow visual stimulation (1.8 Hz alternating checkerboard; Schroeter et

al., 2004). In addition, while older adults fail to show occipital activation in response to 1–8 Hz checkerboard stimulation, unlike younger adults, the level of occipital activation was associated with aerobic fitness among older adults (Fabiani et al., 2014). Apart from checkerboard stimulation, aging is associated with increased parieto-occipital cortex activation during fast but not slow motion coherence perception (Ward, Morison, Simmers, & Shahani, 2018), reflecting compensatory activity for impaired motion perception in old age. Similar to checkerboard stimulation, one study has shown that older adults have reduced right dlPFC activation as compared to younger adults while paying selective attention to melodic contours, thus suggesting an age-related failure to recruit the PFC during selective listening (Jeong & Ryu, 2016).

Regarding vestibular function, there have been two studies on dual-task balance, two on postural control involving multisensory integration, and one on the vestibulo-ocular reflex. One out of two (50%) studies on dual-task balance has reported increased left frontotemporal activation in older adults as compared with younger adults (Marusic et al., 2019; Rosso et al., 2017). Because the motor or cognitive demand in dynamic standing and auditory vigilance tasks (Rosso et al., 2017) is greater than in tandem standing and backward counting tasks (Marusic et al., 2019), older adults may exhibit compensatory activity only when the task demand is sufficiently large. In addition, both studies of postural control involving multisensory integration have reported frontal, temporal-parietal, or occipital hyperactivation and less-lateralized PFC activation in older adults than in younger adults during dynamic balancing (Lin, Barker, Sparto, Furman, & Huppert, 2017; Teo, Goodwill, Hendy, Muthalib, & Macpherson, 2018). The presence of age-related brain hyperactivation without impaired postural control performance (Lin et al., 2017) may reflect compensation for postural control difficulty. Similarly, the study of the vestibulo-ocular reflex reported stronger and more symmetrical temporal cortex activation in older adults than in younger adults during caloric irrigations (Karim, Fuhrman, Furman, & Huppert, 2013). In sum, all five fNIRS studies on vestibular functioning have reported age-related hyperactivation or reduction in functional asymmetry during balance tasks.

3.4. Gross Motor Skills (Walking, Cycling, and Driving)

There have been 28 fNIRS studies on gross motor skills, including walking (n = 23), cycling (n = 3), and driving (n = 2), in healthy older adults (see Supplementary Table 3). Regarding walking, five studies have characterized brain activity during different single-task and dual-task walking (i.e., walking while performing a secondary) protocols in older adults. These studies have shown that walking while reciting alternate alphabets or retrieving words and walking under perceptually or physically challenging conditions induced greater activity in the (lateral)

PFC than walking only in older adults (Clark, Rose, Ring, & Porges, 2014; Hawkins et al., 2018; Holtzer et al., 2015; Holtzer, Izzetoglu, Chen, & Wang, 2018; Mirelman et al., 2017). Regarding the effects of time and practice, two studies have shown that while the level of PFC activity initially increased before gradually returning to baseline during normal walking, PFC activity continued to increase over the course of dual-task walking (Holtzer et al., 2015; Holtzer, Izzetoglu et al., 2018). In addition, while the level of PFC activity did not change over repeated trials of single-task walking, it decreased over repeated trials of dual-task walking or alphabet recitation. Moreover, older adults who showed a greater decline in PFC activity exhibited greater improvements in gait and cognitive task performance over repeated trials of dual-task walking than did those who showed a smaller decline in PFC activity, suggesting that some older adults might improve their PFC efficiency with practice (Holtzer, Izzetoglu et al., 2018).

Although there have been six studies that have examined the effects of age on changes in frontal oxygenation during dual-task walking, the findings of these studies have been mixed. Three studies have reported an age-related reduction in PFC or supplementary motor cortex activity (Beurskens, Helmich, Rein, & Bock, 2014; Holtzer et al., 2011; Stuart, Alcock, Rochester, Vitório, & Pantall, 2019), one study reported an age-related increase in PFC activity (Mirelman et al., 2017), and two studies have reported no age-related changes in PFC activity (Fraser, Dupuy, Pouliot, Lesage, & Bherer, 2016; Hawkins et al., 2018). These discrepancies may be due to the choice of secondary tasks differing across studies. As such, studies that have reported frontal hypoactivation employed alphabet recitation (Holtzer et al., 2011), box checking (Beurskens et al., 2014), and digit vigilance (Stuart et al., 2019) tasks, whereas studies that reported frontal hyperactivation employed the backward counting task (Mirelman et al., 2017). In addition, studies that have reported null findings employed the auditory *n*-back and letter fluency tasks (Fraser et al., 2016; Hawkins et al., 2018). More importantly, one study compared different secondary tasks and showed that a visual secondary task had a larger interfering effect than a verbal secondary task on dual-task walking (Beurskens et al., 2014), generating supportive evidence that the age-related changes in PFC activity during dual-task walking might be task-dependent. It is noteworthy that three of these studies also found that older adults had greater PFC activity than younger adults during single-task performance, such as usual walking (Mirelman et al., 2017; Stuart et al., 2019; Vitorio et al., 2018), suggesting frontal hyperactivation at low cognitive or motor demand.

There have been 11 fNIRS studies that have examined the correlation between various factors and PFC activity while walking among older adults. Three studies have shown that polypharmacy (George, Verghese, Izzetoglu,

Wang, & Holtzer, 2019), diabetes (Holtzer, George et al., 2018), and obesity (Osofundiya, Benden, Dowdy, & Mehta, 2016) were associated with frontal hypoactivation during dual-task walking or frontal hyperactivation during single-task performance, suggesting that cardiovascular disease risk factors might magnify age-related changes in PFC activity during dual-task walking. In addition, three studies have reported mixed findings with respect to the effect of psychological factors on PFC activity during dual-task walking. That is, while two studies have shown that perceived stress and fatigue are associated with frontal hypoactivation (Holtzer et al., 2017a, b), one study has shown that the fear of falling is associated with frontal hyperactivation (Holtzer, Kraut, Izzetoglu, & Ye, 2019). While fatigued older adults might put little effort into the walking task, leading to frontal hypoactivation, older adults who fear falling might be overanxious during dual-task walking, thus leading to higher task-unrelated brain activity persisting over time. Furthermore, five studies have shown that frontal atrophy (Wagshul, Lucas, Ye, Izzetoglu, & Holtzer, 2019), whole-brain white matter degradation (Lucas, Wagshul, Izzetoglu, & Holtzer, 2019), low gait capacity (Chen et al., 2017; Harada, Miyai, Suzuki, & Kubota, 2009), and large gait variability (Mirelman et al., 2017) are associated with frontal hyperactivation during dual-task or precision walking among older adults. As such, hyperactivation may reflect effortful walking related to brain degeneration and poor gait performance.

Apart from correlational studies, three controlled experiments have also investigated the effects of rhythmic auditory cueing, dancing training, and enhanced somatosensory feedback on PFC activity among older adults. All three studies have reported a causal effect of these factors on changes in PFC oxygenation while walking. Specifically, one study has shown that rhythmic auditory cueing leads to increased PFC and motor cortex activation during treadmill walking, possibly reflecting increased attention to cues while walking (Vitorio et al., 2018). In addition, two studies have shown that video game dance training (Eggenberger et al., 2016), and walking with either textured soles or no shoes (Clark, Christou, Ring, Williamson, & Doty, 2014) result in lower PFC activity than balance and stretching training or normal shoes, respectively. Thus, dancing training and enhanced somatosensory feedback may reduce walking effort in older adults.

Similar to what has been observed under physically challenging walking conditions, two studies have reported an age-related reduction in PFC activation in response to high-intensity cycling (Lucas et al., 2012) and while driving (Harada et al., 2007). Nevertheless, older adults still exhibited (right) PFC activation while driving and could improve neural efficiency through repeated driving practice (Harada et al., 2007; Knols et al., 2017). In addition, one study has shown that older adults experience greater activation in the supplementary motor area and premotor

cortex than younger adults when asked to cycle at a certain pedaling rate with the aid of feedback (Lin, Lin, & Chen, 2012). Given that there is no discernable age difference in the activation in these two regions during self-paced cycling, older adults might require more effortful motor control when attempting to cycle at a target cadence. Finally, one study has examined the roles of aerobic fitness and obesity in left PFC activation while cycling; no significant differences among nonobese, high-fit obese, and low-fit obese older adults were found during exercise or recovery (Gayda et al., 2017).

3.5. Fine Motor Skills (Handgrip Force Control, Finger Movement, and Mastication)

There have been eight fNIRS studies on fine motor skills, including handgrip force control (n = 3), finger movement (n = 2), and mastication (n = 3), in older adults (see Supplementary Table 4). Regarding upper extremity control, three studies have shown that aging is associated with increased PFC activity (Mehta & Rhee, 2017), but decreased or less-lateralized motor cortex activity (Mehagnoul-Schipper et al., 2002; Zich, Debener, Thoene, Chen, & Kranczioch, 2017) during the execution or imagination of fine upper limb movements. In addition, two studies have examined the role of psychological factors and found that cognitive fatigue (Shortz, Pickens, Zheng, & Mehta, 2015), but not acute stress (Mehta & Rhee, 2017), can result in reduced PFC activity during handgrip force control in older adults. Thus, aging may be associated with increased PFC activity as a compensatory neural strategy for maintaining motor performance during upper extremity control when cognitive resources are available. Moreover, one study has found that obese OA had weaker functional connectivity between the right lateral premotor area and bilateral medial premotor areas than nonobese OA during handgrip motor fatigue, suggesting a link between obesity and reduced sensorimotor network communication during sustained handgrip control among older adults (Rhee & Mehta, 2018).

With respect to mastication, one study has examined the effects of age, reporting lower PFC activation in older adults than in younger adults while chewing, irrespective of whether a dental prosthesis was worn (Kamiya, Narita, & Iwaki, 2016). In addition, this study and two other studies (Miyamoto, Yoshida, Tsuboi, & Iizuka, 2005; Narita et al., 2009) consistently show that older adults experience greater mid-dorsal PFC and temporal activation while chewing with a dental prosthesis as opposed to chewing without one.

3.6. Semantic Processing (Discourse Comprehension, Lexical Decision-Making, and Syllogistic Reasoning)

There have been four fNIRS studies on semantic processing, including discourse comprehension (n = 2), lexical decision-making (n = 1), and syllogistic reasoning (n = 1), in older adults. Each of these studies reported higher frontal activation in older adults than in younger adults. Specifically, the two studies on discourse comprehension showed that older adults have greater activation in the left dorsolateral prefrontal, frontopolar, and inferior frontal regions than younger adults (Martin et al., 2018) and demonstrate a shift in activation from the posterior temporal cortex regions to the inferior frontal regions while reading narratives (Scherer et al., 2012). In addition, the study on lexical-semantic decision-making has shown that older adults have greater activation in the bilateral dlPFC, inferior frontal gyri, and right posterior middle temporal and occipitotemporal gyri than younger adults when deciding whether the words being presented are real (Amiri et al., 2014). Furthermore, one study has shown that older adults exhibit greater conflict-related activation in the left inferior frontal cortex, resulting in less right-lateralized PFC activation, than younger adults while evaluating syllogisms (Tsujii, Okada, & Watanabe, 2010). Taken together, aging is associated with increased PFC compensatory activity for functional decline across semantic tasks.

3.7. Word Retrieval (Phonemic and Semantic Fluency)

There have been nine fNIRS studies on controlled word retrieval in older adults (see Supplementary Table 5). Five studies have examined the effects of age, and each of these studies reported age-related alterations in frontotemporal and parietal activation during verbal fluency tasks. Specifically, older adults exhibit lower activation in the bilateral frontotemporal regions than younger adults during phonemic and semantic fluency tasks (Heinzel et al., 2013, 2015; Herrmann, Walter, Ehlis, & Fallgatter, 2006; Kahlaoui et al., 2012). They also exhibit weaker activation in the anterior part of the superior frontal region (i.e., Fz), which was associated with poorer task performance during the phonemic fluency task (Obayashi & Hara, 2013). In addition, the age-related reduction in PFC activity was not moderated by the productivity of categories (Kahlaoui et al., 2012), and was more pronounced in the left hemisphere, resulting in less left-lateralized activation (Heinzel et al., 2013, 2015; Herrmann et al., 2006). Furthermore, age predicted activation in the right middle frontal gyrus and bilateral inferior parietal regions during the phonemic fluency task, and in the bilateral motor regions during the semantic fluency task (Heinzel et al., 2013, 2015). Therefore, while aging is associated with reduced left-lateralized PFC activation and hypoactivation in the ventrolateral PFC (vlPFC), it is also associated with hyperactivation in the right dlPFC, and bilateral motor and parietal cortex during word retrieval.

Three studies have shown that cardiovascular disease risk factors—including hyperlipidemia (Kato et al., 2017) and hypertension (Heinzel et al., 2015)—and apolipoprotein-E4 allele in the case of Alzheimer's disease (Katzorke et al., 2017), is associated with reduced activation in the PFC, especially vlPFC, during verbal fluency tasks. It is noteworthy that while one study with 73 older adult subjects failed to report a significant correlation between hypertension and PFC activity during the phonemic fluency task (Kato et al., 2017), another large-scale study with 727 middle-aged and older adult research subject was able to report such correlations (Heinzel et al., 2015). Thus, the null findings of Kato et al. (2017) might possibly be the product of a lack of sufficient statistical power. Because Kato et al. (2017) reported a positive association between hyperlipidemia and reduced PFC activation, hyperlipidemia may exert a larger effect than hypertension on PFC hypoactivation in older adults. In contrast, there have been five studies that show healthy lifestyles, including adequate sleep (Kato et al., 2017), social functioning (Pu et al., 2014), daily outdoor activity (Makizako et al., 2013), not smoking (Kato et al., 2017), and high years of education (Heinzel et al., 2013, 2015), are associated with higher activation in the PFC, especially vlPFC, during verbal fluency tasks. As such, cardiovascular disease and Alzheimer's disease risk factors are linked with lower PFC activity, whereas healthy lifestyle habits are linked with greater activity in the same brain region.

3.8. Attentional Shifting (Task-Switching and Dual-Tasking)

The 11 fNIRS studies on attentional shifting in older adults have shown mixed results (see Supplementary Table 8). Six out of nine (67%) studies have reported different patterns of frontal activation between younger and older adults during shifting tasks. Among the six studies that reported positive results, four found an age-related reduction in superior frontal activation, but an increase in bilateral PFC activation during shifting tasks that involved button presses, including the cued task-switching paradigm (Huppert et al., 2017; Vasta et al., 2018), the psychological refractory period and the dual-task paradigms (Laguë-Beauvais et al., 2015), and the modified Stroop task (Laguë-Beauvais, Brunet, Gagnon, Lesage, & Bherer, 2013). The remaining two studies, on the other hand, found an age-related reduction in lateral PFC activation, but an increase in dorsomedial PFC and sensorimotor cortex activation during shifting tasks that involved psychomotor sequencing (Hagen et al., 2014; Müller et al., 2014). These discrepancies in the altered age-related pattern of activation might be attributable to different task demands across studies (i.e., button presses vs. psychomotor sequencing). In addition, the three studies that reported null findings recruited either female participants only (Dupuy et al., 2015), or employed tasks that involved concurrent upper or lower limb movement and cognitive performance (Corp et al., 2018; Ohsugi,

Ohgi, Shigemori, & Schneider, 2013). Sample sizes in these studies were similar to those reporting positive results (i.e., at least 15 younger and 15 older adults). Therefore, sex and task type may be two factors exerting a moderating influence over PFC activation.

Three studies have examined factors affecting PFC activity during shifting among older adults, with two studies focusing on aerobic fitness, and one study focusing on glucose ingestion. Two studies found that aerobic fitness was associated with increased activation in the right lateral PFC during shifting tasks, including the modified Stroop task (Dupuy et al., 2015), and a random generation task (Albinet, Mandrick, Bernard, Perrey, & Blain, 2014). In addition, one experimental study with older adults without diabetes found that glucose ingestion, as compared to placebo treatment, led to an enhanced ability to coordinate two tasks more equally during the psychological refractory period and dual-task paradigms through the increased recruitment of the (right ventrolateral) PFC (Gagnon et al., 2012).

3.9. Inhibitory Control (Prepotent Motor Inhibition, Reflexive Saccade Inhibition, and Interference Control)

There have been 13 fNIRS studies on inhibitory control, including prepotent motor inhibition (n = 8), reflexive saccade inhibition (n = 2), and interference control (n = 3), in older adults (see Supplementary Table 9). Nine of these studies examined the effect of age by comparing younger and older adults. Regarding prepotent motor inhibition, four out of six (67%) studies have shown that aging is associated with altered PFC activation during task performance. Specifically, three studies reported both vlPFC hypoactivation and dlPFC hyperactivation during the go/no-go task (Heilbronner & Münte, 2013), and the color-word Stroop task (Huppert et al., 2017; Schroeter, Zysset, Kruggel, & von Cramon, 2003). The fourth study reported posterior vlPFC activation in older adults, but not in younger adults, during the color-word Stroop task; later visual inspection revealed lower lateral PFC activity across task conditions in older adults (Laguë-Beauvais et al., 2013). In addition, two studies failed to report any age-related differences in PFC activity during the color-word Stroop task (Dupuy et al., 2015; Lucas et al., 2012); both these studies employed blocked-design tasks, unlike those studies that had reported positive results, which primarily employed event-related tasks (Heilbronner & Münte, 2013; Schroeter et al., 2003). Inhibition tasks with a blocked design have been shown to be associated with a lower congruency effect due to conflict adaptation following consecutive trials of the same type than those with event-related designs (i.e., the Gratton effect; Gratton, Coles, & Donchin, 1992). Thus, task design seems to moderate the age-related differences in PFC activity during prepotent motor inhibition. In addition, one study on interference control, and one out of two (50%) studies on reflexive saccade inhibition, have reported age-related hyperactivation in the PFC, especially

the superior PFC, during the flanker and Simon tasks (Kawai et al., 2012), and the antisaccade task (Bierre, Lucas, Guiney, Cotter, & Machado, 2017), respectively. Null findings might be the result of some participants having accrued extensive practice, thus allowing for adaptation to the demands of the task (Fujiwara et al., 2010)

Four studies have examined factors associated with PFC activity during inhibition among older adults. Two studies used the Multi-Source Interference Task, which requires the resolution of stimulus–response incompatibility. These studies show that a history of falls and poor inhibition are associated with increased lateral PFC activation during task performance (Halliday et al., 2017, 2018). In addition, two studies that used the Stroop task reported a relationship between aerobic fitness and increased right vlPFC activation, and more lateralized PFC activation (Dupuy et al., 2015), as well as a positive effect for acute aerobic exercise on right frontopolar cortex activation during task performance (Hyodo et al., 2012).

3.10. Memory (Working and Episodic Memory)

There have been 14 fNIRS studies on memory function, including verbal working memory (WM; n = 7), visuospatial WM (n = 6), and episodic memory (n = 1), in older adults (see Supplementary Table 7). Regarding verbal WM, all three studies examining the effects of age have shown that older adults experience increased PFC activation (Agbangla, Audiffren, Pylouster, & Albinet, 2019; Vermeij, Meel-van den Abeelen, Kessels, van Beek, & Claassen, 2014), and more bilateral PFC activation, during the letter *n*-back tasks (Vermeij, van Beek, Rikkert, Claassen, & Kessels, 2012). One study also reported weaker fluctuations in the oscillation of PFC blood flow in older adults across WM load conditions as compared with younger adults (Vermeij, Meel-van den Abeelen et al., 2014). Regarding visuospatial WM, all four studies examining the effect of age have reported different patterns in PFC activation between younger and older adults; the nature of these patterns, however, have been mixed. Specifically, two studies found that older adults had greater PFC activation than younger adults during tasks of spatial WM maintenance and manipulation (Oboshi et al., 2014; Yamanaka et al., 2014), whereas one study found that older adults had less PFC activation than younger adults during a spatial WM task that had large executive function demands (Causse, Chua, & Rémy, 2019). In addition, one study found that older adults had larger right dlPFC activation at low WM load, but smaller right dlPFC activation at high WM load than younger adults, although this pattern was found only when dealing with complex spatial, but not simple visual, material (Wijeakumar, Huppert, Magnotta, Buss, & Spencer, 2017). It was further found that older adults demonstrated a shift in activation from the temporo-occipital cortex to the frontal cortex with increasing spatial WM load. Taken

together, aging is associated with PFC hyperactivation at low WM load or executive demand, but hypoactivation at high WM load or executive demand.

Six studies have examined the relationship between various factors and PFC activity during WM tasks among older adults. These studies have shown that healthy lifestyle factors, including aerobic fitness (Agbangla et al., 2019) and sleep quality (Bu, Wang et al., 2018), WM ability (Vermeij, van Beek, Reijs, Claassen, & Kessels, 2014; Yamanaka et al., 2014), but not prolonged flight experience (Causse et al., 2019), are associated with increased PFC activity or functional connectivity within the PFC, and between the PFC and the motor or occipital cortex, during task performance. Level of anxiety is also associated with greater right-lateralized PFC activation during a verbal WM (i.e., arithmetic) task (Adorni et al., 2019). In addition, there have been a total of five controlled experiments on the effects of time stress (Adorni et al., 2019), docosahexaenoic acid supplementation (Jackson et al., 2016), Greek mountain tea (Wightman et al., 2018), combined WM training and transcranial direct current stimulation (Stephens & Berryhill, 2016), and transcranial magnetic stimulation (Yamanaka et al., 2014) on PFC activity during WM tasks. These studies have in general reported null effects. Specifically, Adorni et al. (2019) found a null effect of stress on PFC activity during a verbal WM task. In addition, both neurostimulation studies reported null findings, which may be attributable to short intervention periods (i.e., $\leq$ 5 days; Stephens & Berryhill, 2016; Yamanaka et al., 2014). Furthermore, supplementation studies showed that while older adults who received one dose of Greek mountain tea had greater PFC activation than those who received placebo treatment during verbal WM and attention tasks (Wightman et al., 2018), there was no difference in PFC activation between older adults who received multiple doses of Greek mountain tea (Wightman et al., 2018) or decosahexaenoic acid (Jackson et al., 2016) and those who received placebo treatment.

One study was on episodic memory in older adults. Instead of examining age-related effects, this study sought to examine the effect of music on verbal encoding in older adults (Ferreri et al., 2014). This study reported lower dlPFC activation during verbal encoding and better verbal recognition in the music condition than in the silent condition, suggesting that music might enhance the efficiency and reduce the effort of verbal memory encoding in older adults.

3.11. Emotion and Motivation (Emotion Perception and Value-Based Decision-Making)

There have been three fNIRS studies on the emotional and motivational aspects of behavior in older adults (see Supplementary Table 10). To date, one study has examined the effects of age with respect to emotion and

motivation, and this study has reported an age-related increase in PFC lateralization during frustration. Specifically, Nakata, Kubo-Kawai, Okanoya, and Kawai (2018) found that older adults exhibited greater left-lateralized prefrontal activation while stopping for red lights than seeing green lights during simulated driving, whereas younger adults did not. Older adults also expressed greater anger than younger adults after repeatedly stopping for red lights. Thus, the age-related increase in the approach motivation of anger when facing driving frustration may be mediated by increased left-lateralized frontal activity. With respect to factors influencing PFC activation during emotion perception in older adults, one study found that the medial frontopolar cortex might be the neural correlate of grandmaternal love (Kida et al., 2014). According to this study, grandmothers experience greater medial frontopolar activation in response to seeing their grandchildren than when seeing someone else's grandchild; this effect is consistent regardless of whether the grandchild is smiling or displays a neutral expression (Kida et al., 2014).

