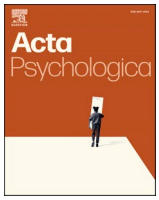
Acta Psychologica 224 (2022) 103525

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy



Functional near-infrared spectroscopy in the neuropsychological assessment of spatial memory: A systematic review

Tania Llana [a], Cristina Fernandez-Baizan [a,b,*], Magdalena Mendez-Lopez [c,d], Camino Fidalgo [c,d], Marta Mendez [a,b,e]

[a] Department of Psychology, University of Oviedo, Faculty of Psychology, Plaza Feijoo s/n, 33003 Oviedo, Asturias, Spain
[b] Neuroscience Institute of Principado de Asturias (INEUROPA), Faculty of Psychology, Plaza Feijoo s/n, 33003 Oviedo, Asturias, Spain
[c] Department of Psychology and Sociology, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Aragón, Spain
[d] IIS Aragón, San Juan Bosco, 13, 50009 Zaragoza, Aragón, Spain
[e] Instituto de Investigación Sanitaria del Principado de Asturias (ISPA), Av. del Hospital Universitario, s/n, 33011 Oviedo, Asturias, Spain

ARTICLE INFO

Keywords:
fNIRS
Cortex
Spatial memory
Working memory
Short-term memory

ABSTRACT

Functional near-infrared spectroscopy (fNIRS) is a non-invasive optical imaging technique that employs near-infrared light to measure cortical brain oxygenation. The use of fNIRS has increased exponentially in recent years. Spatial memory is defined as the ability to learn and use spatial information. This neuropsychological process is constantly used in our daily lives and can be measured by fNIRS but no research has reviewed whether this technique can be useful in the neuropsychological assessment of spatial memory. This study aimed to review empirical work on the use of fNIRS in the neuropsychological assessment of human spatial memory. We used four databases: PubMed, PsycINFO, Scopus and Web of Science, and a total of 18 articles were found to be eligible. Most of the articles assessed spatial or visuospatial working memory with a predominance in computer-based tasks, used fNIRS equipment of 16 channels and mainly measured the prefrontal cortex (PFC). The studies analysed found linear or quadratic relationships between working memory load and PFC activity, greater activation of PFC activity and worse behavioural results in healthy older people in comparison with healthy adults, and hyperactivation of PFC as a form of compensation in clinical samples. We conclude that fNIRS is compatible with the standard neuropsychological assessment of spatial memory, making it possible to complement behavioural results with data of cortical functional activity.

1. Introduction

When a specific brain region is activated, the oxygen demand, which is transported by hemoglobin, increases in this region. Thus, brain blood flow increases in a brain region tightly linked to changes in the activity of neurons, and a change in the local oxy-hemoglobin (O_2Hb) and deoxy-hemoglobin (HHb) occurs. Functional Near-infrared Spectroscopy (fNIRS) is a non-invasive optical imaging technique that employs Near-infrared (NIR) light to measure cortical haemodynamics. Particularly, this technique is based on the assumption that brain activity leads to an increase in oxygen consumption of the neurons, accompanied by a spatially and temporally coordinated increase in cerebral blood flow due to neurovascular coupling (Girouard & Iadecola, 2006). The structural and functional characteristics of the cerebral blood vessels are unique, being in close interaction with neurons and glia. Their intimate structural and functional relationships explain their coordinated pattern of reaction (Girouard & Iadecola, 2006). Neuroimaging techniques can use the cerebrovascular changes induced by activation of neurons to map regional changes in function in the human brain (Devor & Boas, 2012). fNIRS monitors changes in the concentration of O_2Hb and HHb in the cortical layer of the brain, based on NIR light absorption changes in the tissue. The changes in light absorption due to neurovascular coupling are the target of fNIRS, and other physiological signals of other causes should be avoided or removed from the analysis (Tachtsidis & Scholkmann, 2016).

The origin of fNIRS dates back to 1977, when Jöbsis published an article in which he stated the "optical window" (the NIR wavelength range between 650 nm and 900 nm) at which the absorption spectrum of hemoglobin allows the oxygenation of hemoglobin to be detected in real time and non-invasively using transillumination spectroscopy (Jöbsis,

* Corresponding author at: Faculty of Psychology, Plaza Feijoo s/n, 33003 Oviedo, Asturias, Spain.
E-mail address: cristinafernandezbaizan@cop.es (C. Fernandez-Baizan).

https://doi.org/10.1016/j.actpsy.2022.103525
Received 28 July 2021; Received in revised form 19 January 2022; Accepted 26 January 2022
Available online 3 February 2022

1977; Quaresima & Ferrari, 2019). After the discovery of NIR, several instruments were designed and built to investigate the activity of the brain using this approach.

The main component of an fNIRS device includes a channel, that is a path between a light-emitting diode called source, and a detector that, positioned over the scalp surface, can detect changes in the reflectance that emerges from the cortical grey matter by capturing photons (Quaresima & Ferrari, 2019). Then, it is possible to convert, through different algorithms such as the Modified Beer-Lambert Law and multi-distance approaches, raw light intensity data into O_2Hb, HHb and total hemoglobin concentration or variation, as continuous wave systems can only quantify changes and not absolute values, in contrast to time-resolved technique (Scholkmann et al., 2014). fNIRS devices can vary in the number of channels. The maximum number of channels in large systems is usually in the range of 50–200 channels resulting from 16 emitters and 32 receptors (Scholkmann et al., 2014). The number of emitting and receiving diodes in an fNIRS device depends on the cortical area to be monitored. However, few of the studies carried out with this technique include full coverage of the scalp. Devices with a large number of channels are very expensive and include mechanical difficulties associated with the use of many lumps and the detection of light over cortical areas covered by hair (Zhao & Cooper, 2017). More frequently, devices are restricted to covering the frontal region, assessing metabolic demands while performing typically prefrontal cognitive tasks, such as tasks involving working memory (WM) (Bonetti et al., 2019).

The use of this technique has increased exponentially in recent years as in contrast to other neuroimaging techniques, such as functional magnetic resonance imaging (fMRI) and Positron Emission Tomography (PET), fNIRS is silent, non-invasive, inexpensive, portable, and allows for long-time continuous measurements, and is not easily limited by movements (Martinelli & Shergill, 2015; Pandarinathan et al., 2018; Scarapicchia et al., 2017). Some of these advantages make fNIRS especially useful for the assessment of brain activity in natural environments (Zhao & Cooper, 2017). Therefore, it offers the possibility of assessing functional brain activity in an open environment without causing excessive discomfort to the patient or participant and does not interfere with diagnostic, therapeutic or pharmacological procedures (Bonilauri et al., 2020). However, compared to other neuroimaging modalities, such as fMRI, fNIRS does not provide anatomical information, it shows lower spatial resolution and its measurements are restricted to the cortex (Pinti et al., 2020). Another disadvantage of fNIRS is the lack of standardization in data analysis (Pinti et al., 2020) but, nowadays, this is being improved with the development of guides designed to help describe the methods, enhancing the reliability, repeatability and traceability of fNIRS studies (Yücel et al., 2021).

Balancing the advantages and disadvantages of the technique, the fNIRS device has useful applications both in basic and applied science (Bonilauri et al., 2020; Quaresima & Ferrari, 2019). In neurology, fNIRS is used primarily in research with clinical populations (Bonilauri et al., 2020). For example, this technique was used to observe changes in brain activity related to Parkinson's Disease and Multiple Sclerosis (Bonilauri et al., 2020), cerebrovascular disease, epilepsy and headache (Obrig, 2014), as well as to study the cerebral hemodynamics of patients with mild cognitive impairment and dementia in response both to the performance of tasks and the rest state (Yeung & Chan, 2020). Besides, it was also applied in non-clinical populations. In this regard, this technique was used to determine changes in the brain activity of healthy older adults (Yeung & Chan, 2021), obtaining similar results as those found in other studies in which other neuroimaging techniques were used, such as PET (Yeung & Chan, 2021) and fMRI (Cui et al., 2011; Steinbrink et al., 2006).

In the context of neuropsychological research, fNIRS has been employed to assess the activity of brain networks supporting some cognitive tasks at different demands both in typical and clinical samples. Among these studies, some have investigated the relationship between the dorsolateral prefrontal cortex (DLPFC) and WM (Kronovsek et al., 2021; Lucas et al., 2020), how the rostral prefrontal cortex (PFC) is related to prospective memory performance in a slide-based and immersive virtual reality environment (Dong et al., 2019), how the brain processes language (Peelle, 2017), the functioning of the prefrontal cortex network in children with autism spectrum disorder (Krishnamurthy et al., 2020), and brain activity in social interactions to study typical and atypical development in naturalistic social situations (McDonald & Perdue, 2018). These studies demonstrate that fNIRS is useful as a complement to neuropsychological assessment, making it possible to detect cortical haemodynamic changes during task performance in real-time.

Given the high temporal resolution of fNIRS compared to other neuroimaging modalities such as fMRI or PET, the better spatial resolution than EEG and the possibility of its administration in natural contexts (Martinelli & Shergill, 2015; Pandarinathan et al., 2018; Pinti et al., 2018; Scarapicchia et al., 2017), it could be an optimal tool to assess the haemodynamic changes that underlie spatial memory. Spatial memory is defined as the acquisition, storage and retrieval of the location of objects, as well as the recognition of their changing positions in space (Bocchi et al., 2020). An active process of spatial memory, the spatial WM, is composed of a set of cognitive functions that are separated from the traces of past experience and accumulated knowledge in long-term memory, which can retrieve and manipulate the activated spatial contents of long-term memory, allowing those contents to be reinterpreted (Baddeley et al., 2002). Spatial WM can be defined as a system that is responsible for storing and keeping available spatial information and it is specifically devoted to the recall of spatial location and sequences (Fanari et al., 2019). Spatial-related cognitive functions could be assessed employing the fNIRS technique. The interest in using fNIRS in the assessment of spatial memory not only derives from the possibility of evaluating the neuroanatomical areas involved in the execution of the task, but also its usefulness as a diagnostic tool for memory problems.

To our knowledge, there are no systematic reviews assessing the use of fNIRS to study cortical function while evaluating spatial memory. It would be interesting to review how this neuroimaging technique is used to assess spatial memory, as it would help to clarify whether this technique could provide complementary information to behavioural data. It might also help to synthesize the main methodological aspects described in the studies in order to reach some conclusions about procedural aspects to consider when aiming to design new studies. Furthermore, as spatial memory is a process that involves interaction with the environment, especially when it requires remembering visuospatial keys, fNIRS offers the possibility of studying haemodynamic changes in real environments, making it especially interesting in the evaluation of spatial memory. For these reasons, the present work aims to summarize current evidence on the use of fNIRS in the neuropsychological assessment of spatial memory. Specifically, this review addresses (1) whether fNIRS can show central nervous system changes that complement behavioural results observed in spatial memory tasks (2) the evidence in specific brain regions that, according to theoretical evidence, are activated in spatial cognition and (3) the methodology and equipment employed to assess the brain evidence of these neuropsychological assessments. Recommendations for future studies are also included.

2. Method

2.1. Search strategy and study selection

A systematic review of the literature was conducted using the following databases: PubMed, PsycINFO, Scopus and Web of Science. The search terms included were “fNIRS”, “NIRS”, “functional near-infrared spectroscopy”, “spatial memory”, “spatial working memory”, “spatial short-term memory”, “spatial long-term memory”, “spatial recovery”, “spatial recall”, “Corsi” and “Maze”. These two last keywords

were included, given their strong spatial component. No restrictions on the date of publication were applied. The final search was carried out on March 31st, 2021.

This review was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). We met PRISMA criteria 1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 13, 17, 18, 24, 25, 26 and 27. All of them are relevant when conducting qualitative synthesis. Criteria of quantitative synthesis or meta-analysis are not applicable to the procedure of this review.

2.2. Procedure

In the identification of studies, a total of 249 articles were found, of which, after removing duplicates, reviews, conference papers and academic dissertations, 57 studies were reviewed. The inclusion criteria were the following: (1) the studies must focus on neuropsychological assessment of spatial memory, (2) the studies must use fNIRS to show evidence of activity changes in the central nervous system (CNS), and (3) the studies should be performed with human participants. Of those 57 resulting articles, eligibility was tested, excluding those articles that were not performed with humans, did not apply fNIRS, did not assess spatial component, were not carried out in adult samples, and were intervention or methodological articles. After a detailed reading of the articles by two researchers, a total of 18 articles were selected for their inclusion in this review. Fig. 1 represents a flow chart of the process.

We extracted the following information from the original articles: size and characteristics of the sample, experimental design, type of spatial memory process assessed, tasks used for the assessment, characteristics of the fNIRS equipment, brain regions measured and main outcomes obtained.

