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Functional Near-Infrared Spectroscopy for the Study of Attention in Children with Atypical Development

A Systematic Literature Review from 2009-2017

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ABSTRACT

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Although attention has been a topic in cognitive and developmental psychology since the mid-20th century, much is still unknown with respect to the underlying neural differences in developmental attentional trajectories, including the link between differences observed at behavioural and neurophysiological levels. One relatively new emerging method of measuring atypical attention in children is functional near infrared spectroscopy (NIRS). Previously, reviews of NIRS in child development have included a wide range of developmental functions, from language acquisition to facial processing and joint attention. However, no such review has focused on the use of NIRS solely for measuring attention. The purpose of this systematic review was to provide an up-to-date synthesis of the findings. It investigated the evidence for functional differences in attention with a specific focus on the overlap between behavioural and NIRS measures, as well as the corresponding theoretical basis and behavioural implications. A search for peer-reviewed articles was carried out in multiple databases, with thirteen studies included in the analysis. Generally, NIRS shows preliminary evidence for differences in attention for certain attentional dimensions such as response inhibition, but more research is needed to confirm differences in other dimensions such as working memory or attentional control. Behavioural measures are not always reported and only occasionally mapped on to NIRS results. Few studies include a theoretical basis of attention or the behavioural implications of the findings. Limitations and implications for future research are discussed.

Keywords: attention, atypical development, brain imaging, fNIRS, NIRS

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List of abbreviations and key terms

AD – Atypical development

ADHD – Attention Deficit/Hyperactivity Disorder

ASD – Autism Spectrum Disorder

CINSS – Children in need of special support

dACC – Dorsal anterior cingulate cortex

Deoxy-Hb – Deoxygenated hemoglobin

dlPFC – Dorsolateral prefrontal cortex

Hb – Hemoglobin

IFG – Inferior frontal gyrus

IN – Identification number

MFG – Middle frontal gyrus

NIRS – Functional near-infrared spectroscopy

Oxy-Hb – Oxygenated hemoglobin

PFC – Prefrontal cortex

RPS – Rock paper scissors task

RST – Reverse Stroop task

RT – Reaction time

TD – Typically developing

TS – Tourette Syndrome

vlPFC – Ventrolateral prefrontal cortex

WM – Working memory

QAS – Quality assessment score

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1 Background and Rationale

1.1 Introduction

Although progress has occurred in recent decades, much underlying the measurement of attention is still unknown. Uncovering physiological differences in attention has proven challenging and it is still unclear if differences exist because of circuitry or blood flow (Vanderwert & Nelson, 2014). Functional near-infrared spectroscopy (NIRS) has emerged as one important method for investigating attention in children. Differences in attentional processing in NIRS research are often classified as ‘cortical dysfunction’ without specificity regarding the underlying theoretical or behavioural implications of this dysfunction. Clinical differences in attention are generally diagnosed by observing behaviours associated with disorders which are known to involve attention, such as Attention Deficit Hyperactivity Disorder (ADHD) or Autism Spectrum Disorder (ASD) in the Diagnostic and Statistical Manual of Mental Disorders (DSM V, 2015). Occasionally, behavioural measures such as the Stroop task (Stroop, 1935) or the Go/no-go task (Gomez, 2007) or other attentional tasks are used. Behavioural differences are important, but do not always overlap with the associated neurophysiological correlates or brain regions of interest (Aslin, 2012). As such, a question emerges as to the underlying functional basis for differences observed at the behavioural level. Ultimately, this investigation of the research will allow for a more thorough understanding of the potential of NIRS as a measure of attention, as well as how NIRS research can contribute to a more unified understanding of attentional processing.

1.2 Defining attention

The concept of attention has evolved throughout the history of psychology. During the period of Behaviourism and Gestalt theory, attention was viewed as irrelevant as the focus was on the study of behaviour (Kahneman, 1973). However, attention once again gained momentum in the mid 20th century and was considered important in post-Behaviourism, in order to "provide a label for some of the internal mechanisms that determine the significance of stimuli and thereby make it impossible to predict behaviour by stimulus considerations alone" (Kahneman, 1973, p. 2). Today, the phenomenon of attention is largely understood as the process of selecting and directing mental effort towards a particular stimulus (Buschman & Kastner, 2015).