With respect to value-based decision-making, only one study has examined the effect of age on risky decision-making. This study found that older adults were more risk-averse and had more diffuse lateral PFC activation at the time of making decisions, smaller PFC activation in response to wins, and stronger rostrolateral PFC activation in response to losses, than younger adults (Li, Cazzell, Zeng, & Liu, 2017). Because greater PFC activation is correlated with less risk-taking behavior in older adults, specifically in loss cases, the age-related increase in risk aversion might be mediated by increased PFC activity during risk assessment and punishment processing. No studies to date have examined nonage factors in terms of their influence on changes in cerebral oxygenation during value-based decision-making among older adults.

3.12. Risk of Bias and Quality Control Assessment

We conducted risk of bias and quality control assessment for the fNIRS studies reviewed in this article. Table 2 presents the summary of the assessment results, and Supplementary Table 11 shows the assessment results for individual studies. For the summary table, studies spanning more than one domain were counted once when the assessment was conducted across domains. With respect to risk of bias within studies, we found that only 6% of the 114 fNIRS studies have conducted *a priori* power analysis to determine sample size. In addition, we found that 48% of the 48 studies testing more than two regions or channels have applied any correction for multiple channel comparisons. Among the 23 studies that have applied multiple testing corrections, 13 studies used the false discovery rate, four used the Bonferroni–Holm procedure, four used the Bonferroni correction, another four used the Sun's tube formula or expected Euler characteristic methods, and one applied cluster-size corrections.

Among the 64 studies comparing at least two age groups, one-third of the studies have matched the age groups on years of education or adjusted for this variable in the analysis. However, 53% have not reported level of education, and the remaining studies have found an age difference in years of education but have not controlled for this variable in the analysis. In addition, only 19% of the studies comparing different age groups have addressed the age effect on the differential pathlength factor or corrected this factor for age when estimating the levels of hemoglobin concentration.

With respect to risk of bias between studies and quality control, 53% of the fNIRS studies have presented both [oxy-Hb] and [deoxy-Hb], and only 8% of which have found significant results only when [deoxy-Hb] was considered. In addition, 57% of all the studies included in this review have proven normal cognition in each older adult based on the cutoffs of some screening tests for dementia. However, 39% have not reported the use of any screening test; for the rest of the studies, it is unclear whether the older adults were all cognitively normal although screening tests were administered. Among the 65 studies that have proven normal cognition in the elderly sample, the Mini-Mental State Examination was used in most (63%) of the studies. Other screening instruments, including the AD8 (15%), Memory Impairment Screen (14%), and Montreal Cognitive Assessment (12%), were used in only a handful of studies.

Finally, with respect to artifact removal, we found that 74% of the 114 fNIRS studies reviewed have applied any artifact correction. Among these 84 studies, simple filtering methods, including low-pass (n = 25), band-pass (n = 21), moving-average (n = 19), and high-pass (n = 10) filtering were applied in 75% of the studies. In addition, 25% of the studies applied motion corrections, including spline interpolation (n = 8), principal component analysis (n = 6), wavelet filtering (n = 4), correlation-based signal improvement (n = 4), and kurtosis-based wavelet algorithm (n = 1). Also, 21% applied slow drift corrections using various methods other than high-pass filtering, including linear fitting (n = 8), wavelet minimum description length detrending (n = 4), discrete cosine transform-based detrending (n = 3), and other detrending methods (n = 3). Furthermore, 14% removed temporal autocorrelation using precoloring (n = 6), prewhitening (n = 4), or other autocorrelation removal methods (n = 2). Moreover, 14% corrected for systemic changes using the short-distance (n = 8), common average reference corrections (n = 3), or other method (n = 1).

4. Discussion

This article describes a systematic review of 114 published fNIRS articles focused on healthy aging. This review would suggest that aging is associated with changes in the activation and connectivity patterns of the brain, especially the PFC, both in resting and task states. In the resting state, many fNIRS studies have shown that aging is associated with reduced cerebral oxygenation, attenuated blood flow oscillations, and altered functional coupling between brain regions (Amiri et al., 2014; Harada et al., 2007; Tan et al., 2016; Wang et al., 2016). These findings are consistent with PET findings of age-related declines in regional blood flow and glucose metabolism in the frontal lobe (Bentourkia et al., 2000; Kalpouzos et al., 2009). Various mechanisms are thought to underlie these age-related changes in frontal oxygenation and brain networks. First, deteriorated neurovascular coupling, increased vessel stiffness, and impaired myogenic autoregulation may underlie the age-related reduction in cerebral oxygenation and blood flow fluctuations (Fabiani et al., 2014; Farkas & Luiten, 2001). In addition, degraded white matter tracts may underlie disrupted functional connectivity within the PFC, and between the PFC and posterior cortical regions (Head et al., 2004; Salat et al., 2005). Accordingly, increased coupling of the PFC and sensorimotor cortex are thought to reflect the action of other cortical regions compensating for the age-related deterioration in PFC functioning (Huo et al., 2018; Wang et al., 2016).

Regarding sensorimotor functioning, there is a considerable body of fNIRS evidence with which to suggest that aging is associated with hyperactivation of the sensory cortex during active perceptual tasks (Lin et al., 2017; Teo et al., 2018; Ward et al., 2018), while being hypoactivated during passive stimulation tasks (Fabiani et al., 2014; Ward et al., 2015). Hyperactivation in the specialized sensory cortex may reflect the presence of compensatory mechanisms, such as an increased reliance on sensory reweighting, under perceptually challenging conditions. Because no compensatory strategies are available during passive sensory (e.g., visual) stimulation, older adults may exhibit hypoactivation in the corresponding sensory cortex due to impaired neurovascular coupling. Similarly, the fNIRS literature suggests that aging is associated with frontal hyperactivation during simple motor tasks, such as normal-pace walking and handgrip force control (Hawkins et al., 2018; Mehta & Rhee, 2017; Mirelman et al., 2017; Zich et al., 2017), but hypoactivation during complex motor tasks, such as dual-task walking and driving (Beurskens et al., 2014; Harada et al., 2007; Holtzer et al., 2011). Hyperactivation during simple motor tasks may reflect effortful motor control due to age-related declines in various aspects of muscle control necessary for optimal motor performance. Hypoactivation during complex motor tasks, on the other hand, is thought to reflect the failure to recruit the frontal lobe to address the extra cognitive load imposed by the introduction of a secondary task during dual-task walking and the eye-hand coordination, with gross motor movements demanding a considerable load. This would suggest that only cognitively demanding secondary tasks lead to frontal

hypoactivation in older adults (Beurskens et al., 2014), which may explain the inconsistent findings of fNIRS studies with respect to age-related PFC hypoactivation during dual-task walking.

Synthesizing the fNIRS evidence would suggest that age-related frontal hyperactivation is indicative of compensatory activity across multiple cognitive operations, including word retrieval (Heinzel et al., 2013, 2015), task-switching and multitasking (Laguë-Beauvais et al., 2013, 2015), motor inhibition (Huppert et al., 2017), interference control (Kawai et al., 2012), reflexive saccade inhibition (Bierre et al., 2017), WM processing (Agbangla et al., 2019; Oboshi et al., 2014; Vermeij, Meel-van den Abeelen et al., 2014; Yamanaka et al., 2014), and semantic processing (Martin et al., 2018; Scherer et al., 2012; Tsujii et al., 2010). Nevertheless, some studies have reported both frontal hypoactivation and hyperactivation patterns. For example, several studies have reported both age-related vlPFC hypoactivation and dlPFC hyperactivation during verbal fluency and motor inhibition tasks (Heilbronner & Münte, 2013; Heinzel et al., 2013, 2015), as well as age-related lateral PFC hypoactivation and sensorimotor cortex hyperactivation during cognitive set-shifting tasks (Hagen et al., 2014). Some meta-analytic studies and systematic reviews have reported a central role for the left vlPFC in semantic retrieval (Badre & Wagner, 2007; Wagner, Sebastian, Lieb, Tüscher, & Tadić, 2014), the (right) vlPFC in inhibition (Aron, Robins, & Poldrack, 2014), and the lateral PFC in task-switching (Kim, Cilles, Johnson, & Gold, 2012). This would suggest that older adults recruit non-specialized regions to compensate for their functional decline in specialized regions. Altogether, the fNIRS literature is quite consistent with two fMRI meta-analytic studies reporting age-related frontal hyperactivation across multiple cognitive domains (Li et al., 2015; Spreng et al., 2010). In addition, the literature further suggests that aging is associated with reduced activation in task-relevant regions and increased activation in task-irrelevant regions within the PFC, especially during executive function tasks.

The fNIRS findings of age-related increases in PFC compensatory activity across tasks support the three neurocognitive aging theories derived from task-based PET and fMRI studies (Table 3). To this end, while there are a wealth of studies having reported less asymmetric PFC activation during different tasks (e.g., Heinzel et al., 2015; Karim et al., 2013; Teo et al., 2018; Vermeij et al., 2012), studies reporting age-related increases in functional asymmetry are conspicuously absent from the literature. These findings are thus consistent with the Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model, which postulates that older adults exhibit more symmetric PFC activation than younger adults due to the recruitment of the contralateral hemisphere for compensation or because of dedifferentiation (Cabeza, 2002). In addition, two studies have reported age-related PFC hyperactivation at low cognitive load, as well as hypoactivation at high cognitive load (Hawkins et al., 2018;

Wijeakumar et al., 2017). To our knowledge, no studies have reported the opposite pattern. This would provide some support for the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH), which posits that older adults recruit more neural resources than younger adults at lower cognitive loads to compensate for their functional decline, while recruiting fewer neural resources at higher cognitive loads due to the absence of further resources or loss of any performance advantage in deploying additional brain resources (Reuter-Lorenz & Cappell, 2008; Schneider-Garces et al., 2010). In summary, the HAROLD model and CRUNCH are not mutually exclusive, with each capable of explaining a set of findings in different domains. Nevertheless, it should be noted that few fNIRS studies have examined the lateralization of activation or parametrically manipulated cognitive loads, thus limiting the available evidence with which to put these theories to the test.

In addition, two studies have reported an age-related shift in activation from the temporal to the frontal cortex, indicating a posterior-to-anterior shift during WM and semantic tasks (Scherer et al., 2012; Wijeakumar et al., 2017). Conversely, three studies have reported an age-related shift in activation from the lateral PFC to the dorsomedial prefrontal and sensorimotor cortex, indicating an upward or dorsoposterior shift during shifting (Hagen et al., 2014) and verbal fluency tasks (Heinzel et al., 2013, 2015). Thus, at least in non-perceptual domains, there is only limited support for Posterior-Anterior Shift with Aging (PASA) theory, which predicts an age-related shift in brain activity from posterior to anterior regions due to the recruitment of the PFC to maintain cognitive performance when posterior cortical functioning is impaired (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008). In addition, it is noteworthy that four studies have reported an age-related upward shift in frontal activation during cognitive set-shifting (Hagen et al., 2014), word retrieval (Heinzel et al., 2013, 2015), and prepotent motor inhibition (Heilbronner & Münte, 2013). To our knowledge, no studies have reported an age-related downward shift in frontal activation. The age-related upward shift in activation, which is not readily explained by existing theories, might reflect the recruitment of task-irrelevant regions to compensate for the functional decline of task-relevant regions or an attentional shift from contextual control to sensory-motor control during task performance (Badre & Nee, 2018). Further fNIRS studies covering a wider range of brain regions are needed to test the age-related shift in brain activation along the anterior–posterior and dorsal–ventral axes.

Although aging is generally associated with changes in cerebral oxygenation in both the resting and task states, there is considerable variability within the aged population. In particular, healthy lifestyle factors, including aerobic fitness and physical exercise (e.g., Depuy et al., 2015; Fabiani et al., 2014; Hyodo et al., 2016; Suhr & Chelberg, 2013), sleep quality and quantity (Kato et al., 2017), education (Heinzel et al., 2013, 2015), and social

and daily activities (Makizako et al., 2013; Pu et al., 2014) have been shown to be associated with enhanced increases in oxygenation in task-relevant PFC regions and enhanced lateralization of PFC activation across sensory and cognitive tasks. Although these findings are derived from correlational studies, there is a growing body of causal evidence with which to indicate that aerobic exercise promotes angiogenesis, synaptogenesis, and neurogenesis (Hillman, Erickson, & Kramer, 2008), that sleep drives metabolite clearance from the brain (Mendelsohn & Larrick, 2013; Xie et al., 2013), and that prolonged mental stimulation increases blood flow and connectivity in the brain (Chapman et al., 2013). Cardiovascular disease risk factors, on the other hand, including hypertension (Li et al., 2014), diabetes (Suhr & Chelberg, 2013), hyperlipidemia (Kato et al., 2017), polypharmacy (George et al., 2019), and perceived stress and fatigue (Holtzer et al., 2017, 2018), have been shown to be associated with reduced PFC oxygenation changes and connectivity across task states. These factors may exaggerate the disrupted neurovascular coupling, increased vessel stiffness, and impaired myogenic autoregulation that occur in old age and have been shown to be linked with accelerated structural brain aging and cognitive decline (Debette et al., 2011; Farkas & Luiten, 2001; Kivipelto et al., 2001). In summary, the fNIRS literature reveals the protective effects of healthy lifestyles and the detrimental effects of cardiovascular disease risk factors in the brain functioning of older adults.

Our risk of bias and quality control assessment reveals that few fNIRS studies in aging have performed *a priori* power analyses to determine sample size. Many of the studies comparing younger and older adults have recruited less than 26 older adults, which is the sample size required to have enough power (i.e., 0.80) to detect a large age effect (i.e., Cohen's $d = 0.80$), if any. Thus, it is possible that some of the findings reported by these underpowered studies were false-positive errors (Forstmeier et al., 2017). Our findings of the application of multiple testing corrections in only half of the multichannel fNIRS studies also raise the possibility that some of the positive findings reported were due to Type I errors. In addition, our review indicates that no more than one-third of the studies comparing younger and older adults have adequately addressed the potential role of education in brain function (Kelly & Garavan, 2005) or considered the effect of age on the differential pathlength factor (Duncan et al., 1996). These findings suggest that some of the reported age differences in cerebral oxygenation could be due to non-age factors or structural changes with advancing age. Furthermore, we found that only slightly more than half of the studies have reported [deoxy-Hb] in addition to [oxy-Hb]. Because the reporting of [deoxy-Hb] did not change the conclusions drawn in more than 90% of these studies, there is no convincing evidence that fishing for significant results was the reason underlying the reporting of [deoxy-Hb] in those studies. Finally, our review reveals that only nearly 60% of the studies have screened the older adults for cognitive impairment or dementia.

Thus, it is unclear whether the older adults examined in some of the previous studies were representative of the healthy aging population. Considering these limitations, we recommend that future fNIRS studies in healthy aging should carefully address the aforementioned issues to avoid false-positive errors, biases, and misinterpretations.

In addition, there has been a continual improvement in fNIRS data analysis that moves beyond simple filtering (see Scholkmann et al., 2014, for review). Various methods, including spline interpolation (Scholkmann, Spichtig, Muehlemann, & Wolf, 2010) and wavelet filtering (Molavi & Dumont, 2012), have been developed to correct for motion artifacts. Several comparisons of motion correction techniques have shown that wavelet filtering is the most effective method (Brigadoi et al., 2014). In addition, wavelet minimum description length detrending, which has been shown to provide more specific localizations of neural activation than the standard discrete cosine transform-based high-pass filtering, has been developed (Jang et al., 2009). Furthermore, precoloring and prewhitening can be applied to account for serially correlated errors in general linear model-based analyses of fNIRS data, but it remains controversial which of the two methods is better (Huppert, 2016; Ye, Tak, Jang, Jung, & Jang, 2009). Moreover, several methods, such as separation of the observed fNIRS signal into the functional and systemic parts (Yamada et al., 2012) and the common average reference correction (Pfurtscheller, Bauernfeind, Wriessnegger, & Neuper, 2010), have been proposed to reduce the influence of systemic changes on fNIRS signals. Despite these methodological advancements, very few studies in healthy aging have employed or compared the effects of these advanced methods. Given that application of these methods can influence the pattern of age-related changes in cerebral oxygenation during cognitive tasks (Heinzel et al., 2013, 2015), these aspects of methodological changes in data analysis should be considered in future empirical and review studies.

This is the first systematic review of the fNIRS literature with respect to age-related changes in cerebral blood oxygenation in both resting and task states. To this end, this review has shown that fNIRS has been widely applied to the study age-related changes in sensory, motor, and cognitive functions. The growing application of fNIRS in aging research reflects several unique features of fNIRS. First, fNIRS is relatively insensitive to motion artifacts and can be used in a naturalistic environment, making it well-suited for use with sensory, motor, and cognitive tasks, such as postural control, walking, and overt word production—tasks that are not ideal, or are contraindicated, for study by other means. Additionally, fNIRS is a relatively inexpensive and time-efficient technique that is appropriate for use with people who have claustrophobia or metal implants or who are sensitive to noise. As such, fNIRS can be conveniently applied to a large sample (i.e., $n > 165$) to identify factors correlating with better brain

functioning (Heinzel et al., 2015), as well as biomarkers used to predict functional outcomes, such as falls (Verghese, Wang, Ayers, Izzetoglu, & Holtzer, 2017), in older adults.

Nevertheless, we offer a number of suggestions for future aging research using fNIRS. First, future studies that examine the influence of age differences in resting dynamics and brain volume are needed to clarify the specificity and mechanisms underlying age differences in task-evoked activity. In addition, future research that analyzes both local activity and connectivity is needed to provide a more complete picture of the age-related changes in brain functioning. Furthermore, while aging is associated with changes in social, emotional, and motivational behavior (Charles & Carstensen, 2010; Mather & Carstensen, 2005), these aspects have not been adequately studied using fNIRS. Because these behavioral aspects are mediated by the PFC, the activity of which is measurable by fNIRS (Bendall, Eachus, & Thompson, 2016; Cui, Bryant, & Reiss, 2012), future research should evaluate the utility of fNIRS for studying social, emotional, and motivational aging. Specifically, fNIRS-based hyperscanning seems to hold promise for the examination of interacting brains engaged in real social activities, which may help to clarify how naturalistic social interactions appear to exert a protective effect on the aging brain (Seeman, Lusignolo, Albert, & Berkman, 2001). Finally, future fNIRS studies should look to analyze the lateralization of brain activation, parametrically manipulate cognitive load levels, and measure the activity of anterior and posterior brain regions to put all three major neurocognitive aging theories to the test (Table 3). We expect that the utility of whole-head fNIRS systems will facilitate this theoretical advancement.

Although fNIRS is a promising tool to study healthy aging, it has some limitations and potential pitfalls. First, the near-infrared light has a limited depth of penetration. For a source–detector spacing of 3 cm, a continuous-wave fNIRS system, which is used by most task-based studies, can only measure points at a depth of approximately 2 cm from the scalp (Cui et al., 2011). Thus, fNIRS cannot measure activity in deep brain structures, such as the limbic system and subcortical regions, as well as functional coupling between cortical and subcortical regions. In addition, while fNIRS has a relatively high temporal resolution, like fMRI, it relies on the sluggish hemodynamic response with a typical delay of 4–6 seconds (Schroeter et al., 2003). Thus, it is not suitable for capturing dynamic neural events that take place on the order of milliseconds. It is also notable that fNIRS has a poorer spatial resolution than fMRI, and cannot distinguish activity between brain regions that are less than 1 cm apart (Cui et al., 2011). Furthermore, fNIRS measures neural activity without providing anatomical information about the brain regions being studied. Thus, the relationship between age-related changes in brain structure and function cannot be determined solely using this method. Moreover, the signal-to-noise ratio is generally higher in frontal regions

than in other scalp regions because of little hair that can impede optical coupling on the forehead. This difference in signal-to-noise ratio may bias the spatial distribution of age-related changes in cerebral oxygenation.

This review has several limitations. First, gray literature was excluded to ensure high quality of the selected studies, and non-English articles were excluded because of language limitations among the people conducting the research and a lack of translation resources. These exclusions might potentially lead to selection or publication biases. In addition, a qualitative instead of a quantitative synthesis was conducted because of the variability in fNIRS systems and analytic methods used in previous studies. Thus, the exact size of the age effect on fNIRS-measured cerebral oxygenation in the resting and task states remains unclear. Nonetheless, this review shows that the application of fNIRS for the study of healthy aging over the past two decades has enhanced our mechanistic understanding of aging in various ways. First, fNIRS has shown that aging is associated with functional deterioration in terms of reduced resting-state cerebral oxygenation and connectivity in the PFC. Second, fNIRS has confirmed that aging is associated with a reduction in functional hemispheric asymmetry and increased compensatory activity in the frontal lobe across multiple task domains. Third, fNIRS has demonstrated the beneficial effects of healthy lifestyle habits and the detrimental effects of cardiovascular disease risk factors on brain health among nondemented older adults. The growing application of fNIRS to aging research will help to inform neuroscientific models of aging, inspire interventions that might be used to enhance the brain function of older people, and identify biomarkers of aging that can be used to differentiate healthy and pathological aging (Yeung & Chan, in press).

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6. Conflict of Interest

Both authors declare no conflict of interest in the research.

7. References

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Table 1.

Summary of functional near-infrared spectroscopy studies that have examined the effects of age and other factors on brain activity in healthy older adults.