3. Results

A summary of the characteristics of the sample, experimental design, spatial memory assessment, fNIRS equipment employed, data processing, brain regions assessed and main outcomes for each article is shown

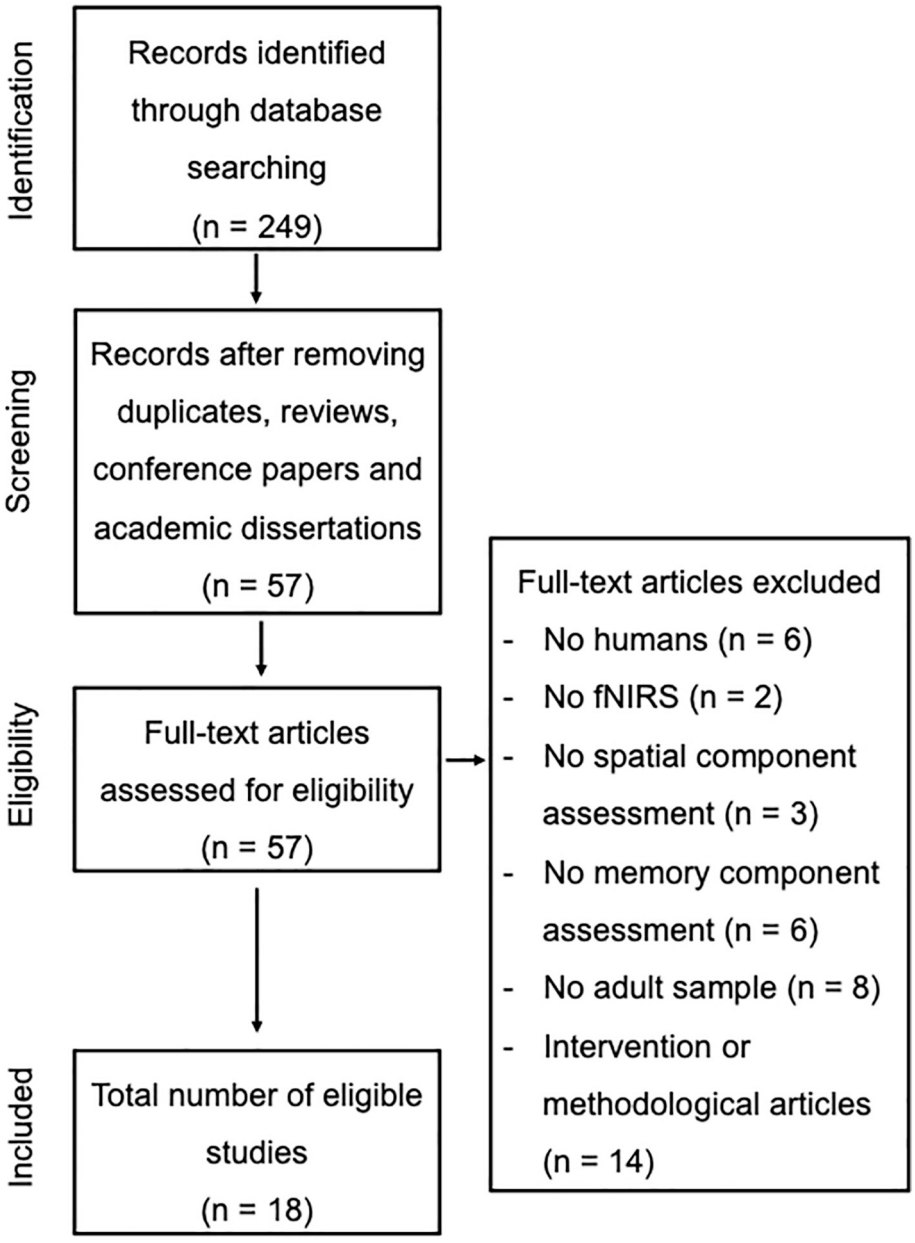


Fig. 1. Flowchart of Literature Search and Study selection Process.

in Table 1 and Fig. 2. The studies were grouped according to the type of spatial memory process assessed.

3.1. Characteristics of the sample

There is a great variety in the assessed samples in the different articles, with samples composed of healthy people (adults and/or older people), people diagnosed with a psychological disorder and people suffering from neurodegenerative diseases.

Specifically, ten of the articles studied healthy young adults exclusively (Aoki et al., 2013; Causse et al., 2020; Chen et al., 2018; Geissler et al., 2020; Herrmann et al., 2016; Lancia et al., 2018; McKendrick & Harwood, 2019; Miyata et al., 2011; Panico et al., 2021; Sato et al., 2014). Two articles also assessed a group of healthy older adults (Causse et al., 2019; Kronovsek et al., 2021). In Vermeij et al. (2014), the authors evaluated only a group of healthy older adults.

Studies also compared healthy individuals and individuals with psychopathology. Specifically, two of the studies assessed individuals with schizophrenia and healthy individuals (Lee et al., 2008; Quaresima et al., 2009), one study analysed ecstasy users and healthy controls (Montgomery et al., 2017), and another research compared recurrent depression patients, bipolar depression patients and healthy controls (Schecklmann et al., 2011).

Finally, Perpetuini et al. (2019) assessed Alzheimer's Disease (AD) patients and healthy older controls.

3.2. Type of experimental design

Ten articles used an observational within-subject study design (Aoki et al., 2013; Causse et al., 2020; Chen et al., 2018; Geissler et al., 2020; Herrmann et al., 2016; Lancia et al., 2018; McKendrick & Harwood, 2019; Miyata et al., 2011; Sato et al., 2014; Vermeij et al., 2014), while the other eight used an observational between-subject study design (Causse et al., 2019; Kronovsek et al., 2021; Lee et al., 2008; Montgomery et al., 2017; Panico et al., 2021; Perpetuini et al., 2019; Quaresima et al., 2009; Schecklmann et al., 2011).

3.3. Type of spatial memory assessed and tasks employed

Most of the studies (15 of 18) assessed the visuospatial component of WM using spatial positions distributed in 2D on a computer screen (Aoki et al., 2013; Causse et al., 2019, 2020; Chen et al., 2018; Geissler et al., 2020; Herrmann et al., 2016; Kronovsek et al., 2021; Lancia et al., 2018; Lee et al., 2008; McKendrick & Harwood, 2019; Montgomery et al., 2017; Quaresima et al., 2009; Sato et al., 2014; Schecklmann et al., 2011; Vermeij et al., 2014). Other studies tested the visuospatial WM using real spatial positions that were distributed in a board (Panico et al., 2021; Perpetuini et al., 2019) or a 3D virtual-navigation task (Kronovsek et al., 2021). The study of Kronovsek et al. (2021) is the only study assessing and comparing spatial WM performance on computer tasks developed in reaching space and navigational space. Two studies used tasks for the assessment of spatial orientation, one of them was performed in 2D on a computer screen (Miyata et al., 2011), and the other was performed in 3D using a computerized virtual environment (Causse et al., 2020).

There is great variability in the tests or tasks used in the studies. Regarding the studies that assessed WM, two of them used tests from the Cambridge Neuropsychological Test Automated Battery (CANTAB) (Causse et al., 2019, 2020), three used the N-back paradigm (Chen et al., 2018; Geissler et al., 2020; Vermeij et al., 2014), four used a delayed-response paradigm (Aoki et al., 2013; Lee et al., 2008; Quaresima et al., 2009; Sato et al., 2014), and six of the studies used the Corsi Block Tapping test (CBT), either the standardized test, a computerized version or a modified version (Herrmann et al., 2016; Kronovsek et al., 2021; Lancia et al., 2018; Montgomery et al., 2017; Panico et al., 2021; Perpetuini et al., 2019). Images of faces were linked to specific locations in the 2D computer task of Schecklmann et al. (2011), who assessed the retention of image-location items. Miyata et al. (2011) assessed spatial planning and orientation through a computerized plus-shaped maze task.

3.4. Study design

Most of the studies used a typical block design in which conditions were repeated over time and spaced out by rest periods (Aoki et al., 2013; Causse et al., 2019, 2020; Chen et al., 2018; Geissler et al., 2020; Herrmann et al., 2016; Lancia et al., 2018; McKendrick & Harwood, 2019; Montgomery et al., 2017; Quaresima et al., 2009; Sato et al., 2014; Schecklmann et al., 2011; Vermeij et al., 2014). Other studies used event-related design (Kronovsek et al., 2021; Lee et al., 2008; Panico et al., 2021; Perpetuini et al., 2019). Duration of the rest periods and the number of blocks and trials were very variable between the studies (Table 1). The time of the rest phases ranged between 3 s (Causse et al., 2019, 2020) to 180 s (Chen et al., 2018). Per task, a minimum of 2 trials (Kronovsek et al., 2021) and a maximum of 60 trials (Vermeij et al., 2014) were performed. Most of the studies assessed baseline cortical activation while watching a fixation cross (Aoki et al., 2013; Lancia et al., 2018; Sato et al., 2014; Vermeij et al., 2014), while others included other activities during this period, such as watching a video with relaxing music (Montgomery et al., 2017), sitting and avoiding movements (Schecklmann et al., 2011) or simply relaxing (Causse et al., 2019, 2020; Quaresima et al., 2009). The duration of baseline cortical activation used for analyses varied between 1 s and 180 s. Most studies used 10 s to quantify baseline cortical activity (Causse et al., 2019, 2020; Schecklmann et al., 2011) (Fig. 2 and Table 1).

3.5. fNIRS equipment, signal processing, data processing, and brain regions assessed

We found a certain variety in the fNIRS equipment used. Regarding the number of channels included in the systems, most of the studies used 16 channels (Causse et al., 2019, 2020; McKendrick & Harwood, 2019; Montgomery et al., 2017), some used 52 channels (Herrmann et al., 2016; Sato et al., 2014; Schecklmann et al., 2011) although others used 4-channel systems (Quaresima et al., 2009; Vermeij et al., 2014) (Fig. 2 and Table 1).

Most of the studies used an interoptode distance of 2.5 cm (Causse et al., 2019, 2020; Montgomery et al., 2017) or 3 cm (Aoki et al., 2013; Chen et al., 2018; Herrmann et al., 2016; Lee et al., 2008; Perpetuini et al., 2019; Sato et al., 2014; Schecklmann et al., 2011). The shortest distance between source and detectors was 1 cm (Lancia et al., 2018), whereas 5 cm was the longest (Quaresima et al., 2009; Vermeij et al., 2014). Some studies used two different interoptode distances (Lancia et al., 2018; Perpetuini et al., 2019), and others did not describe this parameter (Geissler et al., 2020; Kronovsek et al., 2021; McKendrick & Harwood, 2019; Miyata et al., 2011) (Fig. 2 and Table 1).

Almost all the studies used wavelengths between 685 and 859 nm. Only two studies used three wavelengths (Quaresima et al., 2009; Vermeij et al., 2014), whereas the others used two (Fig. 2 and Table 1).

The sampling frequency used also varies between studies, predominating 10 Hz (Aoki et al., 2013; Herrmann et al., 2016; Lancia et al., 2018; Lee et al., 2008; Miyata et al., 2011; Panico et al., 2021; Perpetuini et al., 2019; Sato et al., 2014; Schecklmann et al., 2011) and 2 Hz (Causse et al., 2019, 2020; Montgomery et al., 2017). Two Hz was the lowest sampling frequency employed in the studies, and 60 Hz was the highest (McKendrick & Harwood, 2019). The number of optodes used in each study is highly variable, finding a slight tendency to use 15–16-17 sources and 15 or 16 detectors, resulting in 40-, 47- and 52-channel systems (Aoki et al., 2013; Chen et al., 2018; Herrmann et al., 2016; Sato et al., 2014; Schecklmann et al., 2011). Another tendency observed was the use of 4 sources and 10 detectors, resulting in 16-channel systems (Causse et al., 2019, 2020; Montgomery et al., 2017). Two studies

Table 1
Summary of reviewed articles on the basis of the type of spatial memory process assessed.