Buschman and Kastner (2015) write the following:

> Attention is the selective prioritization of the neural representations that are most relevant to one's current behavioural goals. Such prioritization is necessary because the brain is a limited capacity information system. Representations of external stimuli and internal thoughts compete for access to these limited processing resources, and attention helps to resolve that competition in favour of the information that is currently task relevant. (p. 127)

Attentional processes have been categorized into dichotomous terms such as passive/active or bottom-up/top-down. Passive or bottom-up attention refers to the involuntary experience of external events inserted into perceptual awareness, while active or top-down attention is effortful, and involves alertness, salience determination and distractibility (Peterson & Posner, 2012). However, the use of passive/active and bottom up/top down are not completely agreed upon within the field and as such will not be considered central to the present review (Peterson & Posner, 2012).

Attention is comprised of three main networks in the brain: arousal, orienting and executive (Peterson & Posner, 2012). The arousal network deals with alertness, and implicates the brain stem reticular system. The orienting network involves the capacity to prioritize sensory input by selecting a modality or location and implicates both the frontal and posterior areas of the brain (Peterson & Posner, 2012). Last, the executive network deals with target detection and more specifically how this detection interacts with the limited capacity of the attention system. It implicates the frontal cortex and anterior cingulate cortex (Peterson & Posner, 2012).

According to Ratey (2001), attention is a process which involves noticing incoming information, filtering out other stimuli, balancing the perception of multiple stimuli, and the ability to assign significance (emotional and otherwise) to such perceptions. As such, attention also has many subcomponents. The subcomponents involved in this review are attentional control, response inhibition, working memory, and joint/social attention. Attentional control refers to the ability to direct attention towards a particular stimulus such as a group of words or a visual stimulus (Vanderwert & Nelson, 2014). Response inhibition refers to the ability to inhibit responding to competing stimuli as well as the ability to consider available attentional resources (Ko, 2017). Working memory is the process by which individuals hold immediate perceptual information in mind (Vanderwert & Nelson, 2014). Joint (or social) attention involves attending to and interpreting the meaning of another individual's goal (Vanderwert & Nelson, 2014).

With all of this in mind, the present review will rely on both Ratey's (2001) and Buschman and Kastner's (2015) definitions and acknowledge that the construct of attention consists of numerous subcomponents and operates at neural, physiological and behavioural levels.

1.3 Theories of attention

Multiple theories have been set forth to explain attention. Generally, they aim to answer two questions. First, at what point does stimuli become 'selected' during the attentional process? Second, to what extent do peripheral stimuli enter awareness? Broadbent's (1958) filter theory considers a bottleneck model, where multiple stimuli are shown at once; one selected initially with the others are held in peripheral awareness. Broadbent (1958) posited that the contents of stimuli can only be detected by a smaller attentional system after the initial sensory information has been processed. In attenuation theory, Deutsch and Deutsch (1963) write that a larger attentional system encodes all properties of the stimuli first and the agent later selects which elements to attend to. Lavie, Hirst, de Fockert and Viding (2004) combine these early and late selection approaches with perceptual load theory, which claims that selectivity depends on the differing demands of a task. In instances where processing demands are higher, the selectivity will happen earlier, and thus the peripheral stimuli will be processed to a much lesser extent, whereas in instances where the load is lower, selectivity occurs later, and the individual has a larger range of focus (Lavie et al., 2004). Kahneman's (1973) theory of attention and effort is also of relevance here. He writes, “there is a general limit on man’s capacity to perform mental work and this can be allocated with considerable freedom among concurrent activities” (Kahneman, 1973, p. 8). Here, exerting effort is synonymous with paying attention, as attending to something requires a considerable amount of overall metabolic energy. Different demands require different amounts of effort, with easier tasks requiring less effort and allowing attention to be divided among a variety of stimuli. Baddeley’s model of working memory (2003) breaks down working memory into multiple components. There is a central executive supervisory system, as well as the phonological loop and visuospatial sketchpad which filter incoming auditory and visual perceptual information, respectively. Last, there is the episodic buffer, which links information across systems in Baddeley’s (2003) model. While each of the aforementioned theories rely on distinct mechanisms, they each agree on the notion of a limited capacity theory of attention.