	Age Effect (Old Age > Young Age)		Moderating Factors in Older Adults		Other or Null Findings
	Increased (+)	Decreased (-)	Increased (+)	Decreased (-)	
Resting (Section 3.2) [Frequency intervals (Shiogai et al., 2010): I: 0.6–2.0 Hz (cardiac activity); II: 0.145–0.6 Hz (respiratory activity); III: 0.052–0.145 Hz (myogenic activity); IV: 0.021–0.052 Hz (neurogenic activity); and V: 0.0095–0.021 Hz (endothelial metabolic activity)]	**Sitting, standing, and lying** Connectivity between the prefrontal and sensorimotor cortex in intervals I, II, IV, and V (Wang et al., 2016) Coherence between left PFC activity and arterial blood pressure in intervals I and IV (Cui et al., 2014) Clustering coefficient and characteristic path length (Li et al., 2018) Complexity of the vasogenic component of PFC activity (Mukli et al., 2018) **Postural change** Connectivity from the motor to frontal or occipital cortex in interval I (Huo et al., 2018) Connectivity between the prefrontal and motor cortex in interval IV (Wang et al., 2016)	**Sitting, standing, and lying** PFC activity especially in intervals I, III, and V (Amiri et al., 2014; Hallacoglu et al., 2012; Harada et al., 2007; Li et al., 2013; Tan et al., 2016) Frontal or occipital blood flow oscillations in interval III (Schroeter et al., 2004; Zeller et al., 2019) Connectivity between the left and right PFC in intervals I, II, and III (Huo et al., 2018; Tan et al., 2016; Wang et al., 2016) Connectivity between the prefrontal and sensorimotor cortex in interval III (Wang et al., 2016) Coherence between left PFC activity and arterial blood pressure in interval V (Cui et al., 2014)	**Sitting, standing, and lying** PFC activity in intervals I and II: hypertension with increased arterial flow velocity (Li, Zhang, Xin, Luo, Zhou et al., 2013) Connectivity between the left and right PFC and between the prefrontal and motor cortex in interval IV: better sleep quality (Bu, Wang et al., 2018) Frontal oxygen saturation: weekly physical exercise (Suhr & Chelberg, 2013) Variability in functional connectivity among frontal and sensorimotor regions: obesity (Rhee & Mehta, 2018) Right lateralization of PFC activity: state anxiety (Ishikawa et al., 2014)	**Sitting, standing, and lying** PFC and occipital activity in interval IV: better sleep quality (Bu, Wang et al., 2018) PFC activity: increased arterial flow velocity (Li et al., 2012) and hypertension (Li et al., 2014) Connectivity between the left and right PFC in interval III: hypertension with increased arterial flow velocity (Li et al., 2014) Connectivity among prefrontal, motor, and occipital regions in intervals III and IV: hypertension (Bu, Huo et al., 2018)	**Resting under hypoxia** Frontal cerebral blood volume: acceptable to good correlations between measurements obtained at least two weeks apart (Claassen et al., 2006) **Postural change** PFC activity: comparable between two sessions at the group level despite an intraindividual day-to-day variability (Mehagnoul-Schipper et al., 2001) **Sitting and standing** Relationship between the right

	Coherence between left PFC activity and arterial blood pressure in interval II (Gao et al., 2015)	Normalized clustering and global efficiency (Li et al., 2018) Complexity of the neurogenic component of PFC activity (Mukli et al., 2018) **Postural change** Connectivity from the frontal or occipital to motor cortex in interval I (Huo et al., 2018)		Frontal oxygen saturation: diabetes (Suhr & Chelberg, 2013)	lateralization of PFC activity and level of state anxiety: no age-related difference (Ishikawa et al., 2014)
Sensation and perception (Section 3.3)	**Motion coherence perception** Bilateral parieto-occipital activity at high motion speed (Ward et al., 2018) **Dynamic balance during an auditory vigilance task** Left lateral frontal and superior temporal activity (Rosso et al., 2017) **Dynamic balance in the absence of congruent visual or somatosensory feedback** Lateral frontal and temporal-parietal activity (Lin et al., 2017; Teo et al., 2018) **Vestibulo-ocular reflex**	**Fast checkerboard (> 1.8-Hz) stimulation** Occipital activity (Fabiani et al., 2014; Ward et al., 2015) **Melodic contour identification** PFC activity while paying selective attention to melodic contours (Jeong & Ryu, 2016)	**Visual stimulation** Occipital activity: aerobic fitness (Fabiani et al., 2014)	N/A	**Slow checkerboard (< 1.8-Hz) stimulation** Occipital activity; null age effect (Schroeter et al., 2004) **Tandem standing during backward counting** Left dlPFC activity: null age effect (Marusic et al., 2019)

	Left frontotemporal and parietal cortex activity (Karim et al., 2013)					
Gross motor skills (Section 3.4)	**Typical walking with or without rhythmic cueing** PFC activity (Hawkins et al., 2018; Mirelman et al., 2017; Vitorio et al., 2018) **Dual-task walking during backward counting** PFC activity (Mirelman et al., 2017) **Obstacle negotiation** PFC activity, especially during the initial task period (Hawkins et al., 2018; Mirelman et al., 2017) **Target stationary cycling** Premotor cortex and supplementary motor area activity (Lin et al., 2012).	**Dual-task walking during alphabet recitation or digit vigilance tasks** PFC (Hawkins et al., 2018; Holtzer et al., 2011) and left supplementary motor area (Stuart et al., 2019) activity **Dual-task walking during a visual attention task** PFC activity (Beurskens et al., 2014) **Cycling with increasing exercise intensities** Right PFC activity (Lucas et al., 2012) **Actual driving** Right PFC activity (Harada et al., 2007)	**Typical walking** PFC, premotor cortex, and supplementary motor area activity: rhythmic auditory cueing (Vitorio et al., 2018) **Dual-task walking during alphabet recitation** PFC activity (over time): reduced frontal gray matter (Wagshul et al., 2019), degraded whole-brain white matter tracts (Lucas et al., 2012), and fear of falling (Holtzer et al., 2019) **Brisk walking and obstacle crossing** (Left) PFC activity: low gait capacity (Harada et al., 2009), slow gait (Chen et al., 2017), and large gait variability (Mirelman et al., 2017) **Precision walking**	**Typical and brisk walking** (Left) PFC activity: dancing training (Eggenberger et al., 2016) and enhanced somatosensory feedback (Clark, Christou et al., 2014) **Dual-task walking while performing alphabet recitation** PFC activity: polypharmacy (George et al., 2019), diabetes (Holtzer, George et al., 2018), perceived stress (for males only; Holtzer et al., 2017a), and subjective fatigue (Holtzer et al., 2017b) **Simulated driving** Bilateral PFC activity: video game gameplay (Knols et al., 2017)	**Dual-task walking while performing the auditory *n*-back or the letter fluency task** PFC activity: null age effect (Fraser et al., 2016; Hawkins et al., 2018) **Dual-task walking while performing alphabet recitation** Left PFC activity: predictability of future falls (Verghese et al., 2017) ***S*elf-paced cycling** Premotor cortex and supplementary motor area activity: null age effect (Lin et al., 2012) **Cycling at an increasing intensity**

			PFC activity: obesity (Osofundiya et al., 2016)		PFC activity: null effects of aerobic fitness and obesity (Gayda et al., 2017)
Fine motor skills (Section 3.5)	**Handgrip force control** PFC activity (Mehta & Rhee, 2017) **Motor imagery** Ipsilateral motor cortex activity (Zich et al., 2017)	**Right finger tapping** Left motor cortex activity (Mehagnoul-Schipper et al., 2002) **Mastication** PFC activity (Kamiya et al., 2016)	**Mastication** Bilateral PFC (Kamiya et al., 2016; Narita et al., 2009) and temporal cortex activity (Miyamoto et al., 2005): chewing or clenching with a dental prosthesis	**Handgrip force control** Bilateral PFC activity: cognitive fatigue (Shortz et al., 2015) Connectivity between the right lateral motor area and bilateral medial motor areas during fatigue: obesity (Rhee & Mehta, 2018)	**Hand and finger movements** Sensorimotor activity: null age effect on neurofeedback (Zich et al., 2017); PFC activity: null effect of acute social stress (Mehta & Rhee, 2017)
Semantic processing (Section 3.6)	**Discourse comprehension** Left PFC activity during micropropositional, macropropositional, and situational processing (Martin et al., 2018) Frontal lobe activity relative to temporal lobe activity during micropropositoinal and macropropositional processing (Scherer et al., 2012) **Lexical-semantic decision-making** Bilateral dlPFC and vlPFC and right posterior middle temporal and	N/A	N/A	N/A	N/A

	occipitotemporal activity (Amiri et al., 2014)				
	Syllogistic reasoning				
	Left vlPFC activity (Tsujii et al., 2010)				
Word retrieval (Section 3.7)	**Phonemic fluency**	**Phonemic and semantic fluency combined**	**Phonemic fluency**	**Phonemic fluency**	**Phonemic fluency**
	Right dlPFC and bilateral inferior parietal cortex activity (Heinzel et al., 2013, 2015)	Frontotemporal activity (Heinzel et al., 2013, 2015)	Rate to reach peak [oxy-Hb]: current smoking habit and sleep duration (Kato et al., 2017)	Left vlPFC activity: hypertension (Heinzel et al., 2015)	PFC activity: null effect of hypertension (Kato et al., 2017)
	Semantic fluency	Left-lateralization in the lateral PFC (Heinzel et al., 2013, 2015; Herrmann et al., 2006)	(Left ventrolateral) PFC activity: sleep duration (Kato et al., 2017), years of education (Heinzel et al., 2013), social functioning (Pu et al., 2014) and going outdoors daily (Makizako et al., 2013)	Right dlPFC activity: years of education (Heinzel et al., 2013, 2015)	
	Bilateral motor cortex activity (Heinzel et al., 2013, 2015)	**Phonemic fluency**	**Semantic fluency**	Rate of increase in PFC activity: hyperlipidemia (Kato et al., 2017)	
		PFC (Kahlaoui et al., 2012), frontotemporal (Herrmann et al., 2006), and anterosuperior frontal cortex activity (Obayashi & Hara, 2013)	Left dlPFC activity: *Apolipoprotein*-E4 allele (Katzorke et al., 2017)	**Semantic fluency**	
		Semantic fluency		Right vlPFC activity: *Apolipoprotein*-E4 allele (Katzorke et al., 2017)	
		PFC activity (Kahlaoui et al., 2012)		Right dlPFC activity: years of education (Heinzel et al., 2013, 2015)	

Attentional shifting (Section 3.8)	**Task-switching and dual-tasking not involving psychomotor sequencing** Area of dlPFC activation (Laguë-Beauvais et al., 2013, 2015) **Task-switching involving psychomotor sequencing** Left dorsomedial PFC (Müller et al., 2014) and bilateral somatosensory and primary motor cortex activity (Hagen et al., 2014)	**Task-switching and dual-tasking not involving psychomotor sequencing** Left premotor cortex (Vasta et al., 2018) and right superior frontal cortex activity (Huppert et al., 2017) Asymmetry of lateral PFC activation (Laguë-Beauvais et al., 2015; Müller et al., 2014) **Task-switching involving psychomotor sequencing** Bilateral vlPFC and right dlPFC activity (Hagen et al., 2014)	**Task-switching and dual-tasking not involving psychomotor sequencing** Right vlPFC or dlPFC activity: aerobic fitness (Albinet et al., 2014; Dupuy et al., 2015), glucose ingestion (Gagnon et al., 2012)	N/A	**Task-switching not involving psychomotor sequencing** PFC activity; null age effect in females (Dupuy et al., 2015) **Dual-tasking involving upper or lower limb movement** PFC activity: null age effect (Corp et al., 2018; Ohsugi et al., 2013)
Inhibition (Section 3.9)	**Motor inhibition (measured primarily by tasks with an event-related design)** Right dlPFC (Heilbronner & Münte, 2013) and right superior frontal cortex activity (Huppert et al., 2017) **Reflexive saccade inhibition with little practice** PFC activity (Bierre et al., 2017) **Interference control**	**Motor inhibition (measured primarily by tasks with an event-related design)** Left vlPFC and right posterior vlPFC activity (Heilbronner & Münte, 2013; also see Laguë-Beauvais et al., 2013) and lateral PFC activity (Schroeter et al., 2003)	**Motor inhibition** Right vlPFC and frontopolar cortex activity: aerobic fitness (Dupuy et al., 2015) and acute aerobic exercise (Hyodo et al., 2012) Left-lateralization in the dlPFC: aerobic fitness (Hyodo et al., 2016) **Interference control** (Left) PFC activity: a history of falls (Halliday et al., 2018), poor	N/A	**Motor Inhibition (measured by tasks with a blocked design)** (Right) PFC activity: null age effect (Dupuy et al., 2015; Lucas et al., 2012) **Reflexive saccade inhibition with much practice** PFC activity: null age effect (Fujiwara et al., 2010)

	Left PFC and bilateral superior frontal cortex activity (Kawai et al., 2012)		inhibition ability (Halliday et al., 2017)		
Memory (Section 3.10)	**Verbal WM** PFC activity (Agbangla et al., 2019; Vermeij, Meel-van den Abeelen et al., 2014) **Visuospatial WM** PFC activity during spatial WM maintenance and manipulation (Oboshi et al., 2014; Yamanaka et al., 2014) Right middle frontal activity at low spatial WM load, posterior temporal and inferior parietal activity at low visual and spatial WM loads, and temporo-occipital activity at high spatial WM load (Wijeakumar et al., 2017)	**Verbal WM** Low-frequency (0.07–0.2 Hz) and high-frequency (0.2–0.35 Hz) PFC blood flow oscillations (Vermeij, Meel-van den Abeelen et al., 2014) Asymmetry of PFC activity and increase in PFC activity over time (Vermeij et al., 2012) **Visuospatial WM** PFC activity during the pretask period of a spatial WM manipulation task (Oboshi et al., 2014) Left PFC activity during a spatial WM monitoring task (Causse et al., 2019) Temporo-occipital activity at high visual WM load (Wijeakumar et al., 2017)	**Verbal WM** Left or bilateral PFC activity: aerobic fitness (Agbangla et al., 2019) and one dose of Greek mountain tea (Wightman et al., 2018) Right lateralization of PFC activity: anxiety (Adorni et al., 2019) **Spatial WM** Right PFC activity: WM ability (Vermeij et al., 2014; Yamanaka et al., 2014) Right-lateralization in the PFC: WM ability (Vermeij et al., 2014)	**Verbal WM** Functional connectivity of slow blood flow oscillations (0.01–0.08 Hz) between the left and right PFC and between the frontal and motor or occipital cortex (Bu, Wang et al., 2018) **Verbal episodic memory** Bilateral dlPFC activity: music background during verbal encoding (Ferreri et al., 2014)	**Verbal WM** PFC activity: null effects of time stress (Adorni et al., 2019) and multiple doses of DHA supplementation (Jackson et al., 2006) and Greek mountain tea (Wightman et al., 2018) **Visuospatial WM** PFC activity: null effects of WM training paired with right frontal transcranial direct current stimulation (Stephens & Berryhill, 2016) and unilateral parietal transcranial magnetic stimulation (Yamanaka et al., 2014)
Emotion and motivation (Section 3.11)	**Simulated driving**	**Risky decision-making**	**Emotion perception**	N/A	N/A

Left lateralization in the PFC while repeatedly stopping for red lights (Nakata et al., 2018)	PFC activity in face of wins (Li et al., 2017)	Medial frontopolar cortex activity: grandmaternal love (Kida et al., 2014)
Risky decision-making		
Bilateral dorsolateral and rostrolateral PFC activity at the time of choice and in face of losses (Li et al., 2017)		

Note. dlPFC = dorsolateral prefrontal cortex; PFC = prefrontal cortex; vlPFC = ventrolateral prefrontal cortex; WM = working memory.

Table 2.

Summary of risk of bias and quality control assessment.

	***A Priori* Power Analysis Conducted**	**Correction for Multiple Channel Comparisons Applied**	**Years of Education Matched or Controlled for**	**Differential Pathlength Factor Addressed or Corrected for Age**	**Reporting of Both [oxy-Hb] and [deoxy-Hb]**	**Significant Results Only when Considering [deoxy-Hb]**	**Screening Test for Dementia Given**	**Artifact Correction Performed**
All studies	7/114 (6%)	23/48 (48%)	21/64 (33%)	12/64 (19%)	60/114 (53%)	5/60 (8%)	65/114 (57%)	84/114 (74%)
Resting	0/23 (0%)	2/6 (33%)	1/14 (7%)	1/14 (7%)	10/23 (43%)	0/10 (0%)	3/23 (13%)	14/23 (61%)
Sensation and perception	0/10 (0%)	1/2 (50%)	4/10 (40%)	2/10 (20%)	8/10 (80%)	0/8 (0%)	4/10 (40%)	8/10 (80%)
Gross motor skills	3/28 (11%)	2/9 (22%)	3/10 (30%)	1/10 (10%)	10/28 (36%)	0/10 (0%)	20/28 (71%)	19/28 (68%)
Fine motor skills	1/8 (13%)	2/2 (100%)	0/4 (0%)	1/4 (25%)	3/8 (38%)	1/3 (33%)	1/8 (13%)	6/8 (75%)
Semantic processing	0/4 (0%)	2/3 (67%)	4/4 (100%)	0/4 (0%)	4/4 (100%)	0/4 (0%)	3/4 (75%)	2/4 (50%)
Word retrieval	0/9 (0%)	4/5 (80%)	1/3 (33%)	0/3 (0%)	5/9 (56%)	1/5 (20%)	5/9 (56%)	8/9 (89%)
Attentional shifting	1/11 (9%)	4/8 (50%)	5/8 (63%)	3/8 (38%)	8/11 (73%)	2/8 (25%)	10/11 (91%)	10/11 (91%)
Inhibitory control	1/13 (8%)	5/10 (50%)	4/8 (50%)	3/8 (38%)	9/13 (69%)	1/9 (11%)	9/13 (69%)	8/13 (62%)
Memory	2/14 (14%)	2/6 (33%)	2/7 (29%)	3/7 (43%)	8/14 (57%)	0/8 (0%)	11/14 (79%)	12/14 (86%)
Emotion and motivation	0/3 (0%)	2/2 (100%)	0/2 (0%)	0/2 (0%)	1/3 (33%)	0/1 (0%)	3/3 (100%)	2/3 (67%)

Note. The number of studies passing an assessment item (numerator) and the number of studies being evaluated for the item (denominator) are presented for each domain. The percentage of studies passing each assessment item is shown in parenthesis.

Table 3.

Comparison of functional near-infrared spectroscopy (fNIRS) findings with the three neurocognitive aging theories derived from task-based positron emission tomography and functional magnetic resonance imaging studies.

	Hemispheric Asymmetry Reduction in Older Adults (HAROLD)	Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH)	Posterior-Anterior Shift with Aging (PASA)
Reference	Cabeza (2002)	Reuter-Lorenz and Cappell (2008) and Schneider-Garces et al. (2010)	Davis et al. (2008)
Prediction for brain activity	A reduction in functional hemispheric asymmetry in the frontal lobe	Hyperactivation at low cognitive load but hypoactivation at high cognitive load, and hyperactivation in task-irrelevant regions but hypoactivation in task-relevant regions	A shift in activation from posterior to anterior regions
fNIRS requirement for putting the theory to the test	Measurement of activity in bilateral regions and examination of the lateralization of activation	Parametric manipulation of cognitive load and measurement of activity in task-relevant and task-irrelevant regions	Measurement of activity in anterior and posterior regions
Supportive fNIRS evidence	Caloric stimulation (Karim et al., 2013), postural control (Teo et al., 2018), motor imagery (Zich et al., 2017), syllogistic reasoning (Tsujii et al., 2010), word retrieval (Heinzel et al., 2013, 2015; Hermann et al., 2006), task-switching (Laguë-Beauvais et al., 2015), and verbal WM processing (Vermeij et al., 2012)	Walking (Hawkins et al., 2018) and spatial WM processing (Wijeakumar et al., 2017)	Discourse comprehension (Scherer et al., 2012) and visuospatial working memory processing (Wijeakumar et al., 2017)
Contradictory fNIRS evidence	N/A	N/A	Cognitive set-shifting (Hagen et al., 2014) and word retrieval (Heinzel et al., 2013, 2015)

Figure Legends

Figure 1. Flow of the literature search and study selection process for this systematic review.

Figure 2. (a) The number and (b) cumulative number of functional near-infrared spectroscopy articles published in the domain of healthy aging every year. There were ten articles published between January and May 2019 (not shown).

Figure 3. The total number of functional near-infrared spectroscopy articles published in the domain of healthy aging according to individual domains. In each domain, the total number of articles that examined the effects of only age, both age and non-age factors, and non-age factors only is represented by black, gray, and white, respectively.

Figure 1.

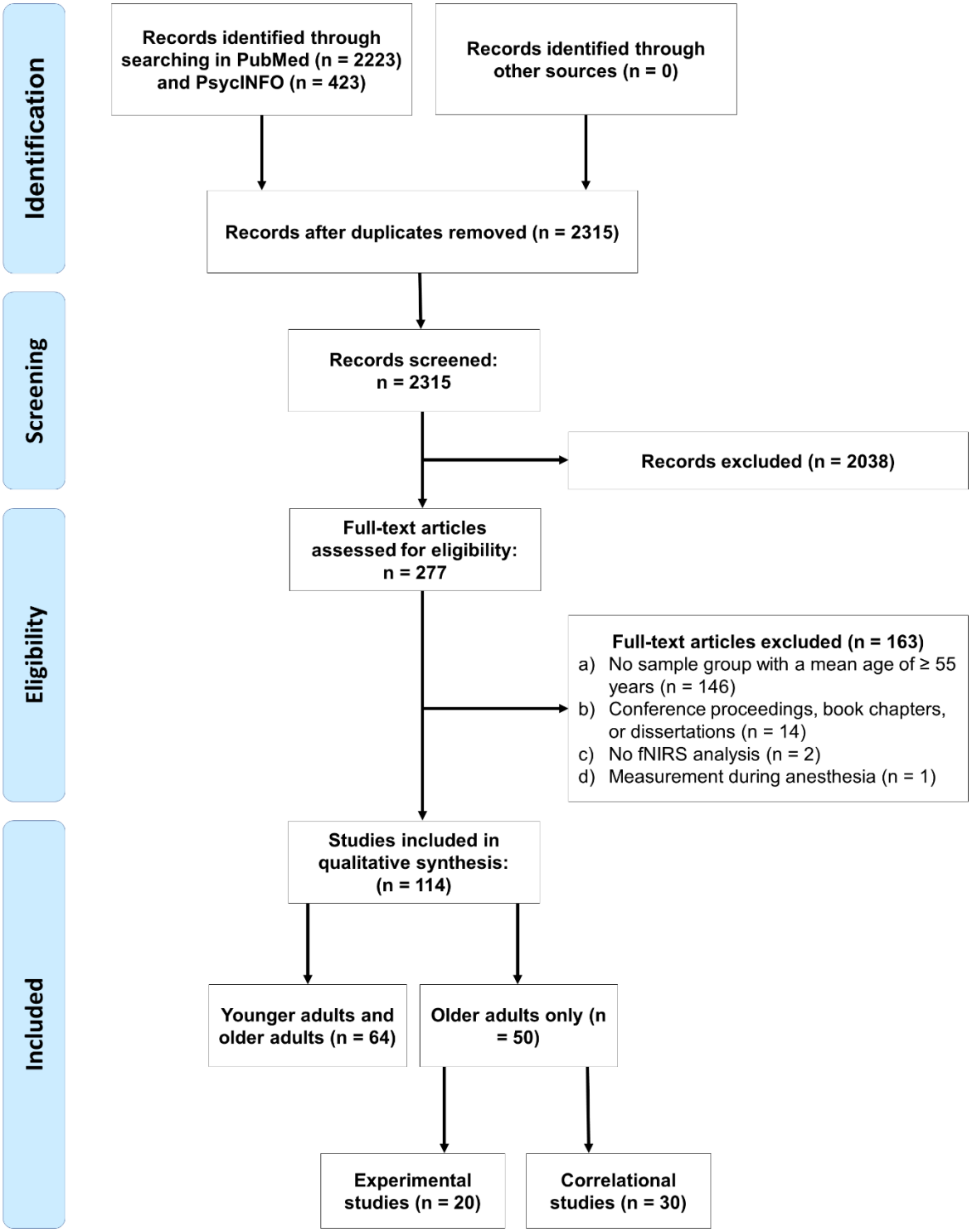
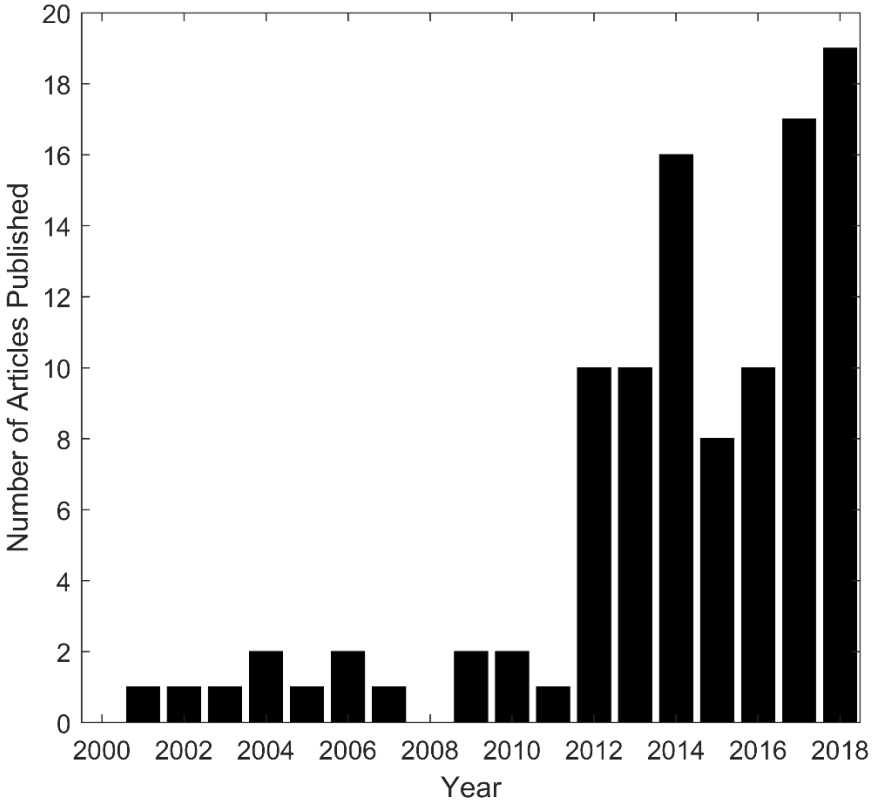

Identification
Screening
Eligibility
Included
Records identified through searching in PubMed (n = 2223) and PsycINFO (n = 423)
Records identified through other sources (n = 0)
Records after duplicates removed (n = 2315)
Records screened: n = 2315
Records excluded (n = 2038)
Full-text articles assessed for eligibility: n = 277
Full-text articles excluded (n = 163)
a) No sample group with a mean age of ≥ 55 years (n = 146)
b) Conference proceedings, book chapters, or dissertations (n = 14)
c) No fNIRS analysis (n = 2)
d) Measurement during anesthesia (n = 1)
Studies included in qualitative synthesis: (n = 114)
Younger adults and older adults (n = 64)
Older adults only (n = 50)
Experimental studies (n = 20)
Correlational studies (n = 30)

Figure 2.