Study	Sample and experimental design	Tasks, Study design	fNIRS equipment and processing	Brain regions assessed	Main outcomes
Retention of spatial locations					
Aoki et al., 2013	Within-subject study with 40 healthy adults (10 F[a], 30 M[a]; 25–52 age range)	Computerized delayed (7 s)-response tasks: spatial task and verbal task. Two loads (2- and 4-items) Block Design 16 blocks (28.5 s each) Baseline duration: 8 s (fixation cross) Rest phase duration: 16 to 24 s (between blocks/ random order)	47-channel system (15 sources and 15 detectors) Interoptode distance of 30 nm Two wavelengths of near-infrared light (695 and 830 nm) Sampling rate: 10 Hz DPF[a]: Not reported Filtering: O_2Hb signal change >0.4 mM·mm over two successive samples (200-ms duration) Time used for analysis: activation period of 5 s (5 s after first stimulus presentation) and response to probe presentation 3 s (after probe) Baseline correction; averaging	Bilateral PFC[a], Temporal and Parietal Cortices (Fp1, Fp2, Fpz, T3, T4, C3 and C4 of the International 10–20 system)	Significant PFC activations during all task conditions. Greater PFC activity for several channels in higher load. No difference in PFC activity between verbal and spatial tasks. O_2Hb signals increased at the presentation of the target stimulus and after the presentation of the probe stimulus (may be reflecting the processes of encoding and retrieval).
Lee et al., 2008	Between-subject study with 13 schizophrenic patients (9 M, 4 F, 34.7 mean age; years of education: 12.8) vs. 11 HC[a] (7 M, 4 F, 36.6 mean age; years of education: 14.1)	Computerized delayed (12 s)-matching to position task (3-items) A score of confidence for each response was calculated Event-Related Design 7 runs of 14 trials (16 s each) Rest phase duration: 8.25 s (between trials)	24-channel system (8 sources and 7 detectors) Two wavelengths (780 and 830 nm) Emitter-detector distance was 30 mm Sampling rate: 10 Hz DPF: Not reported Filtering: BP[a] Filter (0.01–0.5 Hz) Time used for analysis: 16 s (maintenance period since first stimulus presentation)	Bilateral PFC	The hemispheric specialization was greatly reduced in schizophrenic patients. Patients made more false positives, but with a higher degree of confidence, than HC. Patients showed an increased total-Hb in both frontal cortexes in the false memory trial. Patients showed hyperactivation compared with HC in bilateral frontal cortex, assessing O_2Hb and total-Hb, with a greater activation of HHb in the left frontal cortex.
McKendrick & Harwood, 2019	Within-subject studies Study 1: 13 healthy participants (18–35 age range) Study 2: 17 healthy participants (18–45 age range)	Computer task for retention reproduction (study 1) and retention (study 2) of spatial positions with different loads (1 to 10 items) Block Design 10 blocks × 10 trials (14 s each) Baseline duration: Not reported Rest phase duration: 60 s (between blocks)	16-channel system (4 sources and 5 detectors) Two wavelengths (685 and 830 nm) Sampling rate: 60 Hz DPF: 1/0.015 Filtering: LP[a] Filter (0.15 Hz), SMAR algorithm Time used for analysis: 4 s (6 s since first stimulus presentation) baseline correction; averaging	Bilateral BA[a] 10 (Anterior PFC), 46 (DLPFC[a]), 45 (Pars triangularis) and 44 (Pars opercularis)	Study 1: Hemodynamic changes in both left DLPFC and right pars triangularis of the DLPFC occurred in response to WM load. The hemodynamic responses were cubic in the left DLPFC (i.e., increment at the beginning of the task, then asymptote, and then increment again). The hemodynamic responses decrease in the right pars triangularis of the DLPFC (i.e., decrease at the beginning of the task, then increase, then asymptote, and decrease at the end). Study 2 (same protocol of Study 1): No changes occurred in the right pars triangularis of the DLPFC. A cubic polynomial hemodynamic effect was found in the left DLPFC characterized by a pronounced increase at the end of the task. Underload, low load, high load and overload were calculated for each participant in the task. Individual transitions between these different WM loads led to changes in O_2Hb in the left DLPFC, but not to changes in HHb function.
Montgomery et al., 2017	Between-subject study with 20 ecstasy users (11 M, 9 F; 21.76 mean age) vs.	Computerized CBT[a] (participants' span, span+2, span+4,	16-channel system (4 sources and 10 detectors) with 2.5 cm source-detector separation	Bilateral DLPFC and PFC	Groups did not differ in their performance in both tasks. Ecstasy users displayed

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Table 1 (*continued*)

Study	Sample and experimental design	Tasks, Study design	fNIRS equipment and processing	Brain regions assessed	Main outcomes
	20 controls (9 M, 11 F; 19.68 mean age)	span+6) and letter span task Block Design 5 blocks × 6 trials (different loads) Baseline duration: Not reported (watching a video/music) Rest phase duration: Not Reported	Two peak wavelengths (730 and 850 nm) Recording data at 2 Hz DPF: Not reported Filtering: visual inspection, LP Filter (0.1 Hz), Linear phase Filter (order of 20) Time used for analysis: Not reported Baseline correction; averaging		differences in cortical blood oxygenation in all PFC areas compared to controls, but only in letter span, suggesting that their PFC worked harder to achieve the same level of performance. Higher oxygenation in the right PFC was related both to ecstasy and cannabis consumption.
Panico et al., 2021	Between-subject study with 60 university students (31 F, 29 M) Examiners (17 F, 13 M; 22.8 mean age) vs. Examinees (14 F, 16 M; 22.17 mean age)	CBT (standardized version) (span: 2–10) Event-Related Design (participants' span, span-2, span-1, span+1, span+2) Rest phase duration: Not Reported	8-channel system (8 sources and 2 detectors) with 35 mm source-detector distance. Two wavelengths (758 and 840 nm) Data acquired at 10 Hz DPF: Age-dependent value 4.99 + 0.067 x age Filtering: BP Filter (0.01–0.1 Hz) Time used for analysis: events manually inserted according to the start and end of motor responses (only trials with span between 4 and 8 items).	Bilateral PFC (Fp1 and Fp2)	Examinees' and Examiners' PFC activity increased as the spatial span increased, and dropped when the workload exceeded their spatial span. Examiners showed higher left-hemisphere activity as compared to the Examinees, particularly during the response (i.e., reproduction of sequences). Examinees' and Examiners' brain activity increased during correct performance. Examinees' and Examiners' brain activity decreased when Examinees failed. Higher brain activity in both hemispheres was detected in the Examiners as compared to the Examinees during the performance of the CBT. Examinees' activation was higher during the performance compared to the observation.
Perpetuini et al., 2019	Between-subject study with 11 early AD[a] patients (7 M, 4 F; 72.2 mean age) vs. 11 HC (8 M, 3 F; 67.5 mean age)	CBT DST[a] CDT[a] Event-Related Design Rest phase duration: 60 s (between tasks)	21-channel system (32 sources and 4 detectors) with a source-detector distance of either 3 cm or 4 cm Two wavelengths (690 and 830 nm) Sampling rate: 10 Hz DPF: Not reported Filtering: wavelet-based algorithm, BP Filter (0.01–0.4 Hz) Time used for analysis: Not reported	Bilateral DLPFC (BAs investigated: 8, 9 and 46)	CDT scores differed between AD and HC. Changes in O_2Hb occurred during all the tests. AD patients showed higher activity than HC in 10 and 46 BAs, as well as less activation than HC in BA 9. AD patients showed higher activity in 10 and 46 BAs compared to controls in CBT. Although only behavioural CDT scores achieved classifying the cognitive status of the participants in ROC[a] analysis, all the tests provided an above chance classification in ROC curves when complexity-based fNIRS was considered.
Sato et al., 2014	Within-subject study with 26 healthy adults (13 F, 13 M; 20–42 age range; 25.9 mean age)	Computerized delayed matching to position spatial and verbal tasks Block Design 2 blocks (control and WM) x 8 trials (25.5 s each) Baseline duration: 1 s (pre-trial) x 16 (averaged) (fixation cross) Rest phase duration: 15 to 18 s (between trials/ random order)	52-channel system (17 sources and 16 detectors) with 3 cm source-detector distance Two wavelengths (695 and 830 nm) Sampling rate: 10 Hz DPF: Not reported Filtering: BP Filter (0.013–0.8 Hz) Time used for analysis: 6 s (5 s since first stimulus presentation) Baseline correction; averaging	Bilateral PFC and Temporal Lobe	Both tasks required longer reaction times than control task, with longer RT[a] for the verbal task. No changes in the O_2Hb signal occurred for the spatial task. Increase in O_2Hb signal occurred in the verbal tasks in the PFC and in the left temporal pole.
Schecklmann et al., 2011	Between-subject study with 16 patients with recurrent depression (7 F, 9 M; 43.4 mean age) vs. 14 patients	Computerized tasks: OWM[a] task of face recognition, SWM[a] task of retention of face to	52-channel system (17 sources and 16 detectors) with 3 cm source-detector distance Two wavelengths (695 and 830 nm)	Bilateral PFC and Temporal Cortices (Fpz, T3 and T4 of the	For all groups, the most difficult task to solve was the OWM, followed by the SWM and the C. Bipolar patients,

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Table 1 (*continued*)

Study	Sample and experimental design	Tasks, Study design	fNIRS equipment and processing	Brain regions assessed	Main outcomes
	with bipolar affective disorder during a depressive episode (11 F, 3 M; 40.8 mean age) vs. 15 HC (8 F, 7 M; 40.9 mean age)	location information - Control task (C) Block Design 3 blocks (control and WM) x 30 trials (8 s each) Baseline duration: 10 s (sitting, avoiding movements) Rest phase duration: 2 to 6 s (between trials/ random order)	Sampling rate: 10 Hz DPF: Not reported Filtering: 5 s moving average, HP[a] Filter (discrete cosine transform) Time used for analysis: 6 s Baseline correction; averaging	international 10–20 system)	compared to HC, showed slower RT in the SWM and the C. The HC group showed task-related increases of O_2Hb in the VLPFC[a] during the OWM and the SWM compared to the C, and in the DLPFC during the OWM compared to the C. Neither O_2Hb nor HHb differences were found in any group of patients in the different tasks and the different prefrontal areas. HC showed higher O_2Hb increases in the VLPFC compared to bipolar patients in all tasks, and in the DLPFC compared to depressed and bipolar patients in both WM tasks.
Retention and manipulation of spatial locations					
Causse et al., 2019	61 pilots, between-subject study: 18 young (17 M, 1 F; 19–25 age range) vs. 19 middle-aged (17 M, 2 F; 30–48 age range) vs. 24 older (24 M; 51–74 age range)	Computerized tasks from CANTAB[a]: SWM test with 4 levels of difficulty (6, 8, 10 and 12 items); and OTS[a] test of planning Block Design 8 trials (6, 8, 10, 10, 10, 12, 12,12 items) Baseline duration: 10 s (relax) Rest phase duration: 3 s (between trials)	16-channel system (4 sources and 10 detectors) with 2.5 cm source-detector separation Differential path length factor set at 5.76 Two peak wavelengths (730 and 850 nm), recording data at 2 Hz DPF: 5.76 Filtering: BP FIR Filter order of 20 (0.02–0.40 Hz), CBSI[a] method Time used for analysis: entire trial of each condition Baseline correction; averaging	Bilateral and medial PFC	Spatial performance was impaired at the two highest levels of difficulty as a function of age. The level of experience in piloting positively affected the spatial performance. Difficulty of the spatial task is positively related to an increase of O_2Hb concentration in all age groups, more specifically in lateral regions. Patterns of load-modulated activity were different (plateau of PCF activation) in the older group in the two most difficult levels. The older participants showed lower left prefrontal activity than the younger ones at the most difficult levels.
Causse et al., 2020	Within-subject study with novice pilots (18 M; Mean age: 20.6)	Computerized SWM test from CANTAB with 4 levels of difficulty. Navigation task in a virtual flight simulator Block Design 8 trials (6, 8, 10, 10, 10, 12, 12,12 items) Baseline duration: 10 s (relax) Rest phase duration: 3 s (between trials)	16-channel system (4 sources and 10 detectors) with 2.5 cm source-detector separation Two peak wavelengths (730 and 850 nm) Recording data at 2 Hz DPF: Not reported Filtering: BP FIR Filter order of 20 (0.02–0.40 Hz), CBSI method Time used for analysis: entire trial of each condition Baseline correction; averaging	Bilateral and medial PFC	Participants who could use a more efficient strategy in the SWM test were more likely to properly control the altitude of the aircraft. The most difficult levels of the SWM test increased O_2Hb concentration in the PFC compared to the easier levels. A higher fNIRS activity during the highest level of difficulty was associated with a better control of the aircraft's heading in the flight simulator.
Retention of spatial locations and inhibition of interference					
Chen et al., 2018	Within-subject study with healthy subjects (8 M, 9F) (19–26 age range)	Computerized tasks: 3-back WM single-sitting cognitive tasks (SWM and NWM[a]); postural control task (tandem stance paradigm); and DT[a] (standing tasks: Tandem stance task + WM tasks) Block Design 10 Blocks (randomized conditions) x 27 trials (in WM conditions) WM Block duration: 65 s Baseline duration: 5 s	40-channel system (16 sources and 15 optical detectors) with 3 cm source-detector separation Dual-wavelength (780 and 830 nm) Sampling rate: 3.91 Hz DPF: Not reported Filtering: BP Filter (0.01–0.2 Hz) Time used for analysis: entire task Baseline correction; averaging	Bilateral Frontal and parietal cortices	Reaction sensitivity was lower in the standing-SWM task compared with the sitting-SWM task. Posture conditions for the NWM task did not differ. Lower O_2Hb in fronto-parietal areas was found during the standing-SWM task compared to the sitting-SWM task (marginally significant effect). This activity did not differ between the standing and sitting conditions in the NWM task.