1.4 Attention and atypical development

In this review, atypical development is understood as any behavioural or neurophysiological differences as compared to a typically developing control group. Although attention may be implicated in a wide range of disorders and/or impairments, ADHD, ASD and Tourette Syndrome (TS) were the main instances of atypical attention uncovered in this review and thus will be outlined here. Each of these can be classified under the umbrella of neurodevelopmental disorders, which are multifaceted conditions characterized by impairments in cognition, communication, behavior and/or motor skills resulting from abnormal brain development (Mullin et al., 2013).

ADHD is a brain disorder marked by patterns of inattention, hyperactivity, or both which interfere with daily activities. Poor behavioural and response inhibition is understood as the central difficulty in ADHD which impacts a range of behaviours and cognitive processes (Barkley, 1997). Uncovering biomarkers at the neural level for ADHD has proven challenging, and behavioural measures of ADHD do not always show consistent results (Vanderwert & Nelson, 2014). ASD describes a group of conditions which may include motor, cognitive, or social impairments (Farmer, Baron-Cohen & Skylark, 2017).

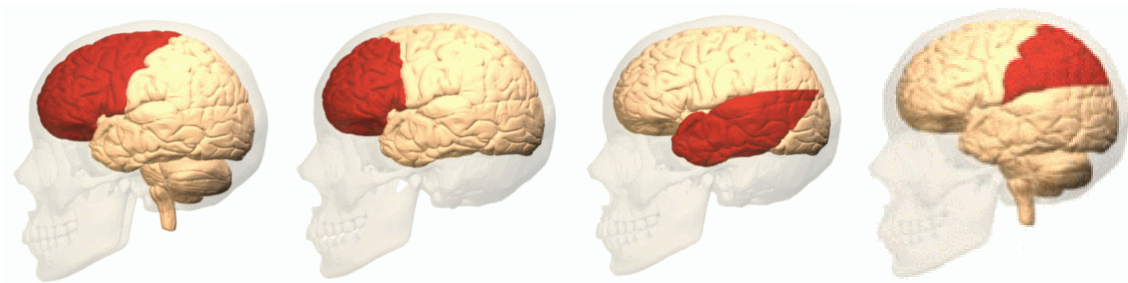
Atypical orienting of attention to social stimuli has been attributed as a primary hallmark of ASD (Murphy et al., 2017). While much work has investigated physiological components of

ASD using EEG, eye-tracking and other methods (Farmer et al., 2017), there is limited research using NIRS to investigate the disorder. Early identification of the disorder is challenging as behavioural signs are not always easy to detect (Lloyd-Fox et al., 2010).

Tourette Syndrome is a neurodevelopmental disorder characterized by the occurrence of brief repetitive movements or vocalizations, also called tics (Swain & Leckman, 2005). Atypical attentional processing has also been implicated as an important characteristic of TS and the relationship between attention and tic generation continues to be investigated, but more research in this area is needed (Misirlisoy et al., 2015).

Interestingly, theories of attention (Broadbent, 1958; Deutsch & Deutsch, 1963; Kahneman, 1973; Lavie et al., 2004) rarely explicitly mention their implications for atypical attentional trajectories and only rarely are brain regions implicated. Indeed, only perceptual load theory has been associated with ADHD (Forster et al., 2014). Deficits in attention are related to increased vulnerability to distraction as in the case of ADHD (Barkley, 1997), social stimuli having less salience than non-social sensory stimuli in ASD (Farmer et al., 2017), and anxiety related to repetitive behaviours or tics monopolizing attentional resources in Tourette Syndrome (Misirlisoy et al., 2015). Although they are oversimplified in this case, these general characterizations support the idea of attention as a limited capacity resource, as in each case attentional resources navigate between competing or more salient stimuli. Some theoretical models of attention include hypothesized neural correlates or brain regions, such as Baddeley's (2003) claim of the dorsolateral prefrontal cortex (dlPFC) as the main correlate of the central executive. However, others, such as filter theory, attenuation theory, perceptual load theory, and capacity theory do not included hypothesized neural correlates. On the other hand, brain regions have been investigated for their roles in various attentional processes. Regions associated with response inhibition are the dlPFC, the ventrolateral prefrontal cortex (vlPFC), the dorsal cingulate (dACC) and parietal cortex (Blasi et al., 2006). Attentional control implicates the frontal gyrus (language processing, Minagawa-Kawai, 2008), and the temporal (auditory processing) and frontal cortex (Lloyd-Fox et al., 2010).In working memory, the PFC and parietal lobes are implicated (Berryhill & Olson, 2008). In joint attention, the dlPFC, temporal and posterior cingulate cortices are involved (Eggebrecht et al., 2017). These are also some of the main areas also implicated in ADHD, ASD, and Tourette Syndrome, as will be shown in the following review. For a general diagram of brain regions, please see Figure 1.