(a)


Number of Articles Published
Year
0
2
4
6
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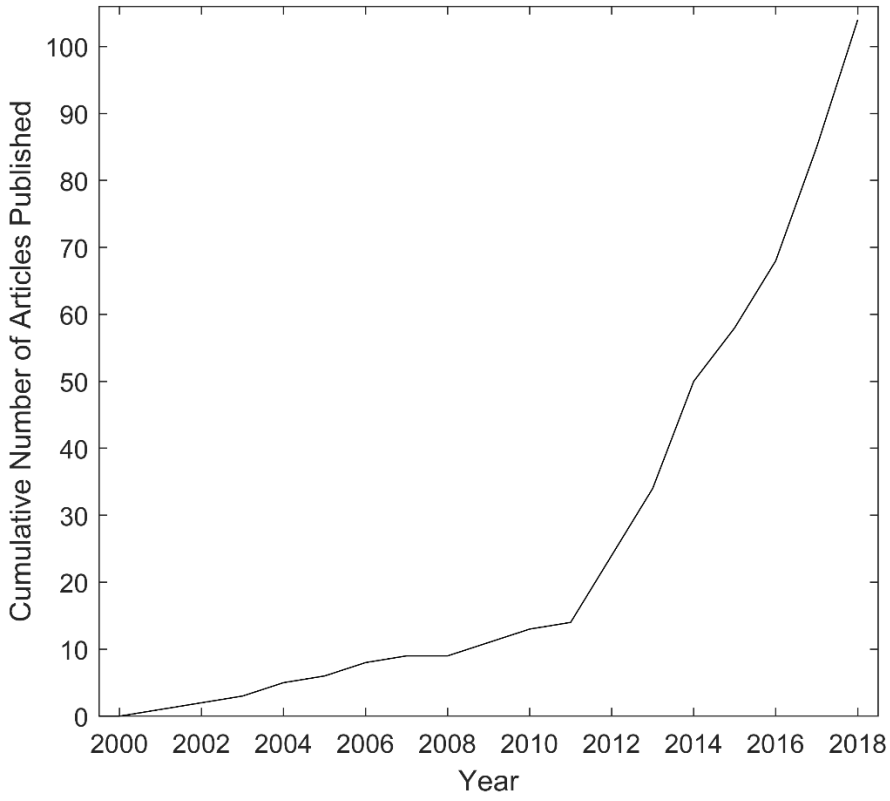
(b)


Cumulative Number of Articles Published
Year
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20
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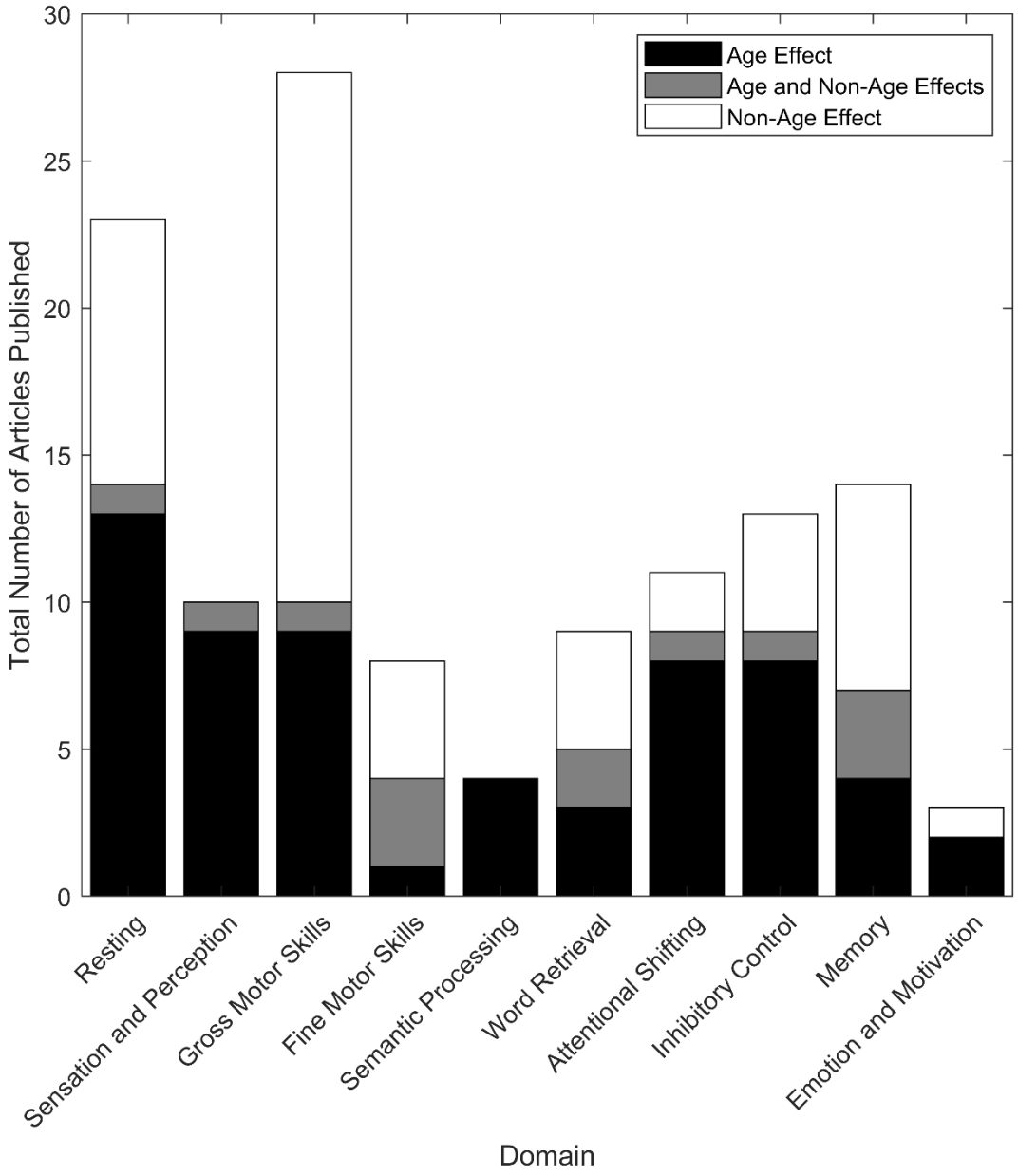
Figure 3.


Age Effect
Age and Non-Age Effects
Non-Age Effect
Total Number of Articles Published
0
5
10
15
20
25
30
Resting
Sensation and Perception
Gross Motor Skills
Fine Motor Skills
Semantic Processing
Word Retrieval
Attentional Shifting
Inhibitory Control
Memory
Emotion and Motivation
Domain

Supplementary Tables 1-11

Supplementary Table 1. A summary of functional near-infrared spectroscopy (fNIRS) studies on resting (i.e., sitting, standing, lying, and postural change) in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Tasks	fNIRS Findings
Mehagnoul-Schipper, Colier, and Jansen	2001	Reproducibility of the effect of posture change on PFC oxygenation among older adults	Old: *n* = 27 (12M, 15F); *M* = 75, *SD* = 7.6, range: 70–84	5.5-cm separation; 1 Hz; 1 right frontal channel (OXYMON, University Medical Centre, Nijmegen, the Netherlands)	Resting (lying in a supine position for at least 10 min and then standing for 10 min; repeated measurement after at least two days)	There were no differences in the group-averaged changes in [oxy-Hb], [deoxy-Hb], and [total-Hb] between the two sessions. The postural changes in blood pressure and each of the three fNIRS signals showed an intraindividual day-to-day variability (i.e., reliability coefficients were nonsignificant).
Schroeter, Schmiedel, and von Cramon	2004	Young v.s. Old	Young: *n* = 14 (7M, 7F); *M* = 23.9; *SD* = 3.1, range: 19–29 Old: *n* = 14 (7M, 7F); *M* = 65.3, *SD* = 2.9, range: 62–71	4- or 5-cm separation; 6 Hz; 2 bilateral occipital channels (NIRO-300 spectrometer; Hamamatsu Photonics K.K., Hamamatsu, Japan)	Resting with eyes closed (6 min)	Older adults had a lower mean power spectral density of low-frequency (0.07–0.11 Hz) oscillations of [oxy-Hb] and [deoxy-Hb] than younger adults at rest. There were no significant group differences in the mean power spectral density of very-low-frequency (0.01–0.05 Hz) oscillations.
Claassen, Colier, and Jansen	2006	Reproducibility of the effect of hypoxia on cerebral oxygenation among older adults	Old: *n* = 16 (12M, 4F); *M* = 73, range: 68–87	5.5-cm separation; 1 frontal and 1 parietal channels; Oxymon, Artinis Medical Systems, The Netherlands)	Breathing through a face mask (two desaturation periods with a normoxic interval of 1 min per block; three measurements)	There was no significant difference in cerebral blood flow between the first and last set of measurements. Correlations between the three cerebral blood volume values were good ($r > 0.8$). Correlation between cerebral blood volume values obtained on different days with an interval of two or more weeks was acceptable ($r = 0.5$).
Harada, Nashihara, Morozumi, Ota, and Hatakeyama	2007	Young v.s. Old	Male younger adults: *n* = 14; *M* = 21.6, *SD* = 0.8 Male older adults: *n* = 7; *M* = 69.9, *SD* = 4.9 Female older adults: *n* = 7; *M* = 66.6, *SD* = 6.0	4-cm separation; 2 bilateral forehead channels (TRS, Hamamatsu Photonics K.K., Japan)	Resting	Older adults (*n* = 14) had lower levels of right frontal [oxy-Hb], [deoxy-Hb], and [total-Hb] than younger adults at rest, with no differences between male and female older adults.

Hallacoglu et al.	2012	Young v.s. Old	Young: *n* = 19 (13M, 6F); *M* = 28, *SD* = 4, range: 21–34 Old: *n* = 36 (10M, 26F); *M* = 85, *SD* = 6, range: 70–96	2- to 3.5-cm (session 1) or 0.8- to 3.8-cm (sessions 2 and 3) separation; 2 bilateral forehead channels (for older adults) and 1 left forehead channel (for younger adults) (ISS Inc., Champaign, Illinois)	Resting	Among older adults, the cross-correlation coefficients of [oxy-Hb], [deoxy-Hb], and [total-Hb] measured during two sessions that were 5 months apart were ≥ 0.8. Older adults exhibited lower resting [oxy-Hb], [deoxy-Hb], and [total-Hb] than younger adults, regardless of source-detector distances (i.e., 2.0–3.5 cm in session 1 and 2.3–3.3 cm in sessions 2 and 3)
Li et al.	2012	Role of risk for atherosclerotic stroke in spontaneous cerebral oscillations in older adults	Older adults without increased arterial flow velocity: *n* = 20 (14M, 6F); *M* = 59.6, *SD* = 10.2 Older adults with increased flow velocity: *n* = 12 (10M, 2F); *M* = 60.2, *SD* = 10.1	3- and 4-cm separation; 10 Hz; 1 left forehead channel (TAH-100; Tsinghua University, China)	Sitting with eyes open (10 min)	Older adults with increased middle cerebral arterial flow velocity had lower amplitudes of frontal [oxy-Hb], [deoxy-Hb], and [total-Hb] across frequencies (i.e., 0.005–2.0 Hz) than older adults without increased arterial flow velocity.
Li, Zhang, Xin, Luo, Cui et al.	2013	Young v.s. Old	Young: *n* = 20 (16M, 4F); *M* = 27.3, *SD* = 7.1 Old: *n* = 15 (11M, 4F); *M* = 70.8, *SD* = 5.1	3- and 4-cm separation; 20 Hz; 1 left forehead channel (TAH-100; Tsinghua University, China)	Sitting with eyes open (10 min)	Older adults had lower amplitudes of [oxy-Hb], [deoxy-Hb], and [total-Hb] than younger adults across multiple frequencies (i.e., 0.005–2.0 Hz).
Li, Zhang, Xin, Luo, Zhou et al.	2013	Role of hypertension in cerebral oxygenation oscillations in older adults	Normotensive older adults: *n* = 20 (14M, 6F); *M* = 70.8, *SD* = 5.2 Hypertensive older adults with increased arterial flow velocity: *n* = 10 (6M, 4F); *M* = 72.8, *SD* = 6.9 Hypertensive older adults without increased arterial flow velocity: *n* = 12	3- and 4-cm separation; 20 Hz; 1 left forehead channel (TAH-100; Tsinghua University, China)	Sitting with eyes open (10 min)	Hypertensive older adults with increased arterial flow velocity had higher amplitudes of [oxy-Hb], [deoxy-Hb], and [total-Hb] in the 0.005–0.15 Hz than normotensive older adults and hypertensive older adults without increased flow velocity (except for [oxy-Hb] in the 0.15–0.4 interval).

			(7M, 5F); *M* = 72.2, *SD* = 5.6			
Suhr and Chelberg	2013	Role of cardiovascular health factors in baseline dorsolateral PFC oxygenation in older adults	Old: *n* = 22 (5M, 17F); *M* = 68.3, *SD* = 8.4, range: 54–89	3- and 4-cm separation; 15 Hz; 2 bilateral dorsolateral prefrontal channels (INVOS 5100 Cerebral Oximeter; Somanetics Corporation, Troy, MI, USA)	Resting (90 s)	The amount of weekly physical exercise correlated with higher resting regional oxygen saturation in the bilateral dorsolateral prefrontal region and with better verbal recall performance, while the presence of diabetes was associated with lower regional oxygen saturation and poorer memory performance. Higher regional oxygen saturation correlated with better verbal recall but not executive functioning.
Amiri et al.	2014	Young v.s. Old	Young: *n* = 23 (8M, 15F); *M* = 23.4, *SD* = 2.7, range: 20–35 Old: *n* = 23 (8M, 15F); *M* = 69.6, *SD* = 4.1, range: 65–75	Device 1: 25 Hz; 58 bilateral frontotemporal channels (TechEn CW6) Device 2: 10-, 15-, 25-, and 30- mm separation; 4 forehead channels	Resting	Older adults had reduced resting [oxy-Hb] and oxygen saturation in bilateral PFC than younger adults. Anatomical magnetic resonance imaging and arterial spin label data also revealed lower resting blood flow in both frontal and temporal lobes than younger adults.
Cui et al.	2014	Young v.s. Old	Young: *n* = 27 (20M, 7F); *M* = 25.2, *SD* = 3.7 Old: *n* = 33 (26M, 7F); *M* = 70.7, *SD* = 7.9	3- and 4-cm separation; 20 Hz; 1 left forehead channel (TAH-100; Tsinghua University, China)	Sitting (15 min)	Older adults had a higher wavelet coherence of [oxy-Hb] and arterial blood pressure measured by a transducer attached to the wrist in 0.4–2 Hz interval but lower wavelet coherence in the 0.0095–0.02 interval than younger adults. Older adults had a higher wavelet phase coherence than younger adults in the 0.02–0.05 Hz interval.
Ishikawa et al.	2014	Young v.s. Old; Role of anxiety in resting-state hemodynamics in older adults	Young: *n* = 19 (6M, 13F); range: 20–24 Old: *n* = 20 (4M, 16F); range: 60–79	3-cm separation; 61.3 Hz; 2 bilateral forehead channels (Pocket NIRS, Hamamatsu Photonics K. K., Japan)	Sitting (3 min)	There was a positive correlation between the right lateralization of [oxy-Hb] changes and the level of state but not trait anxiety in both younger and older adults. There was no age difference in the correlation between lateralization and anxiety.
Li et al.	2014	Role of hypertension in resting-state functional connectivity in older adults	Older adults without hypertension: *n* = 24; *M* = 70.7, *SD* = 8.4 Older adults with hypertension: *n* = 26; *M* = 70.6, *SD* = 7.9	3-cm (near; 2 channels) and 4-cm (far; 2 channels) separation; 20 Hz; 4 bilateral forehead channels	Sitting (15 min)	Older adults with hypertension: lower average wavelet amplitude and phase coherences of differential [oxy-Hb] between the left and right PFC in the 0.05–0.15 Hz interval than older adults without hypertension.

				(TSAH-100; Tsinghua University, China)		
Gao et al.	2015	Young v.s. Old	Young: *n* = 19 (13M, 6F); *M* = 24.9, *SD* = 3.2 Old: *n* = 16 (10M, 6F); *M* = 68.9, *SD* = 7.1	3- and 4-cm separation; 20 Hz; 1 left forehead channel (TAH-100; Tsinghua University, China)	Sitting (15 min), followed by standing (15 min), and sitting again (15 min)	Older adults had a lower wavelet phase coherence than younger adults in the 0.05–0.15 Hz interval while standing, but higher wavelet phase coherences in the 0.15–0.6 Hz and 0.0095–0.02 Hz intervals during the post-standing posture.
Tan et al.	2016	Young v.s. Old	Young: *n* = 40 (27M, 13F); *M* = 24.5, *SD* = 1.7, range: 20–30 Old: *n* = 43 (23M, 20F); M = 69.6, SD = 8.4, range: > 60	10 Hz; 2 bilateral forehead channels (TSAH-200; Tsinghua University, China)	Sitting (20 min)	Older adults had a lower wavelet amplitude in the 0.052–0.145 Hz and 0.0095–0.021 Hz intervals in the left or right PFC than younger adults. Older adults had a lower wavelet phase coherence in the 0.6–2 Hz and 0.052–0.145 Hz intervals than younger adults.
Wang et al.	2016	Young v.s. Old	Young: *n* = 22 (14M, 8F); *M* = 24.4, *SD* = 1.6 Old: *n* = 39 (23M, 16F); *M* = 70.5, *SD* = 7.7	10 Hz; 2 bilateral forehead (TH200; Tsinghua University, China) and 2 bilateral sensorimotor cortex (OXYMON MK III; Artinis Medical Systems, B.V., Netherlands) channels	Sitting (20 min) followed by standing (10 min)	Older adults had lower connectivity between the left and right PFC and between the PFC and sensorimotor cortex across frequency bands (i.e., 0.0095–2 Hz, except 0.052–0.145 Hz) than younger adults while sitting or standing. Older adults had higher connectivity between the prefrontal and sensorimotor cortex in the 0.052–0.145 Hz than younger adults while standing.
Bu, Huo et al.	2018	Role of hypertension in functional and effective connectivity among older adults	Older adults without hypertension: *n* = 16; *M* = 71, *SD* = 5.5 Older adults with hypertension: *n* = 13; *M* = 70, *SD* = 6.5	36 bilateral prefrontal, motor, and occipital channels (NirSmart, Danyang Huichuang Medical Equipment Co., Ltd., China)	Resting with eyes closed (10 min) followed by standing (10 min)	Hypertensive older adults had lower functional connectivity of [oxy-Hb] oscillations in the 0.052–0.145 Hz and 0.021–0.052 Hz intervals among prefrontal, motor, or occipital regions than older adults without hypertension while at rest or standing. Hypertensive older adults also had lower effective connectivity between the left and right occipital regions while at rest and between the left and right motor cortex while standing.
Bu, Wang et al.	2018	Role of sleep quality in functional connectivity among older adults	Older adults without poor sleep quality: *n* = 14 (7M, 7F); *M* = 65.4, *SD* = 1.7 Older adults with poor sleep quality: *n* = 15	10 Hz; 14 bilateral frontal, central, and occipital channels (Nirsmart, Danyang Huichuang, Medical	Resting with eyes closed (15 min)	While at rest, older adults with poor sleep quality had higher wavelet amplitudes of the bilateral PFC and left occipital lobe and lower wavelet phase coherences in slow [oxy-Hb] oscillations (0.01–0.08 Hz) between the left and right PFC, between the prefrontal and motor or occipital

			(8M, 7F); *M* = 64.7, *SD* = 1.7	Equipment Co. Ltd, China)		cortex, and between the motor and occipital cortex than those with better sleep quality.
Huo et al.	2018	Young v.s. Old	Young: *n* = 19 (one excluded; 13M, 7F); *M* = 24.1, *SD* = 1.9 Old: *n* = 17 (one excluded; 13M, 5F); *M* = 69.4, *SD* = 9.6	3-cm separation; 10 Hz; 36 bilateral prefrontal, central, and occipital channels (NirScan Danyang Huichuang Medical Equipment CO. Ltd)	Sitting (15 min) followed by standing (10 min)	Changing from sitting to standing increased regulation of the motor cortex in the PFC and occipital lobe in older adults but increased regulation of the PFC and occipital lobe in the motor cortex in younger adults. Older adults had decreased connectivity between the left and right PFC and from the prefrontal or occipital cortex to the motor cortex than younger adults while sitting and increased connectivity from the motor cortex to the PFC than younger adults while standing.
Li et al.	2018	Young v.s. Old	Young: *n* = 18; *M* = 26.5, *SD* = 2.5 Old: *n* = 30; *M* = 73.3, *SD* = 7.5	3-cm separation; 8.13 Hz; 133 whole-head channels (LABNIRS, Shimadzu Corp., Kyoto, Japan)	Resting with eyes closed (5 min for older adults and 8 min for younger adults)	Older adults had a larger clustering coefficient, a larger characteristic path length, a lower normalized clustering coefficient, and a lower global efficiency than younger adults. Older adults had fewer hubs in the PFC and default mode network than younger adults.
Mukli, Nagy, Racz, Herman, and Eke	2018	Young v.s. Old	Young: *n* = 24; *M* = 30.6, *SD* = 8.2, range: < 45 Old: *n* = 28; *M* = 60.5, *SD* = 12.0, range: ≥ 45	4-cm separation; 2 Hz; 1 forehead channel (NIRO 500; Hamamatsu Photonics, Hersching, Germany)	Sitting	Multifractal [total-Hb] measures revealed increased long-range autocorrelation for vasogenic hemodynamics but less correlated fluctuations for neural hemodynamics in older adults than in younger adults. Fluctuations in [oxy-Hb] and [deoxy-Hb] were anticorrelated in younger adults but not in older adults.
Rhee and Mehta	2018	Role of obesity in functional connectivity among older adults	Nonobese male older adults: *n* = 14; *M* = 74.5, *SD* = 6.4 Obese male older adults: *n* = 11; *M* = 72.7, *SD* = 6.9 Nonobese female older adults: *n* = 14; *M* = 71.5, *SD* = 4.2 Obese female older adults: *n* = 14; *M* = 71.6, *SD* = 5.5	26 bilateral frontal and centroparietal channels; (Techen Inc., MA, United States, CW6 System)	Resting (3 min)	Obese older adults had greater variability but not different levels of functional connectivity among frontal and sensorimotor regions than nonobese older adults.

Zeller et al.	2019	Young v.s. Old	Young: *n* = 25 (6M, 19F); *M* = 34.9, *SD* = 7.4, range: 21–48 Old: *n* = 61 (24M, 37F); *M* = 73.3, *SD* = 1.7, range: 70–76	10 Hz; 52 bilateral frontotemporal (1st measurement) and parietal (2nd measurement) channels (ETG-4000; Hitachi Medical Co., Tokyo, Japan)	Resting (sitting with eyes closed for 5 min)	Younger adults had a higher power spectral density of low-frequency (0.07–0.11 Hz) oscillations of [oxy-Hb] in the frontal cortex, especially in ventral and lateral regions, than older adults. A higher power spectral density of low frequency oscillations of parietal [oxy-Hb] correlated with slower reaction time on a phasic alertness task.