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Table 1 (*continued*)

Study	Sample and experimental design	Tasks, Study design	fNIRS equipment and processing	Brain regions assessed	Main outcomes
		before and 15 s after the block Rest phase duration: 180 s (between blocks)			
Herrmann et al., 2016	Within-subject study with 36 healthy students fNIRS data: 28 participants (19–39 age range)	Computerized tasks: version of the CBT, recognition of EFE[a]; DT consisting in EFE + CBT Block Design 3 Blocks (randomized conditions: EFE, CBT, DT each) x 10 min each WM Block duration: 65 s Baseline duration: not reported Rest phase duration: 120 s (between blocks)	52-channel system (17 emitters and 16 detectors) Interoptode distance 30 mm Two wavelengths (695 and 830) Sampling frequency: 10 Hz DPF: Not reported Filtering: BP Filter (0.02–0.7 Hz), 5 s moving average, Gaussian HRF[a] peak time 6.5 s Signal change with respect to trial onset	Bilateral PFC and Temporal Cortices (Fpz, T3 and T4)	Recognition of EFE is worse in the DT condition as compared to the single task condition. CBT performance was similar in single task and DT conditions. DT condition led to higher activation in bilateral DLPFC. EVP[a] (P100 in O1, Oz and O2) was reduced in DT compared to both single task conditions. P300 amplitude (in P3, Pz and P4) was significantly higher during DT and recognition of EFE single task compared to the single CBT task.
Lancia et al., 2018	Within-subject study with 39 university students (19 F and 20 M) (22–27 age range; years of education: 14.8 ± 1.7)	Computerized CBT with three versions: standard (CBTs), block-suppression (CBTb) and control (CBTc) Block Design 3 Blocks (each containing 3 randomized conditions: CBTs (10 min), CBTb (10 min), CBTc (5 min)) Baseline duration: 180 s (60 s before each block) (fixation cross) Rest phase duration: 120 s (between blocks)	20-channel continuous wave system (8 sources and 10 detectors) Two wavelengths (764 and 856 nm) Detector–illuminator distance was 3.5 cm in 16 measurement points, and 1 cm in four measurement points Data acquired at 10 Hz DPF: Not reported Filtering: Low optical intensity discarded by Function enPruneChannels, some short separated channels (1 cm), heart rate monitoring, wavelet motion correction method (iqr 0.1), GLM (hmrDeconvHRF_DriftSS function), Gaussian HRF functions with 2-s temporal basis (intervals between: 2 and 18 s before and after starting 3-item sequences, 2 and 22 s before and after starting 4-item sequences, 2 and 26 s before and after starting 5-item sequences, 2 and 30 s before and after starting 6-item sequences) Time used for analysis: from beginning to end of each sequence (22 s, 26 s, 30 s) Baseline correction; averaging	Bilateral PFC (Fp1 and Fp2) DLPFC and VLPFC	Hemodynamic changes were found in all sequences of the CBTs and CBTb, although no involvement of specific measurement points were found (contrary to the authors' hypothesis, VLPFC areas were not specifically activated during CBTs, and DLPFC areas were not specifically activated for CBTb).
Quaresima et al., 2009	Between-subject study with 9 schizophrenic patients (5 M, 4F; 32.1 mean age; 12.1 years of education) vs. 9 HC (4 M, 5 F; 32.6 mean age; 13.5 years of education)	Computerized tasks: delayed matching to position with interference during the delay period and verbal fluency Block Design 2 blocks × 12 trials each Baseline duration: 120 s (relax) Rest phase duration: not reported	4-channel system (4 sources and 4 detectors) with 5 cm source-detector distance) Three wavelengths: 735 nm, 810 nm and 850 nm Sampling frequency: 6 Hz DPF: Not reported Filtering: BP Filter (0.013–0.8 Hz) Time used for analysis: 4 s (2 s before and 2 s after maximal change) Baseline correction; averaging	Bilateral PFC (Fp1 and Fp2 of the international 10–20 system)	Patients performed worse than HC on the two tasks. Oxygenation of patients' PFC did not change in response to the two tasks. Correlation was found between the HHb decrease in the left PFC of HC and their performance on the verbal task.
Geissler et al., 2020	Within-subject study with 20 healthy adults (11 F, 9 M, 22.1 mean age, 19–27 age range)	Spatial n-back task Block Design 4 training trials (0-back, 1-back, 2-back and 3-back conditions) 4 test blocks x 24 trials each (12 (1-back); 12 (3-back)) Baseline: 75 s (15 s × 5) Rest phase duration: 15 s	18-channel system (8 sources and 8 detectors) Two wavelengths (760 and 850 nm) Recording data at 7.81 Hz DPF: Not reported Filtering: GLM HRF, AR-IRLS algorithm to correct artifacts Time used for analysis: Not reported	Bilateral frontal cortex (PFC, DLPFC, VLPFC) and middle frontal gyrus of the 10–10 system	Higher average response accuracy was found in 1-back blocks than in 3-back blocks and there was not any effect of WM load on RT. The effects of WM load were presented in the right middle frontal gyrus, driven by right DLPFC activation. Most activation effects were elicited by the 3-back condition over rest and 1-back conditions. A rise in middle frontal gyrus activity with rising WM load was reflected by HHb decrease.

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Table 1 (*continued*)

Study	Sample and experimental design	Tasks, Study design	fNIRS equipment and processing	Brain regions assessed	Main outcomes
Vermeij et al., 2014	Within-subject study with 18 healthy older people (11 F, 7 M; 64–81 age range; 70.8 mean age; 9–18 years of education; 13.1 mean years of education)	Spatial n-back task in three conditions (control = 0-back, low WM load = 1-back and high WM load = 2-back) Block Design 3 blocks × 60 trials each Baseline duration: 180 s (60 s before each block) (fixation cross) Rest phase duration: 120 s (between blocks)	4-channel continuous-wave system (4 sources and 4 detectors) with source-detector distance of 5 cm Three wavelengths (765, 857 and 859 nm) DPF: 6.61 Filtering: 1-s movement average Time used for analysis: entire task, 180 s from the start of the fourth trial of each condition averaging	Bilateral PFC (Fp1 and Fp2 according to the international 10–20 system)	Increasing WM load led to increased PFC activation and decreased behavioural performance. Stronger right PFC activation was found in high performers in comparison with low performers in high WM condition. A decline in task performance with increasing WM load correlated positively with a bilateral increase of prefrontal O_2Hb in low performers.
Retention, manipulation, inhibition and planning of spatial information					
Miyata et al., 2011	Within-subject study with 20 healthy adults (13 F, 7 M, 20–33 age range)	Computerized spatial orientation task in a plus-shaped maze 30 trials (same-goal condition) and 6 trials (goal-change condition) Baseline duration: 5 s before each onset of maze solution Rest phase duration: 10 s (inter-trial)	22-channel system (8 sources and 7 detectors) Two wavelengths (780 and 830 nm) Sampling rate: 10 Hz DPF: Not reported Filtering: visual inspection, 5-s moving average Time used for analysis: 2–6 s and 8.5–12.5 s after onset of maze solution (two windows) of each condition Baseline correction; averaging	Bilateral PFC (central optode at Fpz)	Shorter RT were found in change-error trials (i.e., incorrect movements toward the previous goal location when it had been changed) compared with change-correct trials (i.e., correct movement toward the goal position after the change of location). O_2Hb increased bilaterally in the PFC (especially middle areas) just after the start of solution of same-correct trials (i.e., correct movement toward the goal location that was in the previous goal position). In change-error trials, O_2Hb increased in the right and medial superior-middle cortices of the PFC and two-channels in the right hemisphere showed significant increases in O_2Hb after the first peak, compared with the corresponding-channels in the left hemisphere.
Retention of spatial locations (reaching space and navigational space)					
Kronovsek et al., 2021	Between-subject study with 31 healthy young participants (18–35 age range) vs. 24 healthy older participants (> 65 years)	Computerized CBT performed in the reaching space; VWCT[a] performed in the navigational space. Each task x 2 trials each length (2–9 items) Baseline duration: 20 s Rest phase duration: Not reported	6-channel (6 sources and 2 detector) Two wavelengths (760 and 830 nm) Sampling rate: 50 Hz DPF: $4.99 + 0.067 \times age^{0.814}$ (Young); 5 (Old) Filtering: Matlab-based scripts for motion artifacts, LP Filter (0.1 Hz) Time used for analysis: Encoding sequences last 10 s of span+1 and span task Baseline correction; averaging	Bilateral DLPFC (Fp2 and Fp1)	Young adults had a higher span score than old adults. The span score was higher when performing the reaching space regardless of age. Young adults show strong increase in O_2Hb concentration in the DLPFC both during the CBT and the VWCT, as well as lower HHb concentration in the VWCT, compared to older adults. Older adults showed lower O_2Hb concentration in DLPFC during performance on the VWCT compared with performance on the CBT. DLPFC O_2Hb correlated with the encoding of a larger span

[a] Acronyms used in order of appearance: F: Females; M: Males; DPF: Differential Path Length Factor; PFC: Prefrontal cortex; HC: Healthy controls; BP: Band-pass; LP: Low-pass; BA: Brodmann Area; DLPFC: Dorsolateral prefrontal cortex; CBT: Corsi-block tapping test; AD: Alzheimer's Disease; DST: Digit span test; CDT: Clock drawing test; ROC: receiver operating characteristic; RT: reaction time; HP: High Pass; OWM: Object working memory; SWM: Spatial working memory; VLPFC: Ventrolateral prefrontal cortex; CANTAB: Cambridge Neuropsychological Test Automated Battery; OTS: One touch Stockings; CBSI: Correlation-Based Signal Improvement; NWM: Nonspatial working memory; DT: Dual task; EFE: Emotional facial expressions; HRF: Haemodinamic Response Function; EVP: Early visual processing; VWCT: Virtual walking Corsi task.

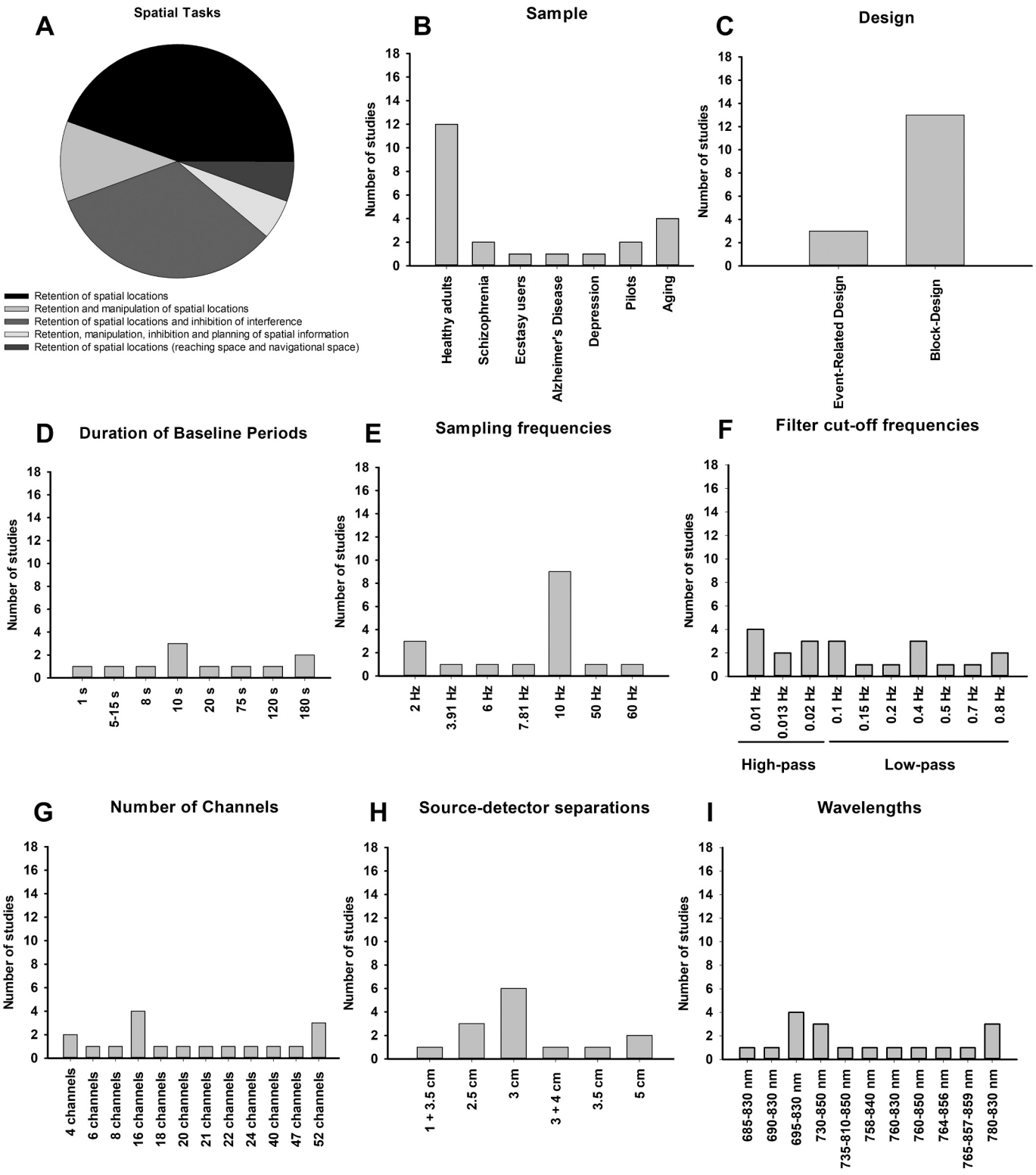

Fig. 2. Overview on (A) spatial task, (B) sample, (C) design, (D) duration of baseline periods, (E) sampling frequencies, (F) filter cut-off frequencies, (G) number of channels, (H) source-detector separations, and (I) wavelengths. s: seconds; Hz: Hertz; cm: centimeters; nm: nanometers.

used 8 sources and 7 detectors, resulting in 22- and 24-channel systems (Lee et al., 2008; Miyata et al., 2011), and another two studies used 4 sources and 4 detectors consisting of two pairs of optodes that were bilaterally placed (Quaresima et al., 2009; Vermeij et al., 2014) (Fig. 2 and Table 1).