Figure 1. *Frontal lobe (far left) prefrontal cortex (PFC, middle left), temporal lobe (middle right), parietal lobe (far right)*



Source: Database Center For Life Science (2018)

The above figure shows the general area of the frontal lobe, and within the frontal lobe the region of the prefrontal cortex, as well as the temporal lobe. The frontal lobe contains a range of regions, including the prefrontal cortex (PFC), which includes some areas outlined in this review, namely the dlPFC, vlPFC, IFG, MFG and the dACC. Other regions involved in this review are located in the temporal lobe, most notably the auditory cortex (Pickles, 2012). Last, the parietal lobes have been implicated in integrating sensory information from different parts of the body, and is sometimes implicated in visuospatial awareness and motor function (Fogassi & Luppino, 2005).

1.5 Attention and engagement

Investigating the neurophysiology of attention has some important practical implications. Attention is part of the engagement construct and has important implications for the promotion of participation for children in need of special support (CINSS). Increasing participation for CINSS can be considered as both a means and an end in childhood interventions for those with functional difficulties or atypical development (Imms et al., 2016). According to Sjöman, Granlund and Almqvist (2015), engagement is, in part, comprised of 'attentional behaviours' (p. 1651) although more research is needed to determine the relationship between attention and engagement. A more nuanced understanding of attention in children with atypical development will develop the construct of engagement. Specifically, it will allow for an understanding of how the neurophysiology of children with atypical development may interact with the environment and translate to certain behaviours, and thereby provide more useful information for professionals when structuring interventions aimed at increasing participation for children in need of special support in a variety of settings.

1.6 Behavioural measures of attention

Behavioural measures of attention range from observational- and self- report to performance on behavioural tasks. Observational measures involve using questionnaires to monitor children's attentional abilities and have been linked to self-regulation (Eisenberg & Morris, 2003) as well as engagement (McWilliam, 1991, as cited in Sjöman, Granlund & Almqvist, 2016). Self-report measures of attention are also used, such as the Attention Control Scale (ACS) (Reinholdt-Dunne, Mogg & Bradley, 2013). Clinical differences in attention are generally observed using these measures which rely on characteristics set forth by the DSM V (2015). These measures may be useful as they are standardized, can be utilized in real-life scenarios, and allow for larger sample sizes and multiple perspectives. However, the objectivity or introspective ability of the observants or participants may be questioned (Reinholdt-Dunne et al., 2013). Moreover, it is not possible to use these measures to reliably uncover the cognitive or physiological mechanisms involved in attention.

Performance on behavioural attentional tasks (hereby referred to as behavioural measures) often involve a particular stimulus and a standardized assessment of child performance or reaction to said stimulus. The most well-known behavioural measures of attention are the Stroop task (1935), the Go/no-go task (2007), and various working memory tasks such as the N-back working memory task which measure response inhibition and working memory, respectively. These and other tests allow researchers to isolate cognitive mechanisms at work and uncover group level differences, and therefore create more robust understandings of how specific components of attention differ across populations. While behavioural measures or tasks offer more objectivity than observation or self-report, they do not always demonstrate ecological validity or the ability to be generalized to real life settings and it is unknown whether they reflect underlying neurophysiological differences (Chaytor, Schmitter-Edgecombe & Burr, 2006). As such, behavioural measures of attention may be strengthened with corroborating evidence of issues at the neurophysiological level.