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 2. A summary of functional near-infrared spectroscopy (fNIRS) studies on sensation and perception, including a) visual processing, b) auditory processing, and c) vestibular functioning, in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Tasks	fNIRS Findings
a) Visual processing						
Schroeter, Schmiedel, and von Cramon	2004	Young v.s. Old	Young: *n* = 14 (7M, 7F); *M* = 23.9, *SD* =3.1, range: 19–29 Old: *n* = 14 (7M, 7F); *M* = 65.3, *SD* = 2.9, range: 62–71	4- or 5-cm separation; 6 Hz; 2 bilateral occipital channels (NIRO-300 spectrometer; Hamamatsu Photonics K.K., Hamamatsu, Japan)	Alternating full-field checkerboard (1.8 Hz; 18-s stimulation period; eight cycles per block, two blocks in one session lasting 13.3 min in total)	Older adults had similar changes in [oxy-Hb], [deoxy-Hb], and [total-Hb] but had weaker low-frequency (0.07–0.11 Hz) [oxy-Hb] and [deoxy-Hb] oscillations in response to visual stimulation than younger adults. Younger and older adults had a comparable power spectral density of very-low-frequency (0.01–0.05 Hz) oscillations of fNIRS signals.
Fabiani et al.	2014	Young v.s. Old; role of aerobic fitness in visual stimulation response in older adults	Young: *n* = 19 (10M, 9F); *M* = 22.3, *SD* = 2.0, range: 20−28 High-fit older adults: *n* = 20 (9M, 11F); *M* = 70.3, *SD* = 4.2, range: 65–81 Low-fit older adults: *n* = 24 (11M, 13F); *M* = 72.2, *SD* = 5.2, range: 65–81	2- to 5-cm separation; 62.5 Hz; Long and short occipital (BA 17) channels (ISS Inc., Champaign, IL)	Black and white checkerboard (1, 2, 4, 6, and 8 Hz; 60 s per block and 19.2 s of stimulation every block)	Visual stimulation led to an increase in [oxy-Hb] in younger adults but not in older adults. Age correlated with a smaller decrease in [deoxy-Hb]. Changes in [oxy-Hb] and [deoxy-Hb] were anticorrelated in younger adults but not in older adults. Aerobic fitness correlated with the increase in [oxy-Hb] among older adults.
Ward, Aitchison, Tawse, Simmers, and Shahani	2015	Young v.s. Old	Young: *n* = 12 (0F, 12F); *M* = 20.5, *SD* = 30, range: 18–27 Old: *n* = 13 (5M, 8F); *M* = 71.2, *SD* = 7, range: 58–83	2 bilateral occipital (O1 and O2) channels (OxiplexTSTM)	Full-field reversing checkerboard (7.5 Hz; check sizes of 15 and 30 minutes of arc used with contrasts of 50% and 100%; 30-s stimulation periods involving 10 cycles of reversing checkerboard)	Older adults had smaller changes in [oxy-Hb] and [deoxy-Hb] than younger adults at both the 50% and 100% contrast levels. The change in [deoxy-Hb] at 50% contrast in younger adults was larger than that the change in [deoxy-Hb] at 100% contrast in older adults. Older adults had smaller changes in [oxy-Hb] and [deoxy-Hb] than younger adults while fixating a gray screen of equal mean luminance to the checkerboard stimulus.

Ward, Morison, Simmers, and Shahani	2018	Young v.s. Middle-aged v.s. Old	Young: *n* = 28 (6M, 22F); *M* = 28, *SD* = 7.3, range: 18–39 Middle-aged: *n* = 22 (11M, 11F); *M* = 50, *SD* = 6.9, range: 40–59 Old: *n* = 23 (11M, 12F); *M* = 70, *SD* = 6.9, range: 60–85	1.9- to 3-cm separation; 1-Hz sampling rate; 2 bilateral parieto-occipital (V5) channels (OxiplexTSTM)	Random-Dot-Kinematogram (each dot moving at 1.5, 3, and 9°/s)	Age linearly correlated with a larger increase in [oxy-Hb] (i.e., older adults > younger adults, middle-aged adults) and with a greater decrease in [deoxy-Hb] (i.e., older adults > younger adults) during the perception of 9°/s motion. Age did not significantly correlate with changes in [oxy-Hb] or [deoxy-Hb] during perception of slow (i.e., 1.5°/s) motion
b) Auditory processing						
Jeong and Ryu	2016	Young v.s. Old	Young: *n* = 13 (10M, 3F); *M* = 23.5, *SD* = 1.7 Old: *n* = 14 (7M, 7F); *M* = 56.1, *SD* = 6.4	1.54 Hz; 16 bilateral forehead channels (Spectratech OEG-16; Shimadzu Co. Ltd., Kyoto, Japan)	Melodic contour identification (focused, selective, and alternating listening conditions with six contour stimuli; 18 items per condition)	Younger but not older adults exhibited changes in [oxy-Hb] in the dorsolateral PFC during contour identification. Older adults had a smaller increase in [oxy-Hb] in the right dorsolateral PFC than younger adults while paying selective attention to melodic contours.
c) Vestibular functioning						
Karim, Fuhrman, Furman, and Huppert	2013	Young v.s. Old	Young: *n* = 10 (5M, 5F); *M* = 25, *SD* = 6 Old: *n* = 10 (6M, 4F); *M* = 74, *SD* = 5	3.2-cm separation; 4 Hz; 32 bilateral frontotemporal and parietal channels (CW6; TechEn Inc, Milford MA)	Caloric left or right ear irrigations during backward counting by 2 (warm, 44ºC, cool, 30ºC, or sham; two blocks for each condition, 45-s active task period)	Older adults had larger increases in [oxy-Hb] in left temporo-parietal regions than younger adults in all four conditions (i.e., warm or cool stimulation × left or right ear). They also had increased bilateral superior temporal activity in all conditions except for cold stimulation to the right ear. Older adults had more symmetric temporal activity than younger adults in general.
Lin, Barker, Sparto, Furman, and Huppert	2017	Middle-aged v.s. Old	Middle-aged: *n* = 15 (5M, 10F); *M* = 46, *SD* = 11 Old: *n* = 15 (8M, 7F); *M* = 73, *SD* = 5	3-cm separation; 4 Hz; 30 bilateral frontal-lateral, temporal-parietal, and occipital channels	Dynamic balance (balancing with or without visual or somatosensory feedback; 40-s active task period)	When somatosensory information was degraded, older adults had greater increases in [oxy-Hb] in the left frontal-lateral, right temporal-parietal, and occipital regions when visual feedback was present, and in the

					(CW6 real-time system; TechEN Inc, Milford, MA, USA)		occipital region when visual feedback was also absent than middle-aged adults. When visual information was degraded, older adults had greater increases in [oxy-Hb] in the right frontal-lateral and temporal-parietal regions when somatosensory feedback was present, and in the right frontal-lateral and occipital regions when somatosensory feedback was also absent than middle-aged adults.
Rosso et al.	2017	Young Old	v.s.	Young: *n* = 6 (4M, 2F); range: 22–30 Old: *n* = 10 (3M, 7F); range: 66–81	3.2-cm separation; 8 left prefrontal, temporal, and central channels (CW6 Real-time; TechEn Inc)	Dynamic balance (standing with feet together and eyes closed on a dynamic platform, auditory choice reaction time task, or both; 121 s per task)	Older adults had larger changes in [oxy-Hb] and [deoxy-Hb] in the left lateral frontal and superior temporal regions than younger adults for both the dual-task response and the sum of single-task responses. In both younger and older adults, changes in [oxy-Hb] and [deoxy-Hb] between single- and dual-task conditions were larger for the postural task than the reaction time task.
Teo, Goodwill, Hendy, Muthalib, and Macpherson	2018	Young Old	v.s.	Young: *n* = 20 (10M, 10F); *M* = 21.5, *SD* = 3.5, range: 18–25 Old: *n* = 18 (10M, 8F); *M* = 69.5, *SD* = 3.4, range: 66–73	3-cm separation; 10 Hz; 8 bilateral dorsolateral PFC channels (Oxymon Mk III; Artinis Medical Systems, The Netherlands)	Sensory Orientation Test (six conditions differing in whether eyes were closed, and whether visual surround and surface were sway-referenced; 20-s active task period)	Older adults had greater increases in [oxy-Hb] in the bilateral dorsolateral PFC in conditions where visual or somatosensory feedback were absent or incongruent, and greater decreases in [deoxy-Hb] in conditions where the surface was sway-referenced than younger adults. Older adults had less right-lateralized activation than younger adults when visual or somatosensory feedback was absent or incongruent.
Marusic et al.	2019	Young Old	v.s.	Young: *n* = 10 (3M, 7F); M = 22.6, SD = 2.8 Old: *n* = 10 (4M, 6F); *M* = 72.3, *SD* = 3.2	4.5-cm separation; 1 left dorsolateral PFC channel (Oxymon, Artinis, The Netherlands)	Dual-task balance (quiet standing, backward counting by 3, standing still in a tandem position, or standing in a tandem position while backward counting; 60-s active task period)	There were no significant main or interaction effects involving age on changes in [oxy-Hb].

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 3. A summary of functional near-infrared spectroscopy (fNIRS) studies on gross motor skills, including (a) walking (i.e., normal walking, dual-task walking, and obstacle negotiation), (b) cycling, and c) driving, in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
a) Walking						
Harada, Nashihara, Morozumi, Ota, and Hatakeyama	2009	Role of gait capacity in cortical activation while walking among older adults	Old: *n* = 15 (2M, 13F); *M* = 63, *SD* = 4	3-cm separation; 5.26 Hz; 42 bilateral frontocentral channels (OMM-2001; Shimadzu, Kyoto, Japan)	Speed treadmill walking [target heart rate = (maximum heart rate - resting heart rate) * 30%, 50%, or 70%, plus resting heart rate]	Older adults with low gait capacity had greater activation in the left PFC than older adults with high gait capacity, specifically at 70% walking intensity. Activation in the left PFC positively correlated with heart rate response, and activation in the supplementary motor area and medial sensorimotor cortex positively correlated with both cadence and walking speed.
Holtzer et al.	2011	Young v.s. Old	Young: *n* = 11 (4M, 7F); range: 19–29 Sedentary older adults who exercised once weekly or less, with gait velocity < 1.0 m/s: *n* = 11 (4M, 7F); range: 69–88	2.5-cm separation; 2 Hz; 16 bilateral prefrontal channels (sensor developed in the Drexel Biomedical Engineering laboratory)	Walking for 15 feet (normal pace walking, and walking while reciting alternate alphabets; six trials per condition)	Older adults had lower peaks of baseline-corrected changes in [oxy-Hb] in the bilateral PFC than younger adults across walking conditions. The group differences were driven primarily by smaller dual-task-related increases in [oxy-Hb] in older adults than in younger adults.
Beurskens, Helmich, Rein, and Bock	2014	Young v.s. Old	Young: *n* = 15; *M* = 24.5, *SD* = 3.3 Old: *n* = 10; *M* = 71.0, *SD* = 3.8	2.2-cm (6 channels) and 2.5-cm (10 channels) separation; 1.81 Hz; 16 bilateral prefrontal channels (DYNOT Imaging System, NIRx Medical Technologies, LLC)	Treadmill walking (walking only, or walking with or without having to check boxes or talk; 30-s active task period)	Older adults had lower changes in [oxy-Hb] and higher changes in [deoxy-Hb] in the bilateral PFC during walking while checking than during walking only than younger adults. There were few differences in changes in [oxy-Hb] between the walk-only and dual-task conditions in younger adults and between the walk-only and walk-and-talk conditions in older adults.
Clark, Christou, Ring,	2014	Effect of enhanced somatosensory	Older adults with mild mobility deficits, (i.e., 400 m walking	3-cm separation; 2 bilateral forehead channels	Self-paced treadmill and overground walking (walking with normal	Relative to normal shoes, walking with either textured soles or no shoes led to a reduction in bilateral prefrontal oxygenation changes

Williamson, and Doty		feedback on walking among older adults	speed less than 1.1 m/s): *n* = 14 (7M, 7F); *M* = 77.1, *SD* = 5.6, range: 65–85	(Niro 200NX; Hamamatsu Photonics, Japan)	shoes, textured insoles, or no shoes, and walking with normal shoes while performing the letter fluency task; 60–120 s at self-paced speed)	during treadmill walking. Textured soles also led to reduced prefrontal oxygenation changes during overground walking. Dual-task performance resulted in a higher oxygen saturation in the PFC during overground walking.
Clark, Rose, Ring, and Porges	2014	Effect of physical and cognitive challenges on walking among older adults	Older adults with mild mobility deficits: *n* = 16 (8M, 8F); *M* = 77.2, *SD* = 5.6	3-cm separation; 2 Hz; 2 bilateral forehead channels (Niro 200NX; Hamamatsu Photonics, Japan)	Walking (along a well-lit and unobstructed pathway (i.e., control condition), during a verbal fluency task, under dim lighting, while carrying a tray, negotiating obstacles, or wearing a weighted vest)	Prefrontal oxygenation changes were higher during active task preparation and performance than during control task preparation, regardless of the type of active tasks. Prefrontal oxygenation changes were higher during task performance than during task preparation in the verbal fluency condition only.
Holtzer et al.	2015	Effect of dual-task demand on walking among older adults	Old: *n* = 348 (143M, 205F); *M* = 76.8, *SD* = 6.8, range: ≥ 65	2.5-cm separation; 2 Hz; 16 bilateral forehead channels (fNIRS Imager 1100; fNIRS Devices, LLC, Potomac, MD)	Walking (single-task: walking or reciting alternate alphabets for 30 s; dual-task: performing two single tasks at the same time)	There were larger increases in [oxy-Hb] in the PFC during walking while talking than during normal walking. There were larger increases in [oxy-Hb] in the bilateral PFC but smaller increases in [oxy-Hb] in the medial PFC during walking while talking than during cognitive task only. [oxy-Hb] continued to increase over dual-task walking but returned to baseline over normal walking.
Eggenberger, Wolf, Schumann, and de Bruin	2016	Effects of video game dancing training on walking among older adults	Old: *n* = 33 (12M, 21F); *M* = 74.9, *SD* = 6.9, range: > 65 [assigned to 8 weeks of either dance (*n* = 19) or balance training (*n* = 14)]	Four different separations; 10 Hz; 2 bilateral prefrontal channels (Oxiplex TS Tissue Spectrometer; ISS Inc., Champaign, IL, USA)	Treadmill walking (preferred or fast walking; 30-s walking periods; four blocks per condition)	There was a reduced increase in bilateral prefrontal [oxy-Hb] during the accelerating phase of self-paced walking after training in general. Dance training led to smaller increases in left [oxy-Hb] than balance training during the decelerating phase of walking at fast pace.
Fraser, Dupuy, Pouliot,	2016	Young v.s. Old	Young: *n* = 19 (7M, 12F); *M* = 21.8 *SD* = 1.9	2.8-cm separation; 28 bilateral prefrontal channels	Self-paced treadmill walking (walking alone, auditory 1- and	When walk speed was controlled for, neither the main effect nor interaction involving group was found.

Lesage, and Bherer			Old: *n* = 14 (2M, 12F); *M* = 66.9, *SD* = 5.3	(CW6; TechEn Inc., Milford, MA, USA)	2-back tasks alone, and walking whil performing the *n*-back tasks; 1- to 2-min active task period)	
Osofundiya, Benden, Dowdy, and Mehta	2016	Role of obesity in dual-task walking among older adults	Nonobese older adults: *n* = 10 (2M, 8F); *M* = 80.6, *SD* = 7.5, range: ≥ 65 Obese older adults: *n* = 10 (4M, 6F); *M* = 80.5, *SD* = 6.8, range: ≥ 65	5 Hz; 2 bilateral forehead channels (NIRO 200 NX; Hamamatsu Photonics, Japan)	Walking (quiet sitting, simple walking, walking while reciting alternate alphabets, and precision walking; 30-s active task period)	Obese older adults exhibited greater increases in [oxy-Hb] in the PFC than nonobese older adults during precision walking but not in other conditions.
Chen et al.	2017	Role of gait speed in obstacle crossing and dual-task walking among older adults	Older adults with normal gait: *n* = 64 (28M, 36F); *M* = 78.3, *SD* = 5.9, range: ≥ 65 Older adults with slow gait: *n* = 26 (16M, 10F); *M* = 77.6, *SD* = 4.5, range: ≥ 65	2.5-cm separation; 2 Hz; 16 bilateral forehead channels (fNIR Imager 1000; fNIR Devices, LLC, Potomac, MD)	Walking (normal pace walking, walking while talking, obstacle negotiation during normal walking, and obstacle negotiation during walking while talking)	Older adults with slow gait had increases in [oxy-Hb] in response to obstacle negotiation than older adults with normal gait, regardless of walk conditions.
Holtzer et al.	2017a	Roles of stress and gender in dual-task walking among older adults	Older adults with low perceived stress: *n* = 147 (78M, 69F); *M* = 76.7, *SD* = 6.9, range: ≥ 65 Older adults with high perceived stress: *n* = 171 (61M, 110F); *M* = 76.6, *SD* = 6.4, range: ≥ 65	2.5-cm separation; 2 Hz; 16 bilateral forehead channels (fNIRS Imager 1000; fNIRS Devices, LLC, Potomac, MD)	Walking (walking, alphabet recitation, and both at the same time; 30 s)	For men but not women, older adults with higher perceived stress had smaller increases in [oxy-Hb] in the PFC than those with lower perceived stress while changing from single-task to dual-task walking.
Holtzer et al.	2017b	Role of subjective fatigue in dual-task walking among older adults	Older adults with low perceived fatigue: *n* = 160 (74M, 86F); *M* = 76.2, *SD* = 6.6, range: ≥ 65 Older adults with high perceived fatigue: *n*	2.5-cm separation; 2 Hz; 16 forehead channels (fNIRS Imager 1000; fNIRS	Walking (single-task: walking or alphabet recitation; dual-task: two single tasks at the same time)	Older adults with high fatigue had smaller increases in [oxy-Hb] in the PFC while changing from single-task to dual-task walking and over the course dual-task walking than older adults with low fatigue. Fatigue did not moderate changes in [oxy-Hb] during normal walking.

			= 154 (65M, 89F); *M* = 77.4, *SD* = 6.7, range: ≥ 65	Devices, LLC, Potomac, MD)		
Mirelman et al.	2017	Young v.s. Old	Young: *n* = 23 (10M, 13F); *M* = 30.9, *SD* = 3.7 Old: *n* = 20 (10M, 10F); *M* = 69.7, *SD* = 5.8	3-, 3.5-, and 4-cm separation; 10 Hz; 2 bilateral forehead channels (PortaLite™ fNIRS System; Artinis Medical Systems, Elst, the Netherlands)	Walking (usual walking, walking while counting backward by 3, and walking while negotiating two physical obstacles; 30-s active task period)	Older adults exhibited larger increases in [oxy-Hb] in the bilateral PFC in all three walking conditions than younger adults. Changes in [oxy-Hb] positively correlated with gait variability during obstacle walking in older adults but not younger adults. Age uniquely predicted changes in [oxy-Hb] during usual walking. Both age and gait speed uniquely predicted changes in [oxy-Hb] during obstacle walking.
Verghese, Wang, Ayers, Izzetoglu, and Holtzer	2017	Predictability of PFC activation during dual-task walking for future falls among older adults	High-functioning older adults with low comorbidity: *n* = 166 (81M, 85F); *M* = 75.0, *SD* = 6.1	2 Hz; 16 bilateral forehead channels (fNIRS Imager 1000; fNIRS Devices LLC, Potomac, MD)	Walking (single-task: normal-pace walking, or alphabet recitation for 30 s; dual-task: two single tasks performing at the same time)	At baseline, a larger increase in left PFC [oxy-Hb] during dual-task walking but not during alphabet recitation predicted future falls over a 50-month study period.
Hawkins et al.	2018	Young v.s. Old	Young: *n* = 9 (4M, 5F); *M* = 22.4, *SD* = 3.2, range: 18–30 Older adults with mild gait deficits: *n* = 15 (7M, 8F); *M* = 77.2, *SD* = 5.6, range: 65–85	3-cm separation; 2 Hz; 2 bilateral prefrontal channels; (Niro 200NX, Hamamatsu Photonics, Japan)	Walking (typical walking, walking over obstacles, walking while performing the letter fluency task)	Older adults had higher changes in [oxy-Hb] than younger adults during the early (7–37 s after task onset) and late (37–67 s after task onset) periods of typical walking and during the early task period of obstacle crossing. Younger and older adults had similar changes in [oxy-Hb] during dual-task walking.
Holtzer, George, Izzetoglu, and Wang	2018	Role of diabetes in dual-task walking among older adults	Older adults without diabetes: *n* = 272 (113M, 159F); *M* = 76.7, *SD* = 6.7, range: ≥ 65 Older adults with diabetes: *n* = 43 (24M, 19F); *M* = 77.7, *SD* = 6.8, range: ≥ 65	2.5-cm separation; 2 Hz; 16 forehead channels (fNIRS Imager 1000; fNIRS Devices, LLC, Potomac, MD)	Walking (walking, alphabet recitation, and both at the same time)	Older adults with diabetes had a larger increase in [oxy-Hb] in the bilateral PFC during alphabet recitation but a lower increase in [oxy-Hb] during dual-task walking than older adults without diabetes.

Holtzer, Izzetoglu, Chen, and Wang	2018	Effect of within-session practice on dual-task walking among older adults	Old: *n* = 83 (42M, 41F); *M* = 78.1, *SD* = 6.4, range: ≥ 65	2.5-cm separation; 2 Hz; 16 bilateral forehead channels (fNIRS Imager 1100; fNIRS Devices, LLC, Potomac, MD)	Walking (walking, alphabet recitation, and both at the same time; three repetitions separated by 5 min)	[oxy-Hb] decreased during single-task walking but increased during dual-task walking [oxy-Hb] decreased over repeated trials of alphabet recitation but decreased over repeated trials of dual-task walking. [deoxy-Hb] increased over repeated trials of dual-task walking and letter generation but not single-task walking.
Vitorio et al.	2018	Young v.s. Old; effect of rhythmic auditory cues on walking	Young: *n* = 17; *M* = 20.3, *SD* = 1.2, range: 20–40 Old: *n* = 18; *M* = 72.6, *SD* = 8.0, range: ≥ 60	3-cm separation 23.8 Hz; 40 bilateral frontocentral channels (LABNIRS; Shimadzu, Kyoto, Japan)	Treadmill walking (usual walking and walking with rhythmic auditory cues; 30-s active task period)	Rhythmic auditory cues led to increases in [oxy-Hb] in the bilateral PFC in both younger and older adults and in the premotor and supplementary motor cortex in older adults while walking. Older adults had larger cue-related increases in [oxy-Hb] in the premotor and supplementary motor cortex than younger adults during cued walking.
George, Verghese, Izzetoglu, Wang, and Holtzer	2019	Role of polypharmacy in dual-task walking among older adults	Older adults without polypharmacy: *n* = 221 (94M, 127F); *M* = 76.0, *SD* = 6.6, range: ≥ 65 Older adults with polypharmacy: *n* = 104 (49M, 55F); *M* = 77.4, *SD* = 6.9, range: ≥ 65	2.5-cm separation; 16 bilateral forehead channels (fNIRS Imager 1100; fNIRS Devices, LLC, Potomac, MD)	Walking (walking, alphabet recitation, and both at the same time)	Older adults with polypharmacy had a smaller increase in [oxy-Hb] than older adults without polypharmacy when changing from single-task to dual-task walking.
Holtzer, Kraut, Izzetoglu, and Ye	2019	Role of fear of falling in dual-task walking among older adults	Older adults without fear of falling: *n* = 56 (31M, 25F); *M* = 76.7, *SD* = 6.4 Older adults with fear of falling: *n* = 19 (6M, 13F); *M* = 79.8, *SD* = 6.0	2.5-cm separation; 2 Hz; 16 bilateral forehead channels (fNIRS Imager 1100; fNIRS Devices, LLC, Potomac, MD)	Walking (walking, alphabet recitation, and both at the same time; three repetitions separated by 5 min)	Older adults with fear of falling had a greater increase in [oxy-Hb] than older adults without fear of falling when changing from single-task walking or alphabet recitation to dual-task walking. Older adults with fear of falling had a smaller decrease in [oxy-Hb] over repeated trials of dual-task walking but a larger decrease in [oxy-Hb] over repeated trials of alphabet recitation.