The differential path length factor (DPF), a scaling factor that specifies how many times the detected light has traveled farther than the source-detector separation, is a constant value in three studies (Causse et al., 2019; McKendrick & Harwood, 2019; Vermeij et al., 2014), whereas only one study (Kronovsek et al., 2021) used age-dependent DPF values. In most of the studies, the DPF is not described (Fig. 2 and Table 1).

Regarding signal filtering and movement artifact removal, three studies applied a low-pass filter (LP) to their data (Kronovsek et al., 2021; McKendrick & Harwood, 2019; Montgomery et al., 2017), only one study used a high-pass filter (HP) (Schecklmann et al., 2011), and most studies used a bandpass filter (BP) (Chen et al., 2018; Herrmann et al., 2016; Lee et al., 2008; Panico et al., 2021; Perpetuini et al., 2019; Quaresima et al., 2009 ; Sato et al., 2014). Two studies applied an LP filter with a cut-off sampling frequency around 0.1 Hz (Kronovsek et al., 2021; Montgomery et al., 2017), whereas one study used an LP filter with a cut-off sampling frequency of 0.15 Hz (McKendrick & Harwood, 2019). The described BP filters were 0.01–0.1 Hz (Panico et al., 2021), 0.01–0.2 Hz (Chen et al., 2018), 0.01–0.4 Hz (Perpetuini et al., 2019), 0.01–0.5 Hz (Lee et al., 2008), 0.013–0.8 Hz (Quaresima et al., 2009; Sato et al., 2014) and 0.02–0.7 Hz (Herrmann et al., 2016). Causse et al. (2019, 2020) used a BP FIR filter order of 20 (0.02–0.40 Hz) and a correlation-based signal improvement (CBSI) method. In order to smooth their data, few studies used the moving average method and applied haemodynamic response function (HRF) filter (Geissler et al., 2020; Herrmann et al., 2016; Lancia et al., 2018). Heart rate monitoring and wavelet motion correction method were used in the study of Lancia et al. (2018). A visual inspection of the data was reported in two studies (Miyata et al., 2011; Montgomery et al., 2017) (Fig. 2 and Table 1).

Baseline correction was applied in almost all studies (Aoki et al., 2013; Causse et al., 2019, 2020; Chen et al., 2018; Kronovsek et al., 2021; Lancia et al., 2018; Mckendrick & Harwood, 2019; Miyata et al., 2011; Montgomery et al., 2017; Quaresima et al., 2009; Sato et al., 2014; Schecklmann et al., 2011), and all of them computed an average of all trials. Some studies did not report baseline correction, although baseline recording was included in their experimental protocol (Geissler et al., 2020; Herrmann et al., 2016; Vermeij et al., 2014).

To identify the studied regions, some studies used the International 10–20 system (Aoki et al., 2013; Herrmann et al., 2016; Kronovsek et al., 2021; Lancia et al., 2018; Miyata et al., 2011; Panico et al., 2021; Quaresima et al., 2009; Schecklmann et al., 2011; Vermeij et al., 2014), whereas others used the Brodmann Areas (BAs) (McKendrick & Harwood, 2019; Perpetuini et al., 2019). Other studies just described in their methods the functional areas they assessed (Causse et al., 2019, 2020; Chen et al., 2018; Lee et al., 2008; Montgomery et al., 2017; Sato et al., 2014). The studies are mainly focused on the PFC, adding other regions such as the parietal (Aoki et al., 2013; Chen et al., 2018) and temporal cortices (Aoki et al., 2013; Herrmann et al., 2016; Sato et al., 2014; Schecklmann et al., 2011). Some studies describe which portions of the cortex were registered in their studies. These regions were the bilateral PFC (Aoki et al., 2013; Causse et al., 2019, 2020; Geissler et al., 2020; Herrmann et al., 2016; Lancia et al., 2018; Lee et al., 2008; Miyata et al., 2011; Montgomery et al., 2017; Panico et al., 2021; Quaresima et al., 2009; Sato et al., 2014; Schecklmann et al., 2011; Vermeij et al., 2014), DLPFC (Geissler et al., 2020; Herrmann et al., 2016; Kronovsek et al., 2021; Lancia et al., 2018; McKendrick & Harwood, 2019; Montgomery et al., 2017; Perpetuini et al., 2019; Schecklmann et al., 2011), the ventrolateral prefrontal cortex (VLPFC) (Geissler et al., 2020; Lancia et al., 2018; Schecklmann et al., 2011), the anterior PFC (McKendrick & Harwood, 2019), the pars triangularis and pars opercularis (McKendrick & Harwood, 2019), the right PFC (Miyata et al., 2011), the left PFC (Causse et al., 2019; Panico et al., 2021), the medial superior-middle PFC (Miyata et al., 2011), the medial PFC (Causse et al., 2019, 2020) and those regions included in the fronto-parietal network (Chen et al., 2018) (Fig. 2 and Table 1).

3.6. Objectives of the reviewed studies and their main results

Due to the heterogeneity of the samples, the results will be summarized in those referred to studies in healthy and/or young adults, older adults and clinical samples.

There are several articles with very different research aims in which healthy adults and/or young adults were used as a sample. The studies that assessed PFC activation in relation to visuospatial task demands, in terms of loads or number of spatial items that are retained or manipulated, found an increase in O_2Hb in highly demanding tasks (Aoki et al., 2013; Causse et al., 2020; Geissler et al., 2020). Also, healthy adults have shown O_2Hb activation associated with highly demanding conditions in a retention of spatial position task in both the left and the right pars triangularis of the DLPFC (McKendrick & Harwood, 2019). The relationship between spatial WM load and O_2Hb increase in the PFC and is linear in some studies (Aoki et al., 2013; Causse et al., 2020), while it is quadratic in others (Causse et al., 2019; McKendrick & Harwood, 2019; Panico et al., 2021).

Other researchers have compared single and dual tasks in terms of their activation of brain regions, finding an increase in the bilateral DLPFC and frontoparietal regions' activation when the dual task was performed (Chen et al., 2018; Herrmann et al., 2016) and less interference when WM baseline was higher (Chen et al., 2018).

The activation of certain brain regions was also explored through three tasks based on the CBT, finding hemodynamic changes in the PFC regardless of the task used (either classic CBT involving spatial WM, CBT presenting distractors, or CBT as a simple motor task without any spatial learning) (Lancia et al., 2018). Another study analysed brain activation during CBT on the different roles assigned to the participants, reporting PFC brain activity recorded in examiners and examinees (Panico et al., 2021). They found that examiners show higher left PFC activity in comparison with examinees. They also showed a relationship between task performance and hemodynamic changes in the PFC (i.e., increased activation when the task was successfully completed and decreased activation when examinees produced spatial movements not matching the given sequences) (Panico et al., 2021). Miyata et al. (2011) aimed to study the relationship between brain activation and spatial planning and orientation, finding increases in O_2Hb and activation of different brain regions according to participant's performance. Correct responses especially activated the middle areas of bilateral PFC, while an incorrect performance, due to a change in location that was not previously notified, showed increases especially in the right and medial superior-middle PFC (Miyata et al., 2011). Sato et al. (2014) observed in their study that there was no significant increase in the O_2Hb signal in the PFC assessed bilaterally during a spatial WM task. They also reported that the spatial condition showed shorter reaction times compared to the verbal one (Sato et al., 2014).

Regarding the two studies that compared the performance of spatial WM tasks of adults and older adults, the main aim was to compare hemodynamic changes and the behavioural performance between age groups (Causse et al., 2019; Kronovsek et al., 2021). Causse et al. (2019) found a significant age-related impairment of spatial WM function only at the highest spatial loads and a lower left prefrontal activity in the older participants than in the younger ones at the highest loads. Kronovsek et al. (2021) found a stronger increase in O_2Hb concentration for young adults in comparison with older adults during a visuospatial WM task. Vermeij et al. (2014) aimed to study hemodynamic changes as a function of WM load only in older adults, finding an increase in prefrontal activation when there was an increase in WM load. They also reported a stronger right prefrontal activation in high performers under the high WM condition, an association between a decline in task performance with increasing WM load condition, and a bilateral increase of O_2Hb of prefrontal activation in low performers (Vermeij et al., 2014).

Regarding the studies using clinical samples, all of them aimed to study differences in the hemodynamic changes between patients and healthy controls. Studies of patients with schizophrenia found a reduced hemispheric specialization, false memory errors with a higher degree of confidence, and failure of verbal and visuospatial WM tasks to induce a PFC oxygenation change (Lee et al., 2008; Quaresima et al., 2009). Montgomery et al. (2017) reported that ecstasy-polydrug users did not display differences in cortical blood oxygenation in any PFC areas compared to controls in spatial span tasks. They have also found correlations between higher oxygenation in the right PFC and ecstasy

consumption (Montgomery et al., 2017). Schecklmann et al. (2011) observed that bipolar patients showed slower reaction times in spatial WM and control tasks compared to controls. They also found higher O_2Hb in DLPFC in healthy participants compared to depressed and bipolar patients both in visual and visuospatial WM tasks (Schecklmann et al., 2011). Finally, Perpetuini et al. (2019) found significantly higher activity in BAs 10 and 46 during the performance of CBT in AD patients compared to control participants, as well as in BAs 10 while performing a clock-drawing task. On the contrary, the AD group showed less activation than control participants in BAs 9 (Perpetuini et al., 2019).

4. Discussion

The main objective of the present review was to summarize the evidence on the use of fNIRS in the neuropsychological assessment of spatial memory. As a secondary aim, we explored whether such a technique can detect cortical activity changes congruent with the results obtained in spatial memory tasks; that is, whether such changes occurred in the regions related to spatial memory reported in previous literature, as well as to analyze the methodology and equipment employed in each study.

4.1. Visuospatial memory in the brain cortex

Almost all studies assessed spatial or visuospatial WM in computer-based tasks. There is a large scientific literature that associates WM function, both for verbal and visuospatial stimuli, with the PFC (Fuster, 2019), and, precisely for this reason, we have found that all the studies reviewed assessed this cortical region. However, it is also well known that WM depends on networks between the PFC and other areas, both cortical and subcortical (Christophel et al., 2017; D'Esposito & Postle, 2015; Nee & D'Esposito, 2018). For this reason, other regions, such as the parietal and temporal areas, were also evaluated in some articles (Aoki et al., 2013; Chen et al., 2018; Herrmann et al., 2016; Sato et al., 2014; Schecklmann et al., 2011). The reason why not all studies recorded activity in these brain regions could be due to the greater difficulty of measuring them using the fNIRS technique and the cost of devices with large numbers of channels (Zhao & Cooper, 2017), besides the fact that the PFC plays a regulatory role in the aforementioned brain areas (D'Esposito & Postle, 2015).

It is also important to mention that the PFC is not considered as a unitary brain region, but is rather subdivided into several anatomical and/or functional areas. In this sense, some of the functional areas that are involved are the DLPFC (Herrmann et al., 2016; Kronovsek et al., 2021), the left DLPFC (McKendrick & Harwood, 2019) and the VLPFC (Schecklmann et al., 2011). The authors who more precisely differentiated cortical functional regions in their PFC assessments found involvement of the frontoparietal network during the performance of a task involving the retention of spatial information and the inhibition of interference (Chen et al., 2018), increased activity of the lateral regions related to an increase in the WM load (Causse et al., 2019), and involvement of the medial superior-middle PFC during a task of spatial planning (Miyata et al., 2011). Those studies that did not discriminate PFC subregions found bilateral PFC activation (Aoki et al., 2013; Causse et al., 2019, 2020; Lancia et al., 2018), left PFC activation (Lee et al., 2008) and predominance of right PFC activation (Miyata et al., 2011), especially in high performers (Vermeij et al., 2014). Furthermore, a differentiation was found between bilateral prefrontal activation and predominant left prefrontal activation based on the performance of the spatial task or the mere observation of spatial performance, respectively (Panico et al., 2021). In general, this is congruent with previous neuroimaging studies using fMRI and PET (Cabeza & Nyberg, 2000). Although generally, visuospatial functions tend to be considered as a lateralized capacity toward the right hemisphere (Smith et al., 1996), no such anatomical specialization was found in the visuospatial WM in the reviewed studies. In this sense, previous evidence using fMRI have shown that both verbal and spatial WM may involve the same bilateral fronto-parietal circuits (Ray et al., 2008). Likewise, visuospatial WM impairment has also been found in patients with right hemisphere damage, where many of them also presented fronto-parietal impairment (Paulraj et al., 2018).