1.7 Physiological measures of attention: functional near-infrared spectroscopy

As a way of uncovering underlying physiological components of attention, a wide range of measures have been used. These include heart rate (Griffiths et al., 2017), eye-tracking (Hoang Duc, Bays & Husain, 2008), electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and functional near-infrared spectroscopy (NIRS) to measure blood flow in brain regions of interest (Nagamitsu, Yamashita, Tanaka & Matsuishi, 2012). NIRS is emerging as one important way of recording attention via blood flow as an alternative to fMRI. Unlike fMRI, NIRS can be used in awake children and is relatively impervious to movement, thus accommodating populations with a wide range of abilities and ages (Nagamitsu et al., 2012). Additionally, NIRS does not require physical or mental restraints, is completely non-invasive and portable, and can record "detailed measurements of rapid changes in cerebral oxygenation during a task under natural conditions" (Nagamitsu et al., 2012, p. 2). However, NIRS has been criticized as it can only access surface-level areas of the brain and thus research involving NIRS cannot investigate cognitive functions which recruit deeper structures (Aslin & Mehler, 2005). The method also has lower temporal resolution than EEG, and there is no possibility of measuring brain structure for anatomical reference (Minagawa-Kawai et al., 2008).

NIRS measures concentration changes in oxyhemoglobin- (oxy-Hb), deoxyhemoglobin (deoxy-Hb) and total hemoglobin (Hb) (Nagamitsu et al., 2012). Put simply, hemoglobin is the oxygen transport protein in red blood cells (Maton et al., 1993). In the NIRS technique, light moves from sources to detectors located on the head by travelling through the skull and underlying brain tissue (Lloyd-Fox, Blasi & Elwell, 2010). The loss of light can be attributed to absorption. Different absorption properties of the light reflect differences in the concentrations of oxy- and de-oxyHb, allowing blood oxygenation in the tissue to be measured (Lloyd-Fox et al., 2010; Nagamitsu et al., 2012). Nagamitsu et al. (2012) write, "a typical hemodynamic response to cortical neuronal activation is an increase in total- and oxy-Hb, with a decrease in deoxy- Hb" (p. 2). NIRS rests on previous findings that increased oxygenation in a region reflect increases in neuronal electrical activity and electrical signals being passed between cells, also called neuro-vascular coupling (Scholkmann et al., 2014). Lloyd-Fox et al. (2010) write, "during this activation, the metabolic demands of neurons change, prompting an increase in oxygen consumption, local cerebral blood flow, and oxygen delivery" (p. 270). With respect to atypical development, Nagamitsu et al. (2012) report that atypical patterns in NIRS may show either less supply *or* less demand for cerebral blood volume during cognitive tasks.

NIRS can sometimes be used for clinical purposes. Much research using NIRS aims to uncover early biomarkers for various disorders as well as to strengthen behavioural or clinical observational measures (Vanderwert & Nelson, 2014). However, NIRS research is often difficult to decipher and even more difficult to connect neurophysiological differences observed to relevant implications at the behavioural level (Vanderwert & Nelson, 2014). NIRS research may have the ability to either strengthen or problematize theories of attention as well as to support behavioural implications of atypical attention. Theoretically, the notion of attention as a limited capacity resource appears to be supported by the principles of NIRS, which is linked to the metabolic limitations of blood oxygenation (Lloyd-Fox et al., 2013). What is less clear, however, is how atypical displays of attention interact with this principle. As mentioned in the previous paragraph, Nagamitsu et al. (2012) write that atypical displays of attention may show up as either increases *or* decreases in blood oxygenation depending on the control group. An increase in oxy-Hb (and decrease in deoxy-Hb) would suggest hyper-activity if compared to no change in a control group; while a decrease in oxy-Hb (and increase in deoxy-Hb) would denote hypo-activity if compared to increases in a typically developing control group. These seem like important distinctions, but not much is known about their differing implications for behaviour, suggesting the need for further probing into this question.

1.8 Methodological challenges of NIRS research

Past research has illuminated much of the methodological challenges of NIRS. First, Aslin (2012), questions the use of both hypothesis-driven and exploratory designs. The more common exploratory search strategy involves four stages: first, activations are gathered from a number of channels, second, each infant is present with multiple stimulus conditions and a baseline condition without a stimulus, and third, activations in the channels are compared across conditions, and averaged to create regions of interest (ROIs). Fourth, significant differences are interpreted as specificity or brain function, which Aslin (2012) criticizes as being post-hoc and therefore limited in value. On the other hand, hypothesis driven research is risky as inferences related to specialization can only be made using a uniform gain assumption (all channel response functions are the same) which is highly unlikely in a NIRS scenario. Aslin (2012) writes “a more powerful design is to ask whether the same NIRS channel shows different levels of activation to variations along some stimulus dimension” (p. 10). Equally, Aslin (2012) notes that it is plausible that a region of the cortex which responds to *any* stimulus exists.