Lucas, Wagshul, Izzetoglu, and Holtzer	2019	Role of white matter intensities in dual-task walking among older adults	Older adults with high WMI: *n* = 28 (13M, 15F); *M* = 73.9, *SD* = 3.9, range: > 65 Older adults with low WMI: *n* = 27 (15M, 12F); *M* = 75.7, *SD* = 5.8, range: > 65	2.5-cm separation; 16 forehead channels (fNIRS Imager 1000; fNIRS Devices, LLC, Potomac, MD)	Walking (walking only and walking while reciting alternate alphabets)	A lower whole-brain fractional anisotropy value correlated with a greater increase in [oxy-Hb] in the PFC in response to dual-task demand.
Stuart, Alcock, Rochester, Vitorio, and Pantall	2019	Young v.s. Old	Young: *n* = 17; *M* = 20.3, *SD* = 1.2, range: 20–40 Old: *n* = 18; *M* = 72.6, *SD* = 8.0, range: ≥ 50	3.5-cm separation 23.8 Hz; 40 bilateral frontocentral channels (LABNIRS; Shimadzu, Kyoto, Japan)	Treadmill walking (walking, digit vigilance task performance, and walking while performing the digit vigilance task at the same time; 30-s active task period)	Older adults had a smaller increase in [oxy-Hb] in the left supplementary motor area during dual-task walking and had greater increases in [oxy-Hb] in the left PFC and premotor cortex during the digit vigilance task than younger adults.
Wagshul, Lucas, Ye, Izzetoglu, and Holtzer	2019	Role of brain volume in dual-task walking among older adults	Old: *n* = 55 (27M, 28F); *M* = 74.8, *SD* = 5.0, range: > 65	2.5-cm separation; 16 bilateral forehead channels (fNIRS Imager 1100; fNIRS Devices, LLC, Potomac, MD)	Walking (walking only and walking while reciting alphabets)	The dual-task-related increase in [oxy-Hb] was associated with reduced frontal gray matter volume, particularly in the bilateral superior and rostral middle gyri, even after controlling for the dual-task-related decrease in walking velocity.
b) Cycling						
Lin, Lin, and Chen	2012	Young v.s. Old	Young: *n* = 13 (8M, 5F); *M* = 23.4, range: 20–28 Old: *n* = 13 (7M, 6F); *M* = 67.6, range: 54–90	3-cm separation; 19.8 Hz; 20 bilateral frontocentral channels (Imagent; ISS Inc., Champaign, IL)	Cycling (free cycling and target cycling with speed feedback; eight cycles of 20-s cycling period per condition)	Younger and older adults had similar increases in [oxy-Hb] in the bilateral somatosensory cortex during free and target cycling. Older adults had greater increases in [oxy-Hb] in the supplementary motor area and premotor cortex than younger adults during target cycling.
Lucas et al.	2012	Young v.s. Old	Young: *n* = 13 (7M, 6F); *M* = 24, *SD* = 5 Old: *n* = 9 (4M, 5F); *M* = 62, *SD* = 3	1 Hz; 1 right forehead channel (NIRO-200; Hamamatsu Photonics KK,	Cycling (resting and cycling at 30% or 70% of heart rate range)	Younger and older adults had similar exercise-induced increases in [oxy-Hb], [deoxy-Hb], and [total-Hb] in general. Older adults had smaller increases in [oxy-Hb] and [total-Hb] than younger adults when

				Hamamatsu, Japan)		changing from low to high exercise intensities.
Gayda et al.	2017	Role of aerobic fitness and obesity in cycling among older adults	Low-fit obese older adults: n = 27 High-fit obese older adults: n = 27 Nonobese older adults: n = 16; M = 64, SD = 4	4.5-cm separation; 10 Hz; 1 left prefrontal channel (Oxymon Mk III, Artinis Medical, Netherlands)	Cycling (a 3-min warm up at 20 Watts followed by a power increase in 10 to 20 Watts/min until exhaustion at a pedaling speed > 60 rpm)	There were no differences in changes in [oxy-Hb] or [deoxy-Hb] among nonobese, high-fit obese, and low-fit obese older adults during exercise or recovery.
c) Driving						
Harada, Nashihara, Morozumi, Ota, and Hatakeyama	2007	Young v.s. Old	Male younger adults: *n* = 14; *M* = 21.6, SD = 0.8 Male older adults: *n* = 7; *M* = 69.9, SD = 4.9 Female older adults: *n* = 7; *M* = 66.6, *SD* = 6.0	4-cm separation; 2 bilateral forehead channels (TRS, Hamamatsu Photonics K.K., Japan)	Actual driving (approximately 7 km, with speed limited to 30–50 km/hr)	Among younger adults, less experienced drivers exhibited increases in [oxy-Hb] and [total-Hb] in the right PFC while driving and stopping at the traffic signal, while experienced drivers showed no change in [oxy-Hb] or [total-Hb] but a decrease in [deoxy-Hb]. Older adults showed an increase in [oxy-Hb] and a decrease in [deoxy-Hb] in the right PFC while driving Older adults tended to have a lower change in right frontal [oxy-Hb] than younger adults while driving.
Knols et al.	2017	Acute effect of a bedside video console on PFC oxygenation among older adults	Old: *n* = 15 (10M, 5F); *M* = 63.7, *SD* = 5.4, range > 55 (fNIRS measurement: *n* = 5)	10 Hz; 2 bilateral forehead channels; (INVOS OXYMETER 5100C; Covidien Somanetics, Troy, MI 48084, USA)	Simulated driving (phasic alertness and selective attention; four stages per condition; five alternations of 1-min gaming exercise and 1-min rest per condition)	There was a decrease in oxygen saturation in the bilateral PFC, especially the right hemisphere, over the course of the phasic alertness gameplay.

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 4. A summary of functional near-infrared spectroscopy (fNIRS) studies on fine motor skills, including a) finger movement, b) handgrip force control, and c) mastication, in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
a) Finger movement						
Mehagnoul-Schipper et al.	2002	Young v.s. Old	Young: *n* = 6 (3M, 3F); *M* = 35, *SD* = 9 Old: *n* = 5 (2M, 3F); *M* = 73, *SD* = 3	4.5-cm separation; 10 Hz; 1 left motor channel (University Medical Center Nijmegen, the Netherlands)	Right forefinger-tapping (seven cycles of 20-s active task period)	Older adults had a smaller maximum increase in [oxy-Hb] and a smaller decrease in [deoxy-Hb] in the left motor cortex than younger adults.
Zich, Debener, Thoene, Chen, and Kranczioch	2017	Young v.s. Old; effect of neurofeedback on motor imagery	Young: *n* = 19 (10M, 9F); *M* = 24.4, *SD* = 2.7 Old: *n* = 18 (8M, 10F); *M* = 62.6, *SD* = 5.7	3-cm separation; 7.81 Hz; 14 bilateral central (and 4 visual channels) NIRScout 816 system; NIRx Medizintechnik GmbH, Berlin, Germany)	Repeated thumb abductions (motor execution and imagery with or without feedback; 5 s per trial and 15 min per block and condition)	Older adults had a weaker lateralization in changes in [deoxy-Hb] but not [oxy-Hb] than younger adults during motor imagery but not motor execution. This difference was attributable to a larger change in ipsilateral [deoxy-Hb] in older adults. Neurofeedback led to an increase in contralateral [deoxy-Hb], which was not moderated by age.
b) Handgrip force control						
Shortz, Pickens, Zheng, and Mehta	2015	Effect of cognitive fatigue on neuromuscular fatigue	Sedentary older adults: *n* = 11 (0M, 11F); *M* = 75.8, *SD* = 7.4	3-cm separation; 5 Hz; 2 bilateral prefrontal channels (NIRO 200 NX, Hamamatsu Photonics, Japan)	Handgrip exercise at 30% of maximum voluntary contraction (alternation between 15 s of work and rest until exhaustion)	Sixty minutes of Stroop and letter 1-back task performance, which induced cognitive fatigue, led to greater decreases in [oxy-Hb] in the bilateral PFC throughout the handgrip exercise than did 60 minutes of documentary watching.
Mehta and Rhee	2017	Young v.s. Old; effect of acute social stress on handgrip force control in older adults	Young: *n* = 10 (4M, 6F); *M* = 24.2, *SD* = 5.0, range: 20–35	50 Hz; Bilateral forehead channels (CW6 system; Techen Inc. MA, USA)	Handgrip force control at 30% maximum voluntary contractions	Older adults had a larger force-related increase in [oxy-Hb] in the bilateral PFC than younger adults, which was not moderated by stress.

			Old: *n* = 9 (3M, 6F); *M* = 74.1, *SD* = 6.5, range: ≥ 65			Acute social stress induced by the Trier Social Stress Test led to similar changes in [oxy-Hb] in the PFC in younger and older adults.
Rhee and Mehta	2018	Role of obesity in functional connectivity among older adults	Nonobese men: *n* = 14; *M* = 74.5, *SD* = 6.4 Obese men: *n* = 11; *M* = 72.7, *SD* = 6.9 Nonobese women: *n* = 14; *M* = 71.5, *SD* = 4.2 Obese women: *n* = 14; *M* = 71.6, *SD* = 5.5	26 bilateral frontal and centroparietal channels; (Techen Inc., MA, United States, CW6 System)	Handgrip force control at 30% maximum voluntary contractions (early and later exercise phases; 3-min active task period)	Nonobese older adults demonstrated a higher level of functional connectivity between the right lateral motor area and medial motor area of both hemispheres than obese older adults in the late but not the early phase of handgrip exercise.
c) Mastication						
Miyamoto, Yoshida, Tsuboi, and Iizuka	2005	Effect of dental prostheses on chewing in older adults	Old: *n* = 9, (2M, 7F); *M* = 56.9	10 Hz; 24 bilateral temporal channels (ETG-100; Hitachimedical, Tokyo, Japan)	Clenching (alternations between 10 s of maximum voluntary clenching, with or without a dental prosthesis, and 30 s of rest for 5 times)	Clenching with a dental prosthesis was associated with a higher level of [total-Hb] in the bilateral temporal cortex than clenching without one.
Narita et al.	2009	Effect of partial dental prostheses on chewing in older adults	Old: *n* = 3 (1M, 2F), range: 57–64	10 Hz; 22 bilateral frontal channels (ETG-100; Hitachi Medical C., Japan)	Chewing gum chewing (unilateral chewing with or without wearing a denture prosthesis; 10-s active task period; five repetitions per condition)	In all three older adults, chewing with a dental prosthesis was associated with a greater increase in [oxy-Hb] in the mid-dorsal PFC than chewing without one.
Kamiya, Narita, and Iwaki	2016	Young v.s. Old; effect of dental prostheses on chewing in older adults	Young: *n* = 12 (6M, 6F); *M* = 22.1, *SD* = 2.3 Partially edentulous older adults: *n* = 12 (6M, 6F); *M* = 63.1, *SD* = 6.1	3-cm separation; 10 Hz; 22 bilateral prefrontal channels (ETG-100; Hitachi Medical Co., Chiba, Japan)	Mastication (rest, chewing with or without wearing a denture; 10-s trials)	Older adults had a smaller increase in [oxy-Hb] in the bilateral PFC than younger adults while chewing, regardless of the use of a dental prosthesis. Chewing with a dental prosthesis led to a greater increase in bilateral [oxy-Hb] in the bilateral PFC than chewing without one among older adults.

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 5. A summary of functional near-infrared spectroscopy (fNIRS) studies on semantic processing (i.e., discourse comprehension, lexical decision-making, and syllogistic reasoning) in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
Tsujii, Okada, and Watanabe	2010	Young v.s. Old	Young: *n* = 32 (16M, 16F); *M* = 21.5, *SD* = 1.7, range: 20–27 Old: *n* = 32 (18M, 14F); *M* = 68.5, *SD* = 4.1, range: 61–78	3-cm separation; 10 Hz; 8 bilateral inferior frontal channels (ETG-7000; Hitachi Medical Co., Tokyo, Japan)	Syllogistic reasoning (congruent and incongruent syllogisms; 80-s blocks, each with four trials)	While younger adults exhibited right-lateralized changes in [oxy-Hb] and [deoxy-Hb], older adults exhibited bilateral frontal changes in both signals. Older adults had a greater increase in [oxy-Hb] and a greater decrease in [deoxy-Hb] than younger adults in the left inferior frontal region. Better conflict control was related to larger changes in [oxy-Hb] in the bilateral inferior frontal regions in older adults.
Scherer et al.	2012	Young v.s. Old	French-speaking younger adults: *n* = 10 (6M, 4F); *M* = 26.4, *SD* = 4.9 French-speaking older adults: *n* = 10 (3M, 7F); *M* = 68.1, *SD* = 3.5	At least 3-cm separation; 24 bilateral frontotemporal channels (TechEnCW5)	Narrative discourse comprehension (micropropositional, macropropositional, and situational processing; 12 probes per condition, 488 s per block)	There was a shift in activation from the temporal lobe to the frontal lobe during micropropositional and macropropositional processing in French-speaking older adults compared to French-speaking younger adults.
Amiri et al.	2014	Young v.s. Old	Young: *n* = 23 (8M, 15F); *M* = 23.4, *SD* = 2.7, range: 20–35 Old: *n* = 23 (8M, 15F); *M* = 69.6, *SD* = 4.1, range: 65–75	Device 1: 25 Hz; 58 bilateral frontotemporal channels (TechEn CW6) Device 2: 10-, 15-, 25-, and 30-mm separation; 4 forehead channels	Lexical-semantic decision-making (words and pseudo-words; stimulus-onset asynchrony ranged from 4–11 s)	Older adults had greater activation in the bilateral PFC and right posterior middle temporal and occipitotemporal gyri than younger adults during lexical decision-making. After controlling for baseline [oxy-Hb] and [deoxy-Hb], age differences in the task-related changes in [oxy-Hb] and [deoxy-Hb] were reduced in the right frontal region but increased at the junction of the right inferior frontal gyrus and inferior precentral sulcus.
Martin et al.	2018	Young v.s. Old	Young: *n* = 18 (7M, 11F); range: 20–27 Old: *n* = 18 (6M, 12F); range: 66–78	58 bilateral frontal and temporal channels (CW6; TECHEN)	Narrative discourse comprehension (micropropositional, macropropositional, and situational processing; 12 trials and 780 s per block)	Older adults had larger and more sustained increases in [oxy-Hb] in the left dorsolateral PFC, the left frontopolar cortex, and part of the Broca's area than younger adults while reading short stories, regardless of condition. There were no group differences in PFC activation while answering the probe questions.

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 6. A summary of functional near-infrared spectroscopy (fNIRS) studies on word retrieval (i.e., phonemic and semantic fluency) in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
Herrmann, Walter, Ehlis, and Fallgatter	2006	Young v.s. Old	Young: *n* = 44 (22M, 22F); (male: *M* = 23.8, *SD* = 2.6, range: 19–31; female: *M* = 23.6, *SD* = 1.6, range: 22–28) Old: *n* = 42 (22M, 22F); (male: *M* = 65.3, *SD* = 8.1, range: 52–80; female: *M* = 62.7, *SD* = 4.6, range: 54–70	3-cm separation; 10 Hz; 24 bilateral frontotemporal channels (ETG-100; Hitachi Medical Co., Japan)	Phonemic (A, F, S) and semantic fluency (animals, fruits, flowers; 30-s active task period)	Older adults had lower increases in [oxy-Hb] in both the left and right frontotemporal regions and tended to have a smaller task-induced decrease in [deoxy-Hb] than younger adults. Older adults tended to have a lower change in [oxy-Hb] in the left hemisphere than younger adults, indicating a lack of left-lateralized frontal activation.
Kahlaoui et al.	2012	Young v.s. Old	Young: *n* = 16 (5M, 11F); *M* = 23.1, *SD* = 3.1 Old: *n* = 16 (4M, 12F); *M* = 70.2, *SD* = 4.6	3-cm separation; 8 bilateral prefrontal channels (CW32; TechEn)	Phonemic and semantic fluency (high and low productivity; 60-s active task period; two 30-s trials in a row)	Older adults had lower increases in [oxy-Hb] in the PFC than younger adults in both the high and low-productivity conditions of the phonemic and semantic fluency tasks.
Heinzel et al.	2013	Role of age, gender, and education in word retrieval among middle-aged and older adults	Middle-aged and older adults: *n* = 325 (122M, 203F); *M* = 64.6, range: 51–82	3-cm separation; 10 Hz; 44 bilateral frontotemporal and parietal channels (ETG-4000; Hitachi Medical Corporation, Tokyo, Japan)	Phonemic (A, F, M) and semantic fluency (professions, fruits, and flowers; weekday; three blocks per condition, each for 30 s)	Age correlated with smaller retrieval-related increases in [oxy-Hb] in the bilateral inferior frontal and middle temporal regions but with larger increases in [oxy-Hb] in the bilateral inferior parietal and middle frontal regions. Age tended to correlate with a weaker left lateralization of inferior frontal activation during the phonemic fluency task. Years of education correlated with greater inferior frontal activation during the phonemic fluency task and with smaller activation in the middle frontal gyrus during both verbal fluency tasks.

Makizako et al.	2013	Role of going outdoor daily in word retrieval among older adults	Old: *n* = 20 (10M, 10F); *M* = 76.1, *SD* = 6.7, range: 66–89	3-cm separation; 1.54 Hz; 16 bilateral prefrontal channels (OEG-16; Spectratech Inc.; Yokohma, Japan)	Phonemic fluency (Japanese syllables "Shi", "I", and "Re"; a 60-s active task period for each syllable)	Older adults who went outdoors daily showed greater increases in [oxy-Hb] in the bilateral PFC than those who did not.
Obayashi and Hara	2013	Young v.s. Old	Young: *n* = 11 (3M, 8F); *M* = 28.4, range: 21–36 Old: *n* = 11 (3M, 8F); *M* = 63.3, range: 53–76	3-cm separation; 10 Hz; 22 bilateral superior frontal channels (ETG-4000; Hitachi Medical Co., Tokyo, Japan)	Phonemic fluency (five initial Japanese letters; five blocks of 20-s active task period)	Older adults had smaller retrieval-related increases in [oxy-Hb] in the anterior section of the superior frontal region than younger adults.
Pu et al.	2014	Role of social functioning in word retrieval among older adults	Old: *n* = 55 (26M, 29F); *M* = 70.1, *SD* = 5.4	3-cm separation; 10 Hz; 52 bilateral frontotemporal channels (ETG-4000; Hitachi Medical Co., Tokyo, Japan)	Phonemic fluency (Japanese syllables; 60-s active task period; three consecutive syllables, each for 20 s, per block)	Greater increases in [oxy-Hb] in the frontopolar cortex and ventrolateral PFC correlated with a higher Social Adaptation Self-evaluation Scale total score and higher interpersonal relationship and interest and motivation factor scores.
Heinzel et al.	2015	Roles of age, sex, education, and vascular burden factors in word retrieval among middle-aged and older adults	Middle-aged and older adults: *n* = 1052 (548M, 504F); *M* = 65.2, *SD* = 6.8, range: 51–83 (analytic sample: *n* = 727; 425M, 302F)	3-cm separation; 44 bilateral frontotemporal and parietal channels	Phonemic (A, F, M) and semantic fluency (professions, fruits, and flowers; weekday; 30-s active task period)	Age predicted greater increases in [oxy-Hb] in the right middle frontal gyrus and bilateral inferior parietal regions during the phonemic fluency task and in the bilateral motor regions during the semantic fluency task; it also predicted smaller increases in [oxy-Hb] in the bilateral frontotemporal regions, including the inferior frontal junction, during both verbal fluency tasks. Age tended to predict less left-lateralized inferior frontal activation. Years of education predicted decreased [oxy-Hb] changes in the right middle frontal gyrus, and hypertension predicted decreased [oxy-Hb] changes in the left inferior frontal junction during both verbal fluency tasks.

Kato et al.	2017	Role of sleep duration in word retrieval among older adults	Old: *n* = 73 (51M, 22F); *M* = 70.1, *SD* = 3.9, range: ≥ 60	3-cm separation; 10 Hz; 2 bilateral forehead channels (HOT121B; Hitachi High-Technologies Co. Ltd., Tokyo, Japan)	Phonemic fluency (Japanese syllables, each for 20 s; three syllables in a row)	Older adults with fewer than seven hours of sleep had smaller changes in [oxy-Hb] than older adults with at least seven hours of sleep. Time to peak change in [oxy-Hb] was shorter in current-smokers than in never-smokers; peak change in [oxy-Hb] was smaller in older adults with hyperlipidemia than older adults without hyperlipidemia. Neither body mass index nor hypertension was associated with changes in [oxy-Hb].
Katzorke et al.	2017	Role of apolipoprotein-E4 in word retrieval among older adults	Older adults with apolipoprotein-E3/E3 (neutral variant): *n* = 210 (107M, 103F); *M* = 73.9, *SD* = 1.6 Older adults with apolipoprotein-E4/E4, E3/E4: *n* = 78 (36M, 42F); *M* = 73.7, *SD* = 1.6	10 Hz; 52 bilateral frontotemporal channels (ETG-4000; Hitachi Medical Corporation, Tokyo, Japan)	Phonemic (A, F, S) and semantic fluency (animals, fruits, flowers) (30-s active task period)	Older adults with apolipoprotein-E4/E4 or -E3/E4 had a larger decrease in [deoxy-Hb] in the left dorsolateral PFC but had a smaller decrease in [deoxy-Hb] in the right inferior frontal junction than older adults with apolipoprotein-E3/E3 during the semantic fluency task. Better task performance correlated with a greater decrease in [deoxy-Hb] in the left dorsolateral PFC.