4.2. Visuospatial working memory and prefrontal cortex in healthy young adults

It is important to mention that most of the articles included in the review assessed healthy young adults. Therefore, we can assume that these data show normative levels of visuospatial WM functioning in relation to the PFC. In this population, the greater load of items to be maintained, 4 spatial items versus 2 spatial items in a delayed response task (Aoki et al., 2013), 10–12 spatial items versus 6–8 spatial items in the SWM test from CANTAB (Causse et al., 2020) or the higher number of items, spatial positions (from 1 to 10) to be retained (McKendrick & Harwood, 2019), increased PFC activation. Similarly, the administration of the WM assessment test CBT itself required higher PFC activity than its execution and this activity increased as the spatial span reach higher levels (Panico et al., 2021). PFC activation was also higher in the execution of dual performance paradigms in comparison with single performance, either in a spatial n-back task that was performed during a tandem stance task (Chen et al., 2018) or a spatial CBT task in combination with a recognition of emotional facial expressions task (Herrmann et al., 2016). Specifically, these activations were found in the DLPFC, both left and bilateral, in the right pars triangularis and in the frontoparietal regions (Aoki et al., 2013; Causse et al., 2020; Chen et al., 2018; Herrmann et al., 2016; Panico et al., 2021). This could be explained by the fact that the tasks in which more cognitive resources are demanded require greater activation of the brain regions involved. McKendrick and Harwood (2019), in a task that requires retention of spatial positions with different loads, 1 to 10 items, found that DLPFC activation increases at the beginning of the task with a low WM load, and such activation continues to increase until reaching an asymptote with medium loads, and it increases again at the highest WM load. These results could reflect a greater demand of cognitive resources both at the beginning of the task, at low loads, and probably related to the beginning of the task and the implementation of the appropriate cognitive processes for its resolution, and at the end of the task, where the spatial load is higher and, again, demands more cognitive resources. These findings are partially consistent with those of Panico et al. (2021), in which a progressive PFC activation was found as WM load increased. This increase reaches the end when participants' span level is reached; at this point, the PFC activation begins to decline. The authors of this study deduced that this lower activation after exceeding the participants' span level could be due to an excess of resource demands from the task at the higher levels, causing the participants to "disconnect" from the task (Panico et al., 2021). fMRI studies have reported same course of PFC activation. Activation can predict load-related changes in task performance, and PFC activity tends to decrease at high-load levels related to low accuracy (Lamichhane et al. (2020). A similar effect has also been described in older people (Causse et al., 2019), which will be discussed later in more detail.

4.3. Visuospatial working memory and prefrontal cortex in older adults

Other articles compared the performance of healthy older participants with healthy adults. We found evidence in favour both of a linear and a quadratic relationship between WM load and PFC activation in older people. Thus, some studies have found that the greater the memory load, the greater the DLPFC activation (Kronovsek et al., 2021), although another study revealed a plateau in the PFC activation in the older group, but not in the younger one, at the highest loads (Causse et al., 2019). These results are congruent with results found using fMRI which show that age and performance level modulate load-related

neural activation in PFC (Bauer et al., 2018). In general, there is insufficient evidence to affirm or disprove a possible linear and/or direct association between a greater amount of information to be retained and greater PFC activation shown by fNIRS in older people. Some studies have found less PFC activation, concretely in the left PFC and the bilateral DLPFC, in older groups compared to younger groups (Causse et al., 2019; Kronovsek et al., 2021). In these studies, not only is lower activation reported in older people, but also worse behavioural results in WM tasks. In order to explain contrasting evidence of both age-related under-recruitment as well as age-related over-recruitment of the PFC during WM performance, Reuter-Lorenz and Cappell (2008) formulated the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH). CRUNCH proposes that, irrespective of age, neural engagement varies with the level of task demand, and activity in cortical regions is up-regulated to a certain level as cognitive load increases. At low levels of cognitive load, older adults need to recruit more neural resources than young adults in order to maintain task performance, due to less efficient neural processing at older ages. This compensatory mechanism is no longer effective at high levels of cognitive load, leading to reduced or equivalent activation in older adults in comparison to young adults. To be precise, Causse et al. (2019) have not found any significant difference in PFC activity between age groups of pilots for low to moderate WM loads, although the CRUNCH model would predict higher activity in older participants. At very high loads of 12 items, older participants showed lower left PFC activity than younger participants, along with impaired performance. This is consistent with predictions from CRUNCH. Older pilots showed under-activation at higher levels of task demand when compared to younger pilots, likely due to a resource ceiling according to the CRUNCH model. However, activity was not significantly different between age groups in lower WM loads, whereas the CRUNCH model would rather predict higher activation in older compared to younger participants. This absence of over-activation in older pilots likely reflects a preservation of spatial WM performance at moderate difficulty level, medium WM loads. Similarly, Kronovsek et al.'s (2021) results corroborate the CRUNCH model, as they observed PFC under-activation for older adults compared to younger adults at high levels of cognitive load, when it is assumed that processing capacity limits are reached and compensatory mechanisms may no longer be effective. Following the CRUNCH model, when assessing AD patients, Perpetuini et al. found that AD participants recruit more neural and executive resources than aged-matched controls at low cognitive load to support WM, while both groups show equivalent WM performances (Perpetuini et al., 2019). Interestingly, when comparing older participants with better WM performance and older participants with worse WM performance, a stronger right PFC activation under high WM conditions is found in high performers in comparison with low performers (Vermeij et al., 2014). Overall, PFCs were less activated in healthy older adults in comparison with younger adults, which could, potentially, lead to poorer performance of the task, such that older participants who achieve better behavioural performance are also those who seem to achieve greater PFC activation. Previous studies show that, in progressive normalized aging, the role of the PFC in WM acquires a less important role, and other areas, such as the parietal cortex, the insula or the cerebellum, begin to be activated, presumably as a mechanism of compensation and brain functional reorganization (Yaple et al., 2019). These findings emphasize the need to take behavioural performance level into account when interpreting and comparing neuroimaging data, as well as the need to include not only records on PFC, but also other more posterior cortical areas to assess brain compensation. Although the study of Vermeij et al. (2014) did not include a group of young adults to examine age-related changes, their results are congruent with the CRUNCH hypothesis that PFC over-recruitment may reflect an age-invariant compensatory mechanism. Vermeij et al. (2014) found a pattern of bilateral recruitment, up-regulation of left and right PFC activation, with increasing spatial WM load. They found a significant interaction between performance level and hemispheric activation, indicating that high performers more strongly activated the right PFC under high WM load than did low performers. These results are congruent with the model of Hemispheric Asymmetry Reduction in Older adults (HAROLD) (Cabeza, 2002), which explains a more bilateral pattern of PFC activation in older adults in tasks for which young adults typically show unilateral activation. According to this model, age-related over-recruitment of the PFC has been observed across several cognitive domains. The recruitment of the right PFC might contribute to successful spatial WM performance in older adults. In contrast, the negative correlation between load-induced changes in activation and performance that was observed in low performers may point toward declined neural efficiency or unsuccessful compensation. Contrary to the HAROLD model, Causse et al. (2019) have not observed less asymmetric activation in older pilots compared to younger pilots.

4.4. *Visuospatial working memory and prefrontal cortex in clinical populations*

Regarding articles that used clinical samples, we have reviewed studies on ecstasy consumers, patients with depression and bipolar disorder, patients with schizophrenia and patients with AD. These studies in patients found that the better the WM performance in the task, the greater the activation in the PFC. Specifically, ecstasy consumers showed high right PFC activation (Montgomery et al., 2017), contrary to fMRI studies which found no differences in cortical activation (Daumann et al., 2003) and AD patients actively involve the BAs 10 and 46 (Perpetuini et al., 2019). In these cases, despite clinical groups showing similar behavioural performance to healthy participants, their cortical activation was different and higher. Other studies did obtain a worse performance of clinical samples in WM tasks compared to controls, but they did not find the hyperactivation described in the previous studies. Thus, studies have revealed a lower hemispheric specialization or inefficient PFC function in schizophrenic patients compared to controls (Lee et al., 2008; Quaresima et al., 2009). These results are congruent with fMRI results (Lee et al., 2008; Potkin et al., 2009). Similarly, lower DLPFC activation was reported in patients with depression and with bipolar disorder compared to healthy participants (Schecklmann et al., 2011). Taken together, these results suggest a tendency to hyperactivate the PFC to compensate for cognitive difficulties in these patients. Thus, prefrontal hyperactivation in the clinical groups could explain why they perform similarly to the control groups, whereas less prefrontal lateralization and less general prefrontal activation would explain why they perform behaviourally worse than the control groups. Thus, for example, patterns of prefrontal hyperactivation in fMRI have been identified in patients with schizophrenia (Thormodsen et al., 2011), as well as in patients with obsessive-compulsive disorder (Henseler et al., 2008), together with a cognitive performance equivalent to that of healthy participants. However, the available studies with clinical samples are still very scarce and include results from highly variable neurodegenerative or psychiatric pathologies. It is, therefore, difficult to draw definitive conclusions in this matter.

4.5. *Variability of assessment tasks, methodologies and samples*

It is important to consider that all the above findings were obtained from different assessment tasks, different methodologies and with diverse samples in size and characteristics. To assess spatial WM, authors used tests from neuropsychological batteries (such as the CANTAB), classical neuropsychological tests for the short-term retention of spatial locations (such as the CBT), adaptations of classical neuropsychological tests or tests created by the authors themselves. This can lead to confusion when interpreting the results obtained. Furthermore, it should be noted that one of the studies assessed spatial planning and orientation using a computerized plus-shaped maze task (Miyata et al., 2011). This task requires a clear involvement of the WM capacity, but also some other complex skills, such as the ability to orient oneself in

space or planning, as the authors themselves point out.

Regarding the methodology and equipment employed in each study, there is a tendency to use 16-, 52- or 4-channel systems, two wavelengths between 685 and 859 nm, an interoptode distance of 2.5–3 cm and a sampling frequency of 10 Hz. The features of fNIRS equipment are relevant for the purpose of the studies. The deepness with which the light can penetrate the brain tissue is influenced by factors such as the light wavelength and the distance between sources and detectors, and the longer distances are optimal to show deeper brain activity (Ferrari & Quaresima, 2012). fNIRS equipment with few optodes, such as that employed by Kronovsek et al. (2021) normally allows portability, cause low discomfort and show lower susceptibility to motion artifacts, so it is an excellent tool for investigating spatial memory tasks in conditions in which mobility is required. However, fNIRS equipment using a great number of channels and optodes that cover extensive regions of the cortex, such as that used by Herrmann et al. (2016), allows more detailed descriptions of the cortical regions activated, and is optimal to explore several interconnected regions but not feasible to assess cortical activity in more realistic settings where motor displacement is required.

Concerning the samples, they are highly variable. The number of participants assessed in the studies ranges from 9 (Quaresima et al., 2009) to 61 participants (Causse et al., 2019). All the studies that specified the years of education resulted in samples with a high level of education or samples composed of university students (Causse et al., 2019, 2020; Herrmann et al., 2016; Lancia et al., 2018; Lee et al., 2008; Montgomery et al., 2017; Panico et al., 2021; Quaresima et al., 2009; Sato et al., 2014; Vermeij et al., 2014), which could bias the results obtained. It is also important to consider the participants' gender, as this variable can influence performance in spatial tasks and brain activation. Males and females show different patterns of brain activation during such tasks (Hill et al., 2014). Most of the studies included in this review presented an unequal distribution of gender in their samples. Some assessed exclusively men (Causse et al., 2020), or men were overrepresented (Aoki et al., 2013; Causse et al., 2019; Lee et al., 2008; Perpetuini et al., 2019), and others studied mainly women (Kronovsek et al., 2021; Miyata et al., 2011; Schecklmann et al., 2011; Vermeij et al., 2014), and this gender bias is an important issue than can affect results.

The searching strategy of this review included keywords to identify as many studies as possible that measure spatial memory. With this aim, we included keywords related to tests that measure the spatial component of memory and WM, such as “Maze” or “Corsi”. However, other studies using these or other tests measuring spatial memory may have been dismissed in our search.