There is no consensus among NIRS researchers as to how many channels to use. NIRS systems use both sources and detectors, where each detector records the amount of light coming from a subset of neighbouring sources with each source-detector pair called a channel (Lloyd-Fox et al., 2010). In the infancy of NIRS, studies used a limited number of channels which ranged from 1-3, which limited the inferences researchers could make (Lloyd-Fox et al., 2010). It is increasingly more common to use a higher number of channels in more recent research (Lloyd-Fox et al., 2010). Despite this, there is still a wide range in the number of channels used to report changes in brain activity. Studies which incorporate only a small number of channels and report hemodynamic changes may be confounded by competing irrelevant cerebral activity or wrong placement of the opcodes with respect to the brain regions of interest (Lloyd-Fox et al., 2010).

Throughout the use of NIRS, researchers have reported either both oxy-Hb and deoxy-Hb, or one or the other to determine levels of activation and significant results (Tachtsidis and Scholkmann, 2016). As oxy-Hb is generally linked to the oxygen inflow of the tissue, while deoxy-Hb is linked to the amount of oxygen absorbed by the tissue, they are considered separate entities (Tachtsidis and Scholkmann, 2016). Many researchers continue to only report changes in oxy-Hb if the results of deoxy-Hb are not statistically significant, as oxy-Hb is more sensitive. However, it is commonly viewed as good practice to report changes in both (Tachtsidis and Scholkmann, 2016). Another issue is related to confounds at the superficial or extracerebral layer which are not related to task-specific changes in brain activity. These changes can be due to nervousness, stress, arousal levels, and a number of other factors, and have been shown to influence NIRS results.

While the aforementioned methodological challenges will not be the main focus of the present review, they will be considered in the information extracted from each of the studies as well as in the quality control process.

1.9 Past literature reviews of NIRS

Past reviews of NIRS and child development have investigated dimensions of language processing, visual and auditory function, face perception, speech acquisition, and some components of attention (Vanderwert & Nelson, 2014; Aslin, 2012; Nagamitsu et al., 2012; Lloyd-Fox et al., 2010; Minagawa-Kawai et al., 2008). While Minagawa-Kawai et al. (2008) focus on speech, Aslin (2012) focuses on methodological issues and Vanderwert and Nelson (2014) focus on developmental trajectories. Overall, the reviews note that results vary widely depending on the population being studied, the associated brain regions, and the classification of atypical development. Vanderwert and Nelson (2014) write, “because the corpus of knowledge of typical development is limited, it is difficult to identify what an atypical hemodynamic response would look like or how to interpret such a response” (p. 6). Reviews have also noted the lack of consistency in NIRS methodology, inconsistent findings and hard-to-decipher results (Aslin, 2012; Lloyd-Fox et al., 2010; Vanderwert & Nelson, 2014).

No reviews to date have focused solely on attention. Additionally, none have investigated the overlap between behavioural and neurophysiological measures. Last, none address how NIRS research may contribute to strengthening behavioural measures of attention as well as underlying biomarkers and functional differences. Reviews infrequently discuss the behavioural implications of NIRS findings. Finally, since the most recent article by Vanderwert and Nelson in 2014, several new studies have been identified, highlighting the need for an up-to-date investigation.

1.10 Rationale of the present review

As mentioned, no reviews have focused solely on the use of NIRS for attention. Additionally, there is an apparent disconnect between conceptions of attention at the theoretical, behavioural and neurophysiological levels. As such, this review aims to tackle three core issues. First, as the evidence for NIRS as a measure of attention is still somewhat inconsistent, this review first examines the basic evidence for functional differences in attention in children with atypical development. Next, behavioural and neurophysiological measures can be strengthened by investigating their relationship to one another. The corresponding question asks whether behavioural and NIRS measures reliably map on to one another. Last, theoretical conceptualizations of attention as well as practical behavioural implications of differences in attention have importance but are occasionally left out of neuro-imaging research. Because of this, the present review seeks to investigate whether theoretical models of attention (or attention dimensions) are highlighted in NIRS research or whether the behavioural implications of the findings are included. Aslin (2012) writes: “the most important question we can ask about NIRS