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 7. A summary of functional near-infrared spectroscopy (fNIRS) studies on attentional shifting (task-switching and dual-tasking) in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
Gagnon et al.	2012	Effect of glucose ingestion on multitasking in older adults without diabetes	Old: *n* = 20 (4M, 16F); *M* = 69.4, range: ≥ 60 (analytic sample: *n* = 15)	3-cm separation; 36 bilateral frontal channels (CW6; TechEn Inc., Milford, MA)	Psychological refractory period and dual-task paradigms with color and letter tasks (single-pure, single-mixed, and dual-mixed conditions; 40 trials per condition)	In both the color and letter tasks, glucose ingestion led to larger increases in [oxy-Hb] and [total-Hb] and a larger decrease in [deoxy-Hb] in the (right) ventrolateral PFC during dual-mixed than single-mixed trials, whereas placebo treatment led to smaller increases in [oxy-Hb] and [total-Hb] and a smaller decrease in [deoxy-Hb] in the right ventrolateral PFC in dual-mixed than single-mixed trials. Glucose ingestion enhanced the ability to coordinate two tasks equally compared to placebo treatment.
Laguë-Beauvais, Brunet, Gagnon, Lesage, and Bherer	2013	Young v.s. Old	Young: *n* = 21 (9M, 12F); *M* = 24.4, *SD* = 4.5, range: 19–36 Old: *n* = 19 (3M, 16F); *M* = 64.0, *SD* = 3.4, range: 59–69	2.8-cm separation; 10 Hz (after downsampling); 26 bilateral prefrontal channels (CW5; TechEn Inc., Milford, MA)	Modified Stroop [neutral, congruent, interference, and switching (i.e., word reading in 25% of the trials) conditions; intertrial intervals ranging from 8–16 s]	While switching led to activation in isolated parts of the bilateral anterolateral PFC in younger adults, it led to widespread activation in the bilateral anterolateral and posterolateral PFC in older adults.
Ohsugi, Ohgi, Shigemori, and Schneider	2013	Young v.s. Old	Young: *n* = 20 (10M, 10F); *M* = 26.0, *SD* = 3.6, range: 21–35 Old: *n* = 15 (6M, 9F); *M* = 77.9, *SD* = 5.3, range: > 65	3-cm separation; 10 Hz; 47 bilateral frontal channels (analyses based on 14 channels) (ETG-7100; Hitachi Medical Co., Tokyo, Japan)	Dual-task motor execution (stepping, backward counting by 7, and stepping during backward counting; 30-s active task period; three repetitions per task)	Older adults had a greater increase in frontal [oxy-Hb] than younger adults within the 10-s period after completion of the dual-task performance but not during task performance. There were no significant differences in [oxy-Hb] changes between younger and older adults during stepping or backward counting.
Albinet, Mandrick, Bernard, Perrey, and Blain	2014	Role of aerobic fitness in shifting among older adults	Old: *n* = 34 (0M, 34F); range: 60–77	4-cm separation; 6 Hz; 2 bilateral forehead channels (NIRO-200; Hamamatsu	Random number generation [ascending counting, cued random number generation at fast or slow pace; 100- or	Low-fit women had a smaller increase in [oxy-Hb] in the right dorsolateral PFC than high-fit women.

				Photonics K.K., Japan)	150-s active task period]	
Hagen et al.	2014	Middle-aged v.s. Old	Middle-aged and older adults: *n* = 16 (8M, 8F); *M* = 59.2, *SD* = 6.2, range: 50–75 [median-split into the younger (< 58 yr) and older (> 58 yr) groups]	10 Hz; 38 bilateral prefrontal and superior parietal channels (ETG-4000; Hitachi Medical Co., Japan)	Trail Making Test (Parts A and B; 60-s active task period; two repetitions per condition)	The older group had larger increases in [oxy-Hb] in the bilateral somatosensory cortex and primary motor cortex but smaller increases in [oxy-Hb] in the bilateral inferior frontal gyri and right dorsolateral PFC than the younger group. While the younger group had shift-related increases in [oxy-Hb] in the inferior frontal gyrus and dorsolateral PFC, the older group tended to show no change or even decreases in [oxy-Hb].
Müller et al.	2014	Young v.s. Old	Young: *n* = 20 (8M, 12F); *M* = 25.7, *SD* = 3.0 Old: *n* = 20 (8M, 12F); *M* = 71.0, *SD* = 3.6	3-cm separation; 10 Hz; 52 bilateral frontotemporal channels (analyses based on 32 frontal channels) (ETG-4000; Hitachi Medical Co., Tokyo, Japan)	Modified Trail Making Test with five more circles per condition (Parts A and B, and motor control conditions; 30-s active task period; three blocks per condition)	While younger adults had right-lateralized increases in task-related [oxy-Hb] in the dorsolateral and dorsomedial frontal regions during Part B of the Trail Making Test, older adults had bilateral increases in [oxy-Hb] and a greater increase in [oxy-Hb] in the left dorsomedial frontal region than younger adults. Neither younger nor older adults had a task-related change in [oxy-Hb] on Part A of the Trail Making Test.
Dupuy et al.	2015	Young v.s. Old; role of physical fitness in task-switching	Young: *n* = 22 (0M, 22F); *M* = 24.6, *SD* = 3.6, range: 19–34 Old: *n* = 36 (0M, 36F); *M* = 62.9, *SD* = 5.4, range: 55–72	2.8-cm separation; 28 bilateral prefrontal channels (CW6, TechEn Inc., Milford, MA)	Modified Stroop (color-naming and executive conditions; 4 s per trial, 60 s per block, and two blocks per condition)	Age did not significantly affect changes in [oxy-Hb] or [total-Hb] during the Stroop test. Higher-fit individuals, regardless of age, had higher changes in [oxy-Hb] and [total-Hb] in the right inferior frontal gyrus than lower-fit individuals in both the naming and executive conditions.
Laguë-Beauvais et al.	2015	Young v.s. Old	Young: *n* = 16 (7M, 9F); *M* = 23.9, *SD* = 2.3, range: 20–29 Old: *n* = 19 (6M, 13F); *M* = 63.5, *SD* = 3.7, range: 55–70	2.8-cm separation; 10 Hz (after down-sampling); 28 bilateral prefrontal channels (CW6, TechEn Inc., Milford, MA)	Psychological Refractory Period and dual-task paradigms with priority or equal instructions (single pure trials and intermixed single- and dual-mixed trials; 40 trials per condition)	When instructed to give priority to one of the two tasks, dual-task demand induced right-sided PFC activation in younger adults but left dorsolateral PFC and bilateral ventrolateral PFC activation in older adults. When instructed to give equal priority to two tasks, dual-task demand induced left PFC activation in younger adults but widespread bilateral dorsolateral PFC activation in older adults. A larger decrease in [deoxy-Hb] in the posterior dorsolateral PFC correlated with poorer dual-

						task performance in the Equal condition among older adults.
Huppert et al.	2017	Role of age in shifting among older adults	Older adults living in residential care communities: *n* = 19; *M* = 88.1, *SD* = 6.0, range: ≥ 65	3.2-cm separation; 200 Hz; 10 bilateral prefrontal channels (NIRS-2; TechEn Inc, Milford, MA, USA)	Shifting Attention Test (90 s)	Age negatively correlated with the change in [total-Hb] in the right superior frontal cortex.
Corp et al.	2018	Young v.s. Old	Experiment 1: Young: *n* = 15 (9M, 6F); *M* = 27.7, *SD* = 3.1, range: 21–35 Old: *n* = 15 (9M, 6F); *M* = 65.2, *SD* = 3.9, range:58–73 Experiment 2: Old: *n* = 15 (7M, 8F); *M* = 66.3, *SD* = 4.6, range: 60–76	10 Hz; 3-cm separation; 2 bilateral prefrontal channels (Oxymon MKIII, Artinis Medical Systems, Zetten, The Netherlands)	Dual-tasking (arm tracking, letter 1-, 2-, and 3-back, foot tapping, letter fluency, and arm tracking plus each of the other tasks; 1-min active task period)	There was no difference in the change in hemoglobin differential (i.e., [oxy-Hb] minus [deoxy-Hb]) collapsed across conditions between younger and older adults in either hemisphere.
Vasta et al.	2018	Young v.s. Old	Young: *n* = 27 (15M, 12F); *M* = 30.0, *SD* = 7.9, range: 18–50 Old: *n* = 11 (6M, 5F); *M* = 57.2, *SD* = 9.3, range: ≥ 50	3-cm separation 48 bilateral frontal, central, and parietal channels (ETG-4000 Optical Topography System; Hitachi Medical Co., Japan)	Cued task-switching paradigm with color and shape tasks (single-task and mixed-task conditions; 20 trials per single-task block, and 40 repeat and 40 switch trials per mixed-task block)	Older adults had lower changes in [oxy-Hb] in the left premotor cortex than younger adults during switch trials. The changes in [oxy-Hb] in the premotor cortex during switch trials (beta = -0.32) and in the superior frontal gyrus during shape single-task trials (beta = 0.34) were the best predictors of age (R^2 = 0.81).

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 8. A summary of functional near-infrared spectroscopy (fNIRS) studies on inhibitory control, including a) motor inhibition, b) reflexive saccade inhibition, and c) interference control, in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
a) Motor inhibition						
Schroeter, Zysset, Kruggel, and von Cramon	2003	Young v.s. Old	Young: *n* = 14 (6M, 8F); *M* = 23.9, *SD* = 3.1, range: 19–29 Old: *n* = 14 (7M, 7F); *M* = 65.1, *SD* = 3.1, range: 62–71	4- or 5-cm separation; 6 Hz; 10 bilateral frontal and parietal channels (NIRO-300; Hamamatsu Photonics K.K., Japan)	Color-word matching Stroop (neutral, congruent, and incongruent trials; 12–14 s per trial; 10 trials per condition and run)	Older adults had a smaller change in [total-Hb] and a smaller difference between [oxy-Hb] and [deoxy-Hb] changes than younger adults in lateral PFC but not in motor or parietal regions. Error rate negatively correlated with lateral PFC activation; reaction time positively correlated with superior parietal activation.
Hyodo et al.	2012	Effect of acute exercise on motor inhibition in older adults	Old: *n* = 16 (13M, 3F); *M* = 69.3, *SD* = 3.5, range: 64–74	3-cm separation; 10 Hz; 48 bilateral frontal channels (ETG-7000; Hitachi Medical Co., Kashiwa, Japan)	Matching Stroop (neutral and incongruent trials; 11–15 s per trial; 30 trials per condition and run)	An acute bout of moderate exercise led to a larger interference-induced increase in [oxy-Hb] in the right frontopolar area, which was associated with the exercise-induced reduction in Stroop reaction time interference, than rest.
Lucas et al.	2012	Young v.s. Old	Young: *n* = 13 (7M, 6F); *M* = 24, *SD* = 5 Old: n = 9 (4M, 5F); *M* = 62, *SD* = 3	1 Hz; 1 right forehead channel (NIRO-200; Hamamatsu Photonics KK, Hamamatsu, Japan)	Color-word matching Stroop (simple and difficult conditions; task performance first at rest, then while cycling at 30% and 70% of the heart rate range)	Younger and older adults had similar changes in [oxy-Hb], [deoxy-Hb], and [total-Hb] during the Stroop task while cycling, regardless of exercise intensity.
Heilbronner and Münte	2013	Young v.s. Old	Young: *n* = 19 (10M, 9F); *M* = 23.1, *SD* = 1.7, range: 20–26 Old: *n* = 16 (11M, 5F); *M* = 68.4, *SD* = 1.4, range: 60–76	10 Hz; 52 bilateral frontotemporal channels (Hitachi ETG-4000; Hitachi Medical Systems)	Visual Go/NoGo (79.8% go and 20.2% no-go trials; 1.4 s per trial; 1083 trials in total)	Older adults had a larger inhibition-elicited decrease in [deoxy-Hb] in the right middle frontal gyrus but smaller decreases in [deoxy-Hb] in the bilateral precentral or inferior frontal regions than younger adults.

Laguë-Beauvais, Brunet, Gagnon, Lesage, and Bherer	2013	Young v.s. Old	Young: *n* = 21 (9M, 12F); *M* = 24.4, *SD* = 4.5, range: 19–36 Old: *n* = 19 (3M, 16F); *M* = 64.0, *SD* = 3.4, range: 59–69	2.8-cm separation; 10 Hz (after downsampling); 26 bilateral prefrontal channels (CW5; TechEn Inc., Milford, MA)	Modified Stroop [neutral, congruent, interference, and switching (i.e., word reading in 25% of the trials) conditions; intertrial intervals ranging from 8–16 s]	While there was no interference-induced PFC activation in younger adults, there was interference-induced activation in the left posterior and right anterior dorsolateral PFC as well as bilateral ventrolateral PFC activation in older adults.
Dupuy et al.	2015	Young v.s. Old; role of physical fitness in motor inhibition	Young: *n* = 22 (0M, 22F); *M* = 24.6, *SD* = 3.6, range: 19–34 Old: *n* = 36 (0M, 36F); *M* = 62.9, *SD* = 5.4, range: 55–72	2.8-cm separation; 28 bilateral prefrontal channels (CW6, TechEn Inc., Milford, MA)	Modified Stroop Color Test [color-naming (i.e., neutral) and executive (i.e., intermixed inhibition and switch trials) conditions; 4 s per trial, 60 s per block)	Age did not affect changes in [oxy-Hb] or [total-Hb] during the Stroop task. Regardless of age, higher-fit individuals, who had a higher maximal oxygen uptake, had higher changes in [oxy-Hb] and [total-Hb] in the right inferior frontal gyrus than lower-fit individuals in both the color-naming and executive conditions.
Hyodo et al.	2016	Role of aerobic fitness in motor inhibition among older adults	Old: *n* = 60 (60M, 0F); *M* = 70.3, *SD* = 3.2	3-cm separation; 10 Hz; 48 bilateral frontal, temporal, and parietal channels (bilateral dorsolateral PFC as regions of interest) (ETG-7000; Hitachi Medical Corporation. Kashiwa, Japan)	Color-word matching Stroop (neutral and incongruent trials; event-related design; 11–15 s per trial)	Stroop interference reaction time negatively correlated with ventilatory threshold and with the left-lateralized increases in [oxy-Hb] in the dorsolateral PFC. Ventilatory threshold but not age or years of education positively correlated with left-lateralized dorsolateral PFC activation, which partially mediated the association between ventilatory threshold and Stroop interference reaction time.
Huppert et al.	2017	Role of age in motor inhibition among older adults	Older adults living in residential care communities: *n* = 19; *M* = 88.1, *SD* = 6.0, range: ≥ 65	3.2-cm separation; 200 Hz; 10 bilateral prefrontal channels (NIRS-2; TechEn Inc, Milford, MA, USA)	Stroop Test (word reading, congruent, and incongruent conditions; 30, 45, and 90 s, respectively)	Age positively correlated with the change in [total-Hb] in the right superior frontal cortex in both the incongruent and congruent conditions of the Stroop task.
b) Reflexive saccade inhibition						
Fujiwara et al.	2010	Young v.s. Old	Young: *n* = 22 (12M, 10F); *M* = 22.4, *SD* = 2.2, range: 20–29	3-cm separation; 10 (ETG-4000) or 2 Hz (NIRO-200);	Antisaccade (prosaccade and antisaccade	Younger and older adults had comparable increases in [oxy-Hb] in all conditions.

			Old: *n* = 96 (51M, 45F); *M* = 72.2, *SD* = 5.0, range: 60–85	Bilateral frontal channels (ETG-4000; Hitachi Medical, Japan; NIRO-200; Hamamatsu Photonics, Japan)	conditions; 60-s active task period)	
Bierre, Kirstin, Guiney, Cotter, and Machado	2017	Young v.s. Old	Young: *n* = 36 (16M, 20F); *M* = 21.9, *SD* = 2.7, range: 18–30 Old: *n* = 36 (16M, 20F); *M* = 66.2, *SD* = 3.8, range: 60–72	4.5-cm separation; 1 Hz; 2 bilateral forehead channels (NIRO-200; Hamamatsu Photonics K.K., Hamamatsu, Japan)	Antisaccade (prosaccade, antisaccade, and mixed-task conditions; 2.4–3.2 s per trial; 20 prosaccade trials, followed by 20 antisaccade trials, and ended with 40 mixed-task trials)	After controlling for years of education, older adults had higher changes in [oxy-Hb] and [total-Hb] in the PFC than younger adults only in the two conditions with antisaccade trials. The changes in [oxy-Hb] and [total-Hb] correlated with a faster reaction time in the mixed-task condition in older adults.
c) Interference control						
Kawai, Kubo-Kawai, Kubo, Terazawa, and Masataka	2012	Young v.s. Old	Young: *n* = 13 (8M, 5F); *M* = 22.6, range: 20–31 Old: *n* = 15 (13M, 2F); *M* = 70.0, range: 65–75	3-cm separation; 1 Hz; 8 bilateral prefrontal channels (NIRO-200; Hamamatsu Photonics, Hamamatsu, Japan)	Simon and flanker (congruent and incongruent trials; 12–14 s per trial)	Older adults had larger increases in [oxy-Hb] in the left PFC in the flanker task and in the bilateral superior PFC in the Simon task across congruency conditions.
Halliday et al.	2017	Role of functional brain activation in interference control among older adults	Old: *n* = 25 (12M, 13F); *M* = 75.9, *SD* = 3.3, range: 71–81	1.5-cm (2 channels) and 3-cm (8 channels) separation 50 Hz; 10 bilateral prefrontal channels (TechEn CW6; TechEn Inc., Milford, Massachusetts)	Multisource Interference Test (control and interference conditions; 30-s active task period; 4 blocks per condition)	At the group level, a higher change in [oxy-Hb] in the (left) PFC correlated with less accurate performance in both the control and interference conditions. At the individual level, a higher change in [oxy-Hb] in the right PFC correlated with a faster reaction time in the control condition but with a less accurate performance in the interference condition.
Halliday et al.	2018	Role of fall history in interference control	Older adults without a history of falls over the past two years: *n* = 15 (8M, 7F); *M* =	3-cm separation (8 channels) and 1.5-cm separation (2 channels);	Multisource Interference Test (control and interference	Fallers had a higher change in [oxy-Hb] in the lateral PFC than nonfallers in both the control and interference conditions relative to baseline.

among older adults	75.9, *SD* = 3.4, range: 71–81 Older adults with a history of falls: *n* = 12 (4M, 8F); *M* = 76.3, *SD* = 3.2, range: 71–81	10 bilateral prefrontal channels (TechEn CW6; TechEn Inc., Milford, Massachusetts)	conditions; 30-s active task period; four blocks per condition)

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 9. A summary of functional near-infrared spectroscopy (fNIRS) studies on memory function, including a) verbal working memory, b) visuospatial WM, and c) episodic memory, in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
a) Verbal WM						
Vermeij et al.	2012	Young v.s. Old	Young: *n* = 17 (7M, 10F); *M* = 25.9, *SD* = 3.0, range: 21–32 Old: *n* = 17 (6M, 11F); *M* = 70.7, *SD* = 5.2, range: 64–81	5-cm separation; 125 Hz; 2 bilateral forehead channels (Oxymon; Artinis Medical Systems, The Netherlands)	Letter *n*-back (0-, 1-, and 2-back conditions; 3.5 s per trial; 180 s per condition)	While younger adults had a right-lateralized increase in [oxy-Hb] in the PFC, older adults had a less-lateralized increase in [oxy-Hb] during the 0-back and 1-back tasks. While there were linear changes in [oxy-Hb], [deoxy-Hb], and [total-Hb] during the late task period in younger adults, these signals reached plateau or even declined during the late task period in older adults during the 2-back task.
Vermeij, Meel-van den Abeelen, Kessels, van Beek, and Claassen	2014	Young v.s. Old	Young: *n* = 14 (6M, 8F); *M* = 26.4, *SD* = 3.0, range: 23–32 Old: *n* = 14 (4M, 10F); *M* = 70.3, *SD* = 4.7, range: 64–78	5-cm separation; 2 bilateral prefrontal channels (Oxymon Mk III, Artinis Medical System, The Netherlands)	Letter *n*-back (0- and 2-back conditions; 180-s active task period; 60 trials with 17 targets per condition)	Older adults tended to have larger [oxy-Hb] changes than younger adults during the 2-back but not 0-back task. Older adults demonstrated weaker very-low-frequency (0.02–0.07 Hz) [oxy-Hb] and [total-Hb] oscillations than younger adults during the 0-back but not 2-back task. Older adults had weaker low-frequency (0.07–0.2 Hz) and high-frequency (0.2–0.35 Hz) [oxy-Hb], [deoxy-Hb], and [total-Hb] oscillations than younger adults, regardless of WM load.
Agbangla, Audiffren, Pylouster, and Albinet	2019	Young v.s. Old; role of aerobic fitness in verbal WM among older adults	Young: *n* = 19 (17M, 2F); *M* = 19.7, *SD* = 1, range: 18–22 Old: *n* = 37 (15M, 22F); *M* = 69.0, *SD* = 4.7, range: 60–77 (higher-fit: *n* = 21; lower-fit: *n* = 16)	3.5-cm separation 10 Hz; 8 bilateral dorsolateral and ventrolateral PFC channels (OxyMon MkIII; Artinis Medical Systems BV, Zetten, Netherlands)	Letter *n*-back (0-, 1-, 2-, 3-back conditions; 150-s active task period; 30% targets)	Older adults had greater WM-related increases in bilateral frontal [oxy-Hb] than younger adults during the 1-back but not 2- and 3-back tasks. Higher-fit older adults had a larger WM-related increase in [oxy-Hb] and a larger decrease in [deoxy-Hb] in the left PFC than lower-fit older adults. Three-back sensitivity was associated with the change in left PFC [oxy-Hb] among higher-fit older adults.

Jackson et al.	2016	Effect of six months of docosahexaenoic acid (DHA) supplement on WM and attention in older adults	Placebo: *n* = 28 (10M, 18F); M = 59.6, SD = 5.3, range: 50–70 DHA-rich fish oil multinutrient: *n* = 30 (12M, 18F); *M* = 60.0, *SD* = 4.7, range: 50–70 DHA-rich fish oil: *n* = 26 (10M, 16F); *M* = 60.3, *SD* = 4.9, range: 50–70	4-cm separation; 2 bilateral forehead channels (Oxymon; Artinis Medical Systems B.V., Zetten, The Netherlands)	Cognitive Demand Battery (Serial 3 and 7 subtractions, and Rapid Visual Information Processing; 9 min in total)	Neither DHA multinutrient supplement nor DHA-rich fish oil led to significant changes in [oxy-Hb], [deoxy-Hb], or [total-Hb] in the PFC during task performance.
Bu, Wang et al.	2018	Role of sleep quality in functional connectivity during WM updating among older adults	Older adults without poor sleep quality: *n* = 14 (7M, 7F); *M* = 65.4, *SD* = 1.7 Older adults with poor sleep quality: *n* = 15 (8M, 7F); *M* = 64.7, *SD* = 1.7	10 Hz; 14 bilateral frontal, central, and occipital channels (Nirsmart, Danyang Huichuang Medical Equipment Co. Ltd, China)	One-back task (3-digit version; 15 min)	Older adults with poor sleep quality had higher wavelet amplitudes in the left PFC and occipital lobe and exhibited lower wavelet phase coherences of slow [oxy-Hb] oscillations (0.01–0.08 Hz) between the left and right PFC and between the PFC and the motor or occipital cortex than those without poor sleep quality during task performance.
Wightman et al.	2018	Effect of Greek mountain tea on cognition in older adults	Old: *n* = 57 (26M, 31F); *M* = 60.1	2- to 3.5-cm separation; 5 Hz; 2 bilateral forehead channels (OxiplexTS, ISS, Inc., Champaign, IL, USA)	Cognitive Demand Battery (Serial 3 and 7 subtractions, and Rapid Visual Information Processing; 9 min in total)	Older adults who drank low and high doses of Greek mountain tea containing the *Sideritis scardica* extract had higher changes in [oxy-Hb] and [deoxy-Hb] than those who received placebo treatment while undertaking the Cognitive Demand Battery at Day 1 but not at Day 28.
Adorni et al.	2019	Effect of time stress or role of anxiety in arithmetic among older adults	Old: *n* = 18 (10M, 8F); *M* = 70, *SD* = 6.3, range: 60–85	3-cm separation; 61.3 Hz; 2 bilateral dorsolateral prefrontal channels (PocketNIRS Duo, DynaSense, Hamamatsu, Japan)	Arithmetic (stress and control conditions; sum and subtraction operations; 5-min blocks)	Time stress did not lead to different changes in [oxy-Hb] or [deoxy-Hb] during arithmetic tasks. Level of Anxiety positively correlated with the right lateralization of changes in [oxy-Hb] while solving arithmetic operations under stress.
b) Visuospatial WM						

Oboshi et al.	2014	Young v.s. Old	Young: *n* = 60 (27M, 44F); *M* = 21.7, *SD* = 3.3, range: 19–33 Old: *n* = 60 (29M, 31F); *M* = 71.0, *SD* = 6.4, range: 59–87	3-cm separation; 1.53 Hz; 16 bilateral prefrontal channels (OEG-16, Spectratech Inc.)	Mental rotation [nonflipped and flipped images (i.e., easy and difficult conditions); 28.8-s active task period]	Older adults had lower changes in [oxy-Hb] in the bilateral prefrontal and frontopolar regions than younger adults during the pretask period. The changes in [oxy-Hb] in medial and right-lateral frontal regions during the pretask period positively correlated with task performance in both younger and older adults. Older adults had greater manipulation-related changes in [oxy-Hb] in the bilateral PFC, which correlated with poorer accuracy, than younger adults.
Vermeij, van Beek, Reijs, Claassen, and Kessels	2014	Effect of spatial WM load on PFC activity in older adults	High-performing older adults: *n* = 9 (4M, 5F); *M* = 69.0, *SD* = 3.8, range: 65–77 Low-performing older adults: *n* = 9 (3M, 6F); *M* = 72.7, *SD* = 5.6, range: 64–81	5-cm separation; 2 bilateral forehead channels (Oxymon Mk III; Artinis Medical Systems, Netherlands)	Spatial *n*-back (0-, 1-, and 2-back conditions; 14 locations and 28.3% targets; 60 trials per condition, each trial for 3 s)	Low-performers had a smaller change in [oxy-Hb] in the right PFC than high-performers in the 2-back condition but not in other conditions. During the 2-back task, there was a left-lateralized increase in [oxy-Hb] in the PFC among low-performers, whereas there tended to be a right-lateralized increase in [oxy-Hb] in the PFC in high-performers.
Yamanaka et al.	2014	Young v.s. Old; effect of parietal transcranial magnetic stimulation on spatial WM	Young: *n* = 52 (30M, 22F); *M* = 23.5, *SD* = 2.7 Old: *n* = 38 (17M, 21F); *M* = 72.5, *SD* = 4.7, range: 64–83	3-cm separation; 10 Hz; 52 bilateral frontotemporal channels (ETG-4000; Hitachi Medical Corporation, Tokyo, Japan)	Spatial delayed match-to-sample (control and WM tasks under real or sham TMS; ten 42-s trials per condition; 17 s per trial)	Older adults had larger increases in frontal [oxy-Hb] than younger adults in all conditions, with high-performers showing a larger increase in [oxy-Hb] than low-performers among older adults. For younger adults, real transcranial magnetic stimulation at P3 induced decreases in frontal [oxy-Hb] during the WM task but increases in [oxy-Hb] during the control task, while transcranial magnetic stimulation at P4 led to an opposite pattern. For older adults, transcranial magnetic stimulation over either side of the parietal cortex had no effect on [oxy-Hb].
Stephens and Berryhill	2016	Effect of transcranial	Old: *n* = 90 (equally assigned to sham or	50 Hz;	Visual *n*-back (0- and 2-back conditions;	Regardless of the transcranial direct current stimulation condition, there was a larger

		direct current stimulation paired with WM training on visual WM in older adults	1 mA or 2 mA of transcranial direct current stimulation paired with WM training)	14 bilateral prefrontal channels (TechEn CW6 fNIRS System; Milford, MA)	21-s active task period)	number of right PFC channels showing smaller increases in [oxy-Hb] relative to the pre-stimulation baseline period. The percentage of channels with decreased right PFC activation was associated with better 2-back performance.
Wijeakumar, Magnotta, and Spencer	2017	Young v.s. Old	Young: *n* = 24; *M* = 25.4, *SD* = 4.3 Old: *n* = 24; *M* = 70.5, *SD* = 5.2	1-cm (4 channels) and 3-cm (36 channels) separation; 25 Hz; 40 bilateral frontal and parietal channels (TechEn CW6 system)	Change Detection task ('simple' color and 'complex' shape tasks; WM load varied from 1 to 3 items; 20 same and 20 different trials per load and run)	Older adults generally had lower increases in [oxy-Hb] in posterior regions but larger increases in [oxy-Hb] in anterior regions than younger adults. Older adults had decreased activity in the right intraparietal lobule and left supramarginal gyrus during the simple task but had increased activity in these regions during the complex task. Older adults had increased activity in the right middle frontal gyrus at low load but decreased activity in this region at high load during the complex task; there was no modulation of right middle frontal activity during the simple task.
Causse, Chua, and Rémy	2019	Young v.s. Middle-aged v.s. Old; role of flying experience in spatial WM among older adults	Young: *n* = 18 (17M, 1F); *M* = 21.0, *SD* = 1.6, range: 19–25 Middle-aged: *n* = 19 (17M, 2F); *M* = 38.3, *SD* = 6.9, range: 30–48 Old: *n* = 24 (24M, 0F); *M* = 62.3, *SD* = 6.6, range: 51–74	2.5-cm separation; 2 Hz; 16 forehead channels (Biopac fNIR 100)	Cambridge Neuropsychological Test Automated Battery Spatial WM (four difficulty levels) and One Touch Stockings of Cambridge (six difficulty levels)	Older adults had a lower increase in [oxy-Hb] in the left lateral PFC than younger adults at the high difficulty level of the spatial WM task. Flying experience did not affect the level of [oxy-Hb] in the left PFC among older adults. There was no effect of age on [oxy-Hb] during the tower task.
c) Episodic memory						
Ferreri et al.	2014	Effect of music on episodic memory in older adults	Old: *n* = 16 (6M, 10F); *M* = 64.5, *SD* = 2.5	3.5-cm separation; 20 Hz; 8 bilateral dorsolateral prefrontal channels (Oxymon Mk III;	Word recognition (music and silence conditions; 28-s verbal encoding periods preceded and	There were smaller increases in [oxy-Hb] and [total-Hb] in the bilateral dorsolateral PFC in the music condition than in the silence condition during verbal encoding.

	Artinis Medical Systems B.V., The Netherlands)	followed by 15 s of music or silence; seven words per block)	Verbal recognition was better when words were encoded with the music background than in silence.

Note. PFC = prefrontal cortex; WM = working memory; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration; [total-Hb] = total hemoglobin concentration.

Supplementary Table 10. A summary of functional near-infrared spectroscopy (fNIRS) studies on emotion and motivation (i.e., emotion perception and value-based decision-making) in healthy older adults.

Author Names	Year	Study Type	Sample Characteristics	fNIRS Parameters	Activation Task	fNIRS Findings
Kida et al.	2014	Effect of the sight of one's own grandchild on PFC activity in female older adults	Old: *n* = 17 (0M, 17F); *M* = 63.7, *SD* = 6.6	0.5 Hz; 10 bilateral forehead channels (NIRO-200, Hamamatsu Photonics, Japan)	Video clip watching (the neutral and smiling expressions of one's own or someone else's grandchild; 30-s task period)	Relative to viewing someone else's grandchild, viewing one's own grandchild led to increased [oxy-Hb] and decreased [deoxy-Hb] changes in the medial frontopolar cortex, regardless of expression. Subjective love rating positively correlated with [oxy-Hb] changes in the medial frontopolar cortex.
Li, Cazzell, Zeng, and Liu	2017	Young v.s. Old	Young: *n* = 40 (17M, 23F); *M* = 28.8, *SD* = 5.4, range: 25–40 Old: *n* = 60 (22M, 38F); *M* = 76.2, *SD* = 6.5, range: 60–92	3-cm (older adults) or 3.25-cm (younger adults) separation; 72 (older adults) or 40 (younger adults) bilateral frontal channels (Cephalogics, Washington University, USA)	Balloon Analog Risk Task (alternations between choice and feedback; 15 balloon trials, each allowing 3–10 s for choice)	Older adults exhibited more diffuse changes in [oxy-Hb] in the bilateral PFC at the time of choice, less diffuse changes in [oxy-Hb] in face of wins, and a higher change in [oxy-Hb] in the rostrolateral PFC in face of losses than younger adults. A larger [oxy-Hb] change in response to losses correlated with less risk-taking behavior in male and female older adults.
Nakata, Kubo-Kawai, Okanoya, and Kawai	2018	Young v.s. Old	Young: *n* = 22; *M* = 21.7, range: 19–31 Old: *n* = 20; *M* = 70.2, range: 65–74	1.52 Hz; 16 bilateral forehead channels; (OEG−16; Spectratech Inc., Yokohama, Japan)	Simulated driving (green- and red-light conditions with six traffic lights per condition)	While older adults had left-lateralized increases in prefrontal [oxy-Hb] while stopping at red lights, younger adults did not. Both age groups did not exhibit lateralized increases in prefrontal [oxy-Hb] while stopping at green lights. Older adults expressed greater anger after repeatedly stopping at red lights than younger adults.

Note. PFC = prefrontal cortex; [deoxy-Hb] = deoxyhemoglobin concentration; [oxy-Hb] = oxyhemoglobin concentration.

Supplementary Table 11. Risk of bias and quality control assessment for individual studies on (a) resting, (b) sensation and perception, (c) gross motor skills, (d) fine motor skills, (e) semantic processing, (f) word retrieval, (g) attentional shifting, (h) inhibitory control, (i) memory, and (j) emotion and motivation.

Authors	Year	*A Priori* Power Analysis Conducted	Correction for Multiple Channel Comparisons Applied	Years of Education Matched or Controlled for	Differential Pathlength Factor Addressed or Corrected for Age	Reporting of Both [oxy-Hb] and [deoxy-Hb]	Significant Results Only when Considering [deoxy-Hb]	Screening Test for Dementia Given	Artifact Correction Performed
(a) Resting									
Mehagnoul-Schipper, Colier, and Jansen	2001	N	/	/	/	Y	N	N	N
Schroeter, Schmiedel, and von Cramon	2004	N	/	?	Y	Y	N	N	N
Claassen, Colier, and Jansen	2006	N	/	/	/	N	/	N	N
Harada, Nashihara, Morozumi, Ota, and Hatakeyama	2007	N	/	?	N	Y	N	N	N
Hallacoglu et al.	2012	N	/	?	N	Y	N	N	N
Li et al.	2012	N	/	/	/	Y	N	N	Short-distance correction
Li, Zhang, Xin, Luo, Cui et al.	2013	N	/	?	N	Y	N	N	Short-distance correction
Li, Zhang, Xin, Luo, Zhou et al.	2013	N	/	/	/	Y	N	N	Short-distance correction
Suhr and Chelberg	2013	N	/	/	/	N	/	RBANS	N
Amiri et al.	2014	N	/	Y	N	Y	N	MoCA	N
Cui et al.	2014	N	/	?	N	N	/	N	Short-distance correction
Ishikawa et al.	2014	N	/	?	N	N	/	N	N
Li et al.	2014	N	/	/	/	N	/	N	Short-distance correction
Gao et al.	2015	N	/	?	N	N	/	N	Short-distance correction
Tan et al.	2016	N	/	?	N	N	/	N	Moving average, band-pass filtering, short-distance correction
Wang et al.	2016	N	N	?	N	N	/	N	Band-pass filtering, moving average
Bu, Huo et al.	2018	N	N	/	/	N	/	? (MMSE, MoCA)	Spline interpolation, band-pass filtering

Bu, Wang et al.	2018	N	N	/	/	N	/	N	Spline interpolation, band-pass filtering
Huo et al.	2018	N	N	?	N	N	/	? (MMSE)	Spline interpolation, band-pass
Li et al.	2018	N	/	?	N	N	/	N	Band-pass filtering, global autocorrelation removal
Mukli, Nagy, Racz, Herman, and Eke	2018	N	/	?	N	Y	N	N	Correlation-based signal improvement
Rhee and Mehta	2018	N	False discovery rate	/	/	N	/	N	Low-pass filtering, spline interpolation, kurtosis-based wavelet, band-pass filtering
Zeller et al.	2019	N	Bonferroni–Holm	?	N	Y	N	DemTect, MMSE	N
(b) Sensation and perception									
Fabiani et al.	2004	N	/	?	N	Y	N	MMSE	Low-pass filtering, Gaussian filtering, short-distance correction
Schroeter, Schmiedel, and von Cramon	2004	N	/	?	Y	Y	N	N	N
Karim, Fuhrman, Furman, and Huppert	2013	N	/	?	N	Y	N	N	Discrete cosine transform, prewhitening
Ward, Aitchison, Tawse, Simmers, and Shahani	2015	N	/	?	N	Y	N	N	Moving average
Jeong and Ryu	2016	N	N	Y	N	N	/	N	Low-pass filtering, high-pass filtering
Lin, Barker, Sparto, Furman, and Huppert	2017	N	False discovery rate	?	N	N	/	N	Prewhitening
Rosso et al.	2017	N	/	?	N	Y	N	RBANS	Prewhitening
Teo, Goodwill, Hendy, Muthalib, and Macpherson	2018	N	/	N (controlled for)	Y	Y	N	MMSE	Principal component analysis filtering, band-pass filtering
Ward, Morison, Simmers, and Shahani	2018	N	/	Y	N	Y	N	MMSE	Moving average, detrending
Marusic et al.	2019	N	/	Y	N	Y	N	? (MoCA)	N

(c) Gross motor skills								
Harada, Nashihara, Morozumi, Ota, and Hatakeyama	2007	N	/	?	N	Y	N	N	N
Harada, Miyai, Suzuki, and Kubota	2009	N	N	/	/	Y	N	MMSE	N
Holtzer et al.	2011	N	N	Y	N	N	/	MMSE	Low-pass filtering, combined independent and principal component analyses
Lin, Lin, and Chen	2012	N	N	?	Y	N	/	N	Band-pass filtering, principal component analysis
Lucas et al.	2012	N	/	?	N	Y	N	N	N
Beurskens, Helmich, Rein, and Bock	2014	N	Sun's tube formula	?	N	Y	N	N	Spline interpolation, precoloring, wavelet minimum description length detrending
Clark, Christou, Ring, Williamson, and Doty	2014	N	/	/	/	N	/	MMSE	N
Clark, Rose, Ring, and Porges	2014	N	/	/	/	N	/	MMSE	N
Holtzer et al.	2015	N	N	/	/	N	/	AD8	Low-pass filtering
Eggenberger, Wolf, Schumann, and de Bruin	2016	Y	/	/	/	Y	N	N	Moving-average detrending, extreme value exclusion
Fraser, Dupuy, Pouliot, Lesage, and Bherer	2016	N	N	Y	N	Y	N	MMSE	N
Osofundiya, Benden, Dowdy, and Mehta	2016	N	/	/	/	N	/	N	N
Chen et al.	2017	N	/	/	/	N	/	MIS	Low-pass filtering
Gayda et al.	2017	N	/	/	/	Y	N	N	Moving average
Holtzer et al.	2017a	N	/	/	/	N	/	AD8, MIS	Low-pass filtering
Holtzer et al.	2017b	N	/	/	/	N	/	AD8, MIS	Low-pass filtering
Knols et al.	2017	N	/	/	/	N	/	MoCA	N
Mirelman et al.	2017	N	/	Y	N	N	/	MoCA	Band-pass filtering, wavelet filtering, correlation-based signal improvement

Verghese, Wang, Ayers, Izzetoglu, and Holtzer	2017	N	/	/	/	N	/	AD8, MIS	Low-pass filtering
Hawkins et al.	2018	N	/	N	N	Y	N	MMSE	Extreme value exclusion with linear interpolation
Holtzer, George, Izzetoglu, and Wang	2018	N	/	/	/	Y	N	AD8, MIS	Low-pass filtering
Holtzer, Izzetoglu, Chen, and Wang	2018	N	/	/	/	Y	N	AD8, MIS	Low-pass filtering
Vitorio et al.	2018	Y	N	N	N	N	/	MoCA	Precoloring, wavelet minimum description length detrending
George, Verghese, Izzetoglu, Wang, and Holtzer	2019	N	/	/	/	N	/	AD8, MIS	N
Holtzer, Kraut, Izzetoglu, and Ye	2019	N	/	/	/	N	/	AD8, MIS	Low-pass filtering
Lucas, Wagshul, Izzetoglu, and Holtzer	2019	N	/	/	/	N	/	AD8	Low-pass filtering
Stuart, Alcock, Rochester, Vitorio, and Pantall	2019	Y	N	N	N	N	/	? (MoCA)	Precoloring, wavelet minimum description length detrending
Wagshul, Lucas, Ye, Izzetoglu, and Holtzer	2019	N	Bonferroni	/	/	N	/	AD8, MIS	Low-pass filtering
(d) Fine motor skills									
Mehagnoul-Schipper et al.	2002	N	/	?	Y	Y	N	N	N
Miyamoto, Yoshida, Tsuboi, and Iizuka	2005	N	/	/	/	N	/	N	High-pass filtering
Narita et al.	2009	N	/	/	/	Y	N	N	Principal component analysis
Shortz, Pickens, Zheng, and Mehta	2015	N	/	/	/	N	/	Mini-Cog	N
Kamiya, Narita, and Iwaki	2016	Y	Bonferroni	?	N	N	/	N	Moving average, linear fitting

Mehta and Rhee	2017	N	/	?	N	N	/	N	Low-pass filtering, wavelet-based motion artifact removal
Zich, Debener, Thoene, Chen, and Kranczioch	2017	N	/	N	N	Y	Y (lateralization)	N	High-pass filtering, low-pass filtering
Rhee and Mehta	2018	N	False discovery rate	/	/	N	/	N	Low-pass filtering, spline interpolation, kurtosis-based wavelet, band-pass filtering
(e) Semantic processing									
Tsujii, Okada, and Watanabe	2010	N	/	Y	N	Y	N	MMSE	Moving average
Scherer et al.	2012	N	Bonferroni	Y	N	Y	N	N	N
Amiri et al.	2014	N	Expected Euler	Y	N	Y	N	MoCA	Gaussian filtering, high-pass filtering, precoloring
Martin et al.	2018	N	N	Y	N	Y	N	MoCA	N
(f) Word retrieval									
Herrmann, Walter, Ehlis, and Fallgatter	2006	N	N	?	N	Y	N	N	Moving average, linear fitting
Kahlaoui et al.	2012	N	/	Y	N	N	/	MMSE	Band-pass filtering
Heinzel et al.	2013	N	False discovery rate	/	/	Y	N	MMSE	Moving average, band-pass filtering, common average reference correction
Makizako et al.	2013	N	/	/	/	N	/	? (MMSE)	Low-pass filtering, linear fitting
Obayashi and Hara	2013	N	/	N	N	Y	N	N	Linear fitting, moving average
Pu et al.	2014	N	False discovery rate	/	/	Y	N	MMSE	Linear fitting, moving average
Heinzel et al.	2015	N	False discovery rate	/	/	N	/	MMSE	Common average reference correction
Kato et al.	2017	N	/	/	/	N	/	N	N
Katzorke et al.	2017	N	False discovery rate	/	/	Y	Y	DemTect, MMSE	Discrete cosine transform, moving average, common average reference correction

(g) Attentional shifting								
Gagnon et al.	2012	N	N	/	/	Y	N	MMSE	Low-pass filtering, high-pass filtering
Laguë-Beauvais, Brunet, Gagnon, Lesage, and Bherer	2013	N	N	Y	N (addressed)	Y	N	MMSE	Downsampling, discrete cosine transform, partial volume effect correction
Ohsugi, Ohgi, Shigemori, and Schneider	2013	N	/	?	N	N	/	MMSE	Moving average, low-pass filtering, high-pass filtering, linear fitting
Albinet, Mandrick, Bernard, Perrey, and Blain	2014	N	/	/	/	Y	N	MMSE	Low-pass filtering
Hagen et al.	2014	N	Bonferroni–Holm	Y	N	Y	N	MMSE	Linear fitting
Müller et al.	2014	N	False discovery rate	N	N	N	/	DemTect, MMSE	High-pass filtering, moving average, low-pass filtering, correlation-based signal improvement
Dupuy et al.	2015	N	Expected Euler	Y	N	Y	N	MMSE	Principal component analysis, high-pass filtering, precoloring
Laguë-Beauvais et al.	2015	N	N	Y	N (addressed)	Y	Y (for most channels)	MMSE	N
Huppert et al.	2017	Y	False discovery rate	/	/	N	/	SPMSQ	Prewhitening
Corp et al.	2018	N	/	?	Y	Y	Y (hemoglobin differential)	MMSE	Spline interpolation, low-pass filtering
Vasta et al.	2018	N	N	Y	N	Y	N	N	Moving average, band-pass filtering
(h) Inhibitory control								
Schroeter, Zysset, Kruggel, and von Cramon	2003	N	N	?	Y	Y	N	N	N
Fujiwara et al.	2010	N	/	?	N	N	/	N	N
Hyodo et al.	2012	N	Bonferroni–Holm	/	/	Y	N	MMSE	Band-pass filtering

Kawai, Kubo-Kawai, Kubo, Terazawa, and Masataka	2012	N	N	?	N	N	/	MMSE	N
Lucas et al.	2012	N	/	?	N	Y	N	N	N
Heilbronner and Münte	2013	N	False discovery rate	Y	N (addressed)	Y	Y	N	Wavelet minimum description length detrending, hemodynamic response function precoloring
Laguë-Beauvais, Brunet, Gagnon, Lesage, and Bherer	2013	N	N	Y	N (addressed)	Y	N	MMSE	Downsampling, discrete cosine transform, partial volume effect correction
Dupuy et al.	2015	N	Expected Euler	Y	N	Y	N	MMSE	Principal component analysis, high-pass filtering, precoloring
Hyodo et al.	2016	N	Bonferroni–Holm	/	/	Y	N	MMSE	Band-pass filtering
Bierre, Kirstin, Guiney, Cotter, and Machado	2017	N	/	N (controlled for)	N	Y	N	MMSE	N
Huppert et al.	2017	Y	False discovery rate	/	/	N	/	SPMSQ	Prewhitening
Halliday et al.	2018a	N	N	/	/	N	/	MMSE	Wavelet-based motion artifact removal, band-pass filtering
Halliday et al.	2018b	N	N	/	/	Y	N	MMSE	Wavelet-based motion artifact removal, band-pass filtering
(i) Memory									
Vermeij et al.	2012	N	/	N	Y	Y	N	MMSE	Moving average
Ferreri et al.	2014	N	/	/	/	Y	N	MMSE	Low-pass filtering
Vermeij, Meel-van den Abeelen, Kessels, van Beek, and Claassen	2014	N	/	N	Y	Y	N	MMSE	High-pass filtering
Vermeij, van Beek, Reijs, Claassen, and Kessels	2014	N	/	/	/	Y	N	MMSE	Moving average

Yamanaka et al.	2014	N	N	?	N	N	/	MMSE	Linear fitting, moving average
Oboshi et al.	2015	N	N	N	N	N	/	MMSE	High-pass filtering, global direct current trend correction
Jackson et al.	2016	Y	/	/	/	N	/	MMSE	N
Stephens and Berryhill	2016	N	/	/	/	N	/	MMSE	Low-pass filtering, spline interpolation
Wijeakumar, Magnotta, and Spencer	2017	N	Cluster-size correction	?	N	Y	N	MoCA	Principal component analysis, band-pass filtering
Bu, Wang et al.	2018	N	N	/	/	N	/	N	Spline interpolation, band-pass filtering
Wightman et al.	2018	Y	N	/	/	Y	N	N	N
Adorni et al.	2019	N	/	/	/	Y	N	MoCA	Band-pass filtering, removal of systemic effects
Agbangla, Audiffren, Pylouster, and Albinet	2019	N	/	Y	Y	Y	N	MMSE	Moving average, spline interpolation
Causse, Chua, and Rémy	2019	N	False discovery rate	Y	N	N	/	N	Band-pass filtering, correlation-based signal improvement
(j) Emotion and motivation									
Kida et al.	2014	N	Bonferroni	/	/	Y	N	MMSE	N
Li, Cazzell, Zeng, and Liu	2017	N	False discovery rate	?	N	N	/	MoCA	Band-pass filtering, depth compensation
Nakata, Kubo-Kawai, Okanoya, and Kawai	2018	N	/	?	N	N	/	Revised Hasegawa Dementia Scale	Low-pass filtering

Note. MIS = Memory Impairment Screen; MMSE = Mini-Mental State Examination; MoCA = Montreal Cognitive Assessment; N = No; RBANS = Repeatable Battery for the Assessment of Neuropsychological Status; SPMSQ = Short Portable Mental Status Questionnaire; Y = Yes; ? = unclear; / = not applicable