Based on the findings of the present review, certain needs and unresolved issues were identified that could be addressed in future research. First, while it is true that there are studies in which the temporal and parietal cortex have been established as regions of interest, in addition to the PFC, there are still few studies that do so. Including these regions would be of particular importance, as, according to scientific evidence, these regions are also activated by a spatial WM task. Second, there are more ecological methodologies that measure spatial WM, such as the use of virtual reality, which can approximate the natural conditions under which spatial memory skills occur in everyday contexts. However, these paradigms are not employed in any of the reviewed studies, even though fNIRS equipment can be adapted to the application of such tests. Third, concerning clinical samples, some disorders are typically related to a dysfunction of the PFC, such as the attention deficit and hyperactivity disorder or frontotemporal dementia, in which it would be worthwhile to test PFC functioning during spatial WM tasks using fNIRS. However, our search did not find any studies that covered these aims. Finally, it is also important to consider that results reported in this review are mainly centred on immediate recall and WM, showing that the long-term retrieval of spatial information is underestimated in research. In this sense, other functional neuroimaging techniques have recently reported interesting conclusions assessing spatial long-term memory (Guo et al., 2021), which may support the use of fNIRS to approach this process.

4.6. Recommendations for future studies

Over the last few decades, fNIRS has become a powerful method to assess cortical activity during cognitive functions that cannot be studied in artificial contexts, such as in an fMRI scanner (Pinti et al., 2018). As spatial memory is a cognitive process very dependent on the context, the use of fNIRS in this field is very interesting. In this sense, although almost all studies assessed spatial or visuospatial WM in computer-based tasks, fNIRS enables cortical activity assessment during task performance in the reaching space or the navigational space (Kronovsek et al., 2021), and other spatial memory processes, apart from WM or short-term memory, can be explored using this technique. Most of the studies clearly probe a strong relationship between spatial WM load and activity in the PFC. In this sense, future research on spatial WM could benefit from using fNIRS as a tool for quantifying users' workload in spatial tasks. In the field of passive brain-computer interfaces, it is desirable to obtain a measure of the state of the user to adapt a user interface accordingly. fNIRS signals measured from the PFC were used to quantify mental workload in a verbal n-back task, revealing that levels of workload induced by n-back tasks can be discriminated by fNIRS in single-trial assessment (Herff et al., 2014). Future research on spatial memory could benefit from the potential use of fNIRS for assessing user state monitoring to show the degree of workload a subject was experiencing, and this is also possible in real-life scenarios.

No studies have used fNIRS during 2D, 3D or real spatial navigation in order to measure acquisition and retrieval of spatial memories. We highlight the relevance of exploring fNIRS activity under other approaches. An example of the usability of fNIRS to measure cortical activity during the acquisition of spatial memory can be found in the methodological article of Ayaz et al. (2011), which explores the use of MazeSuite and fNIRS within a cognitive processing learning paradigm.

Methodologically, most of the articles used fNIRS equipment of 16 channels and mainly measured the PFC. By exploring other cortical regions, studies could evaluate bilateral occipital, temporal and parietal cortex function during spatial memory performance. This is especially important when assessing cognitive decline because compensatory activations may provide scaffolding to support aging cognition. Studies are predominantly focused on spatial WM and used 52 or 16-channel systems when they aimed to measure with great precision. The use of wavelengths between 685 and 859, interoptode distances of 2.5–3 cm, and a sampling frequency of 10 Hz is very common. However, not all studies reported all technical configurations and design-related details. It is recommended to clearly describe DPF values with selection process, duration of task, trials, and baseline and rest periods (Yücel et al., 2021). It is desirable to calculate DPF values depending on age and cortical region assessed (Scholkmann & Wolf, 2013). Baseline correction or baseline normalization should be applied to fNIRS data, which should be averaged across channels, regions and trials (Tachtsidis & Scholkmann, 2016). Additional measures, such as heart rate, should be used to monitor systematic changes, especially in those experiments that include navigation, where moving average filters are especially needed (Herold et al., 2017, 2018). In order to process data, the use of BP filters is recommended (Yücel et al., 2021). Optode placement should be based on the international 10–20 system (Yücel et al., 2021).

5. Conclusion

fNIRS is compatible with the standard neuropsychological assessment of spatial memory, making it possible to complement behavioural results with data of cortical functional activity. The studies analysed, mainly focused on immediate or short-term recall of spatial information and spatial WM, showed involvement of the PFC in spatial WM tasks, with the DLPFC, the VLPFC, and the bilateral PFC being specifically activated. Some studies found a linear relationship between WM load

and PFC activity, while other studies reported quadratic relationships, with higher PFC activity at the beginning of the spatial WM task and at higher levels of difficulty. In comparison with healthy adults, healthy older people showed greater activation of the PFC when performing these tasks, in addition to worse results in these neuropsychological tests, finding similar relationships in this age group to those found in healthy adults in terms of PFC activity and WM load. Clinical samples show hyperactivation of the PFC as a form of compensation for a poorer performance of the task. The methodology and equipment of fNIRS vary depending on whether the spatial task requires some mobility, thus needing a smaller number of optodes, or the task can be performed statically, thus allowing the use of a larger number of optodes and measurement channels and being, therefore, more specific in the measurement of cerebral hemodynamic changes.

Not all studies reported all technical configurations and design-related details. It is recommended to clearly describe DPF values with selection process, duration of task, trials, and baseline and rest periods. It is desirable to calculate DPF values depending on age and cortical region assessed, as well as to apply baseline correction or baseline normalization to fNIRS data. Those experiments that include navigation need additional measures, such as heart rate, and moving average filters.

No studies have used fNIRS during spatial navigation in order to measure acquisition and retrieval of spatial memories. Future research on spatial WM could benefit from using fNIRS as a tool for quantifying users' workload in spatial tasks. It would be of great interest to use fNIRS to measure cortical activity during the acquisition and retrieval of spatial memory using virtual and real mazes.

Declaration of competing interest

None.

Acknowledgements

This work was supported by Departamento de Psicología y Sociología of Universidad de Zaragoza; Gobierno de Aragón (Departamento de Ciencia, Universidad y Sociedad del Conocimiento) and FEDER 2014-2020 “Construyendo Europa desde Aragón” for the Group S31_20D to MML, and MINECO (Ministerio de Economía y Competitividad del Gobierno de España) PSI2017-83893-R to MM.

References

Aoki, R., Sato, H., Katura, T., Matsuda, R., & Koizumi, H. (2013). Correlation between prefrontal cortex activity during working memory tasks and natural mood independent of personality effects: An optical topography study. *Psychiatry Research - Neuroimaging, 212*(1), 79–87. https://doi.org/10.1016/j.pscychresns.2012.10.009

Ayaz, H., Shewokis, P. A., Curtin, A., Izzetoglu, M., Izzetoglu, K., & Onaral, B. (2011). Using MazeSuite and functional near infrared spectroscopy to study learning in spatial navigation. *Journal of Visualized Experiments: JoVE, 56*, 3443. https://doi.org/10.3791/3443

Baddeley, A., Kopelman, M., & Wilson, B. (2002). *The Handbook of Memory Disorders* (Second edi). Chichester, UK: John Wiley & Sons Ltd.

Bauer, E., Sammer, G., & Toepper, M. (2018). Performance level and cortical atrophy modulate the neural response to increasing working memory load in younger and older adults. *Frontiers in Aging Neuroscience, 10*, 265. https://doi.org/10.3389/fnagi.2018.00265

Bocchi, A., Palermo, L., Boccia, M., Palmiero, M., D'Amico, S., & Piccardi, L. (2020). Object recognition and location: Which component of object location memory for landmarks is affected by gender? Evidence from four to ten year-old children. *Applied Neuropsychology: Child, 9*(1), 31–40. https://doi.org/10.1080/21622965.2018.1504218

Bonetti, L. V., Hassan, S. A., Lau, S. T., Melo, L. T., Tanaka, T., Patterson, K. K., & Reid, W. D. (2019). Oxyhemoglobin changes in the prefrontal cortex in response to cognitive tasks: A systematic review. *International Journal of Neuroscience, 129*, 195–203. https://doi.org/10.1080/00207454.2018.1518906

Bonilauri, A., Sangiuliano Intra, F., Pugnetti, L., Baselli, G., & Baglio, F. (2020). A systematic review of cerebral functional near-infrared spectroscopy in chronic neurological diseases-actual applications and future perspectives. *Diagnostics (Basel, Switzerland), 10*(8), 581. https://doi.org/10.3390/diagnostics10080581

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging, 17*(1), 85–100. https://doi.org/10.1037//0882-7974.17.1.85

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12*(1), 1–47. https://doi.org/10.1162/08989290051137585

Causse, M., Chua, Z., & Matton, N. (2020). Performance and brain activity during a spatial working memory task: Application to pilot candidate selection. *Adv. Intell. Syst. Comput., 953*, 45–55. https://doi.org/10.1007/978-3-030-20473-0_5

Causse, M., Chua, Z. K., & Rémy, F. (2019). Influences of age, mental workload, and flight experience on cognitive performance and prefrontal activity in private pilots: A fNIRS study. *Scientific Reports, 9*(1). https://doi.org/10.1038/s41598-019-44082-w

Chen, Y., Yu, Y., Niu, R., & Liu, Y. (2018). Selective effects of postural control on spatial vs. nonspatial working memory: A functional near-infrared spectral imaging study. *Frontiers in Human Neuroscience, 12*, 243. https://doi.org/10.3389/fnhum.2018.00243

Christophel, T. B., Klink, P. C., Spitzer, B., Roelfsema, P. R., & Haynes, J. D. (2017). The distributed nature of working memory. *Trends in Cognitive Sciences, 21*(2), 111–124. https://doi.org/10.1016/j.tics.2016.12.007

Cui, X., Bray, S., Bryant, D. M., Glover, G. H., & Reiss, A. L. (2011). A quantitative comparison of NIRS and fMRI across multiple cognitive tasks. *NeuroImage, 54*(4), 2808–2821. https://doi.org/10.1016/j.neuroimage.2010.10.069

D'Esposito, M., & Postle, B. R. (2015). The cognitive neuroscience of working memory. *Annual Review of Psychology, 66*, 115–142. https://doi.org/10.1146/annurev-psych-010814-015031

Daumann, J., Fimm, B., Willmes, K., Thron, A., & Gouzoulis-Mayfrank, E. (2003). Cerebral activation in abstinent ecstasy (MDMA) users during a working memory task: A functional magnetic resonance imaging (fMRI) study. *Cognitive Brain Research, 16*(3), 479–487. https://doi.org/10.1016/s0926-6410(03)00075-2

Devor, A., & Boas, D. (2012). Neurovascular imaging. *Frontiers in Neuroenergetics, 4*, 1. https://doi.org/10.3389/fnene.2012.00001

Dong, D., Wong, L. K. F., & Luo, Z. (2019). Assess BA10 activity in slide-based and immersive virtual reality prospective memory task using functional near-infrared spectroscopy (fNIRS). *Applied Neuropsychology:Adult, 26*(5), 465–471. https://doi.org/10.1080/23279095.2018.1443104

Fanari, R., Meloni, C., & Massidda, D. (2019). Visual and spatial working memory abilities predict early math skills: A longitudinal study. *Frontiers in Psychology, 10*, 2460. https://doi.org/10.3389/fpsyg.2019.02460

Ferrari, M., & Quaresima, V. (2012). A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application. *NeuroImage, 63*(2), 921–935. https://doi.org/10.1016/j.neuroimage.2012.03.049

Fuster, J. M. (2019). The prefrontal cortex in the neurology clinic. *Handbook of Clinical Neurology, 163*, 3–15. https://doi.org/10.1016/B978-0-12-804281-6.00001-X

Geissler, C. F., Domes, G., & Frings, C. (2020). Shedding light on the frontal hemodynamics of spatial working memory using functional near-infrared spectroscopy. *Neuropsychologia, 146*, Article 107570. https://doi.org/10.1016/j.neuropsychologia.2020.107570

Girouard, H., & Iadecola, C. (2006). Neurovascular coupling in the normal brain and in hypertension, stroke, and Alzheimer disease. *Journal of Applied Physiology (Bethesda, MD: 1985), 100*(1), 328–335. https://doi.org/10.1152/japplphysiol.00966.2005

Guo, J., Zhang, K., Zhang, J., Zhao, R., Liang, Y., Lin, Y.Yang, X., … (2021). Decoding spatial memory retrieval in cubical space using fMRI signals. *Frontiers in Neural Circuits, 15*, 34. https://doi.org/10.3389/fncir.2021.624352

Henseler, I., Gruber, O., Kraft, S., Krick, C., Reith, W., & Falkai, P. (2008). Compensatory hyperactivations as markers of latent working memory dysfunctions in patients with obsessive-compulsive disorder: An fMRI study. *Journal of Psychiatry and Neuroscience, 33*(3), 209–215.

Herff, C., Heger, D., Fortmann, O., Hennrich, J., Putze, F., & Schultz, T. (2014). Mental workload during n-back task-quantified in the prefrontal cortex using fNIRS. *Frontiers in Human Neuroscience, 7*, 935. https://doi.org/10.3389/fnhum.2013.00935

Herold, F., Wiegel, P., Scholkmann, F., & Müller, N. G. (2018). Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise-cognition science: a systematic, methodology-focused review. *Journal of Clinical Medicine, 7*(12), 466. https://doi.org/10.3390/jcm7120466

Herold, F., Wiegel, P., Scholkmann, F., Thiers, A., Hamacher, D., & Schega, L. (2017). Functional near-infrared spectroscopy in movement science: a systematic review on cortical activity in postural and walking tasks. *Neurophotonics, 4*(4), 41403. https://doi.org/10.1117/1.NPh.4.4.041403

Herrmann, M. J., Neueder, D., Troeller, A. K., & Schulz, S. M. (2016). Simultaneous recording of EEG and fNIRS during visuo-spatial and facial expression processing in a dual task paradigm. *International Journal of Psychophysiology, 109*, 21–28. https://doi.org/10.1016/j.ijpsycho.2016.09.013

Hill, A. C., Laird, A. R., & Robinson, J. L. (2014). Gender differences in working memory networks: A BrainMap meta-analysis. *Biological Psychology, 102*, 18–29. https://doi.org/10.1016/j.biopsycho.2014.06.008

Jöbsis, F. F. (1977). Noninvasive, infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. *Science, 198*(4323), 1264–1266. https://doi.org/10.1126/science.929199

Krishnamurthy, K., Yeung, M. K., Chan, A. S., & Han, Y. M. Y. (2020). Effortful control and prefrontal cortex functioning in children with autism spectrum disorder: an fnirs study. *Brain Sciences, 10*(11), 1–17. https://doi.org/10.3390/brainsci10110880

Kronovsek, T., Hermand, E., Berthoz, A., Castilla, A., Gallou-Guyot, M., Daviet, J. C., & Perrochon, A. (2021). Age-related decline in visuo-spatial working memory is reflected by dorsolateral prefrontal activation and cognitive capabilities. *Behavioural Brain Research, 398*, Article 112981. https://doi.org/10.1016/j.bbr.2020.112981

Lamichhane, B., Westbrook, A., Cole, M. W., & Braver, T. S. (2020). Exploring brain-behavior relationships in the N-back task. *NeuroImage, 212*, Article 116683. https://doi.org/10.1016/j.neuroimage.2020.116683

Lancia, S., Cofini, V., Carrieri, M., Ferrari, M., & Quaresima, V. (2018). Are ventrolateral and dorsolateral prefrontal cortices involved in the computerized Corsi block-tapping test execution? An fNIRS study. *Neurophotonics, 5*(01), 1. https://doi.org/10.1117/1.nph.5.1.011019

Lee, J., Folley, B. S., Gore, J., & Park, S. (2008). Origins of spatial working memory deficits in schizophrenia: An event-related fMRI and near-infrared spectroscopy study. *PLoS ONE, 3*(3). https://doi.org/10.1371/journal.pone.0001760

Lucas, I., Urieta, P., Balada, F., Blanco, E., & Aluja, A. (2020). Differences in prefrontal cortex activity based on difficulty in a working memory task using near-infrared spectroscopy. *Behavioural Brain Research, 392*, Article 112722. https://doi.org/10.1016/j.bbr.2020.112722

Martinelli, C., & Shergill, S. (2015). Everything you wanted to know about neuroimaging and psychiatry, but were afraid to ask. *BJPsych Adv., 21*(4), 251–260. https://doi.org/10.1192/apt.bp.114.013763

McDonald, N. M., & Perdue, K. L. (2018). The infant brain in the social world: Moving toward interactive social neuroscience with functional near-infrared spectroscopy. *Neuroscience and Biobehavioral Reviews, 87*, 38–49. https://doi.org/10.1016/j.neubiorev.2018.01.007

McKendrick, R., & Harwood, A. (2019). Cognitive workload and workload transitions elicit curvilinear hemodynamics during spatial working memory. *Frontiers in Human Neuroscience, 13*, 405. https://doi.org/10.3389/fnhum.2019.00405

Miyata, H., Watanabe, S., & Minagawa-Kawai, Y. (2011). Two successive neurocognitive processes captured by near-infrared spectroscopy: Prefrontal activation during a computerized plus-shaped maze task. *Brain Research, 1374*, 90–99. https://doi.org/10.1016/j.brainres.2010.12.047

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., Altman, D., Antes, G.Tugwell, P., … (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine, 151*, 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

Montgomery, C., Fisk, J. E., & Roberts, C. A. (2017). Updating of working memory in ecstasy polydrug users: Findings from fNIRS. *Human Psychopharmacology, 32*(3). https://doi.org/10.1002/hup.2609. doi:10.1002/hup.2609

Nee, D. E., & D'Esposito, M. (2018). The representational basis of working memory. *Current Topics in Behavioral Neurosciences, 37*, 213–230. https://doi.org/10.1007/7854_2016_456

Obrig, H. (2014). NIRS in clinical neurology — A 'promising' tool? *NeuroImage, 85*, 535–546. https://doi.org/10.1016/j.neuroimage.2013.03.045

Pandarinathan, G., Mishra, S., Nedumaran, A. M., Padmanabhan, P., & Gulyás, B. (2018). The potential of cognitive neuroimaging: A way forward to the mind-machine interface. *Journal on Imaging, 4*, 70. https://doi.org/10.3390/jimaging4050070

Panico, F., De Marco, S., Sagliano, L., D'Olimpio, F., Grossi, D., & Trojano, L. (2021). Brain hemodynamic response in examiner-examinee dyads during spatial short-term memory task: An fNIRS study. *Experimental Brain Research, 239*(5), 1607–1616. https://doi.org/10.1007/s00221-021-06073-0

Paulraj, S. R., Schendel, K., Curran, B., Dronkers, N. F., & Baldo, J. V. (2018). Role of the left hemisphere in visuospatial working memory. *Journal of Neurolinguistics, 48*, 133–141. https://doi.org/10.1016/j.jneuroling.2018.04.006

Peelle, J. E. (2017). Optical neuroimaging of spoken language. *Language, Cognition and Neuroscience, 32*(7), 847–854. https://doi.org/10.1080/23273798.2017.1290810

Perpetuini, D., Chiarelli, A. M., Cardone, D., Filippini, C., Bucco, R., Zito, M., & Merla, A. (2019). Complexity of frontal cortex fNIRS can support alzheimer disease diagnosis in memory and visuo-spatial tests. *Entropy (Basel, Switzerland), 21*(1), 26. https://doi.org/10.3390/e21010026

Pinti, P., Aichelburg, C., Gilbert, S., Hamilton, A., Hirsch, J., Burgess, P., & Tachtsidis, I. (2018). A review on the use of wearable functional near-infrared spectroscopy in naturalistic environments. *Japanese Psychological Research, 2*(2), 20801. https://doi.org/10.1111/jpr.12206

Pinti, P., Tachtsidis, I., Hamilton, A., Hirsch, J., Aichelburg, C., Gilbert, S., & Burgess, P. W. (2020). The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. *Annals of the New York Academy of Sciences, 1464*(1), 5–29. https://doi.org/10.1111/nyas.13948

Potkin, S. G., Turner, J. A., Brown, G. G., McCarthy, G., Greve, D. N., Glover, G. H., Manoach, D. S., Belger, A., Diaz, M., Wible, C. G., Ford, J. M., Mathalon, D. H., Gollub, R., Lauriello, J., O'Leary, D., van Erp, T. G., Toga, A. W., Preda, A., Lim, K. O., & FBIRN. (2009). Working memory and DLPFC inefficiency in schizophrenia: The FBIRN study. *Schizophrenia Bulletin, 35*(1), 19–31. https://doi.org/10.1093/schbul/sbn162

Quaresima, V., & Ferrari, M. (2019). A mini-review on functional near-infrared spectroscopy (fNIRS): Where do we stand, and where should we go? *Photonics, 6*(3), 87. https://doi.org/10.3390/photonics6030087

Quaresima, V., Giosuè, P., Roncone, R., Casacchia, M., & Ferrari, M. (2009). Prefrontal cortex dysfunction during cognitive tests evidenced by functional near-infrared spectroscopy. *Psychiatry Research - Neuroimaging, 171*(3), 252–257. https://doi.org/10.1016/j.pscychresns.2008.02.002

Ray, M. K., Mackay, C. E., Harmer, C. J., & Crow, T. J. (2008). Bilateral generic working memory circuit requires left-lateralized addition for verbal processing. *Cerebral Cortex, 18*(6), 1421–1428. https://doi.org/10.1093/cercor/bhm175

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science, 17*(3), 177–182. https://doi.org/10.1111/j.1467-8721.2008.00570.x

Sato, H., Dresler, T., Haeussinger, F. B., Fallgatter, A. J., & Ehlis, A. C. (2014). Replication of the correlation between natural mood states and working memory-related prefrontal activity measured by near-infrared spectroscopy in a German sample. *Frontiers in Human Neuroscience, 8*(1), 37. https://doi.org/10.3389/fnhum.2014.00037

Scarapicchia, V., Brown, C., Mayo, C., & Gawryluk, J. R. (2017). Functional magnetic resonance imaging and functional near-infrared spectroscopy: Insights from combined recording studies. *Frontiers in Human Neuroscience, 11*, 419. https://doi.org/10.3389/fnhum.2017.00419

Schecklmann, M., Dresler, T., Beck, S., Jay, J. T., Febres, R., Haeusler, J.Fallgatter, A. J., … (2011). Reduced prefrontal oxygenation during object and spatial visual working memory in unpolar and bipolar depression. *Psychiatry Research - Neuroimaging, 194*(3), 378–384. https://doi.org/10.1016/j.pscychresns.2011.01.016

Scholkmann, F., Kleiser, S., Metz, A. J., Zimmermann, R., Mata Pavia, J., Wolf, U., & Wolf, M. (2014). A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. *NeuroImage, 85*, 6–27. https://doi.org/10.1016/j.neuroimage.2013.05.004

Scholkmann, F., & Wolf, M. (2013). General equation for the differential pathlength factor of the frontal human head depending on wavelength and age. *Journal of Biomedical Optics, 18*(10), Article 105004. https://doi.org/10.1117/1.JBO.18.10.105004

Smith, E. E., Jonides, J., & Koeppe, R. A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6*(1), 11–20. https://doi.org/10.1093/cercor/6.1.11

Steinbrink, J., Villringer, A., Kempf, F., Haux, D., Boden, S., & Obrig, H. (2006). Illuminating the BOLD signal: Combined fMRI-fNIRS studies. *Magnetic Resonance Imaging, 24*(4), 495–505. https://doi.org/10.1016/j.mri.2005.12.034

Tachtsidis, I., & Scholkmann, F. (2016). False positives and false negatives in functional near-infrared spectroscopy: Issues, challenges, and the way forward. *Neurophotonics, 3*(3), 30401. https://doi.org/10.1117/1.NPh.3.3.030401

Thormodsen, R., Jensen, J., Holmèn, A., Juuhl-Langseth, M., Emblem, K. E., Andreassen, O. A., & Rund, B. R. (2011). Prefrontal hyperactivation during a working memory task in early-onset schizophrenia spectrum disorders: An fMRI study. *Psychiatry Research - Neuroimaging, 194*(3), 257–262. https://doi.org/10.1016/j.pscychresns.2011.05.011

Vermeij, A., van Beek, A. H., Reijs, B. L., Claassen, J. A., & Kessels, R. P. (2014). An exploratory study of the effects of spatial working-memory load on prefrontal activation in low- and high-performing elderly. *Frontiers in Aging Neuroscience, 6*, 303. https://doi.org/10.3389/fnagi.2014.00303

Yaple, Z. A., Stevens, W. D., & Arsalidou, M. (2019). Meta-analyses of the n-back working memory task: fMRI evidence of age-related changes in prefrontal cortex involvement across the adult lifespan. *NeuroImage, 196*, 16–31. https://doi.org/10.1016/j.neuroimage.2019.03.074

Yeung, M. K., & Chan, A. S. (2020). Functional near-infrared spectroscopy reveals decreased resting oxygenation levels and task-related oxygenation changes in mild cognitive impairment and dementia: A systematic review. *Journal of Psychiatric Research, 124*, 58–76. https://doi.org/10.1016/j.jpsychires.2020.02.017

Yeung, M. K., & Chan, A. S. (2021). A systematic review of the application of functional near-InfraredSpectroscopy to the study of cerebral hemodynamics in healthy aging. *Neuropsychology Review, 31*(1), 139–166. https://doi.org/10.1007/s11065-020-09455-3

Yücel, M. A., Lühmann, A. V., Scholkmann, F., Gervain, J., Dan, I., Ayaz, H., Boas, D., Cooper, R. J., Culver, J., Elwell, C. E., Eggebrecht, A., Franceschini, M. A., Grova, C., Homae, F., Lesage, F., Obrig, H., Tachtsidis, I., Tak, S., Tong, Y., Torricelli, A. Wolf, M., … (2021). Best practices for fNIRS publications. *Neurophotonics, 8*(1), Article 012101. https://doi.org/10.1117/1.NPh.8.1.012101

Zhao, H., & Cooper, R. J. (2017). Review of recent progress toward a fiberless, whole-scalp diffuse optical tomography system. *Neurophotonics, 5*(01), 1. https://doi.org/10.1117/1.nph.5.1.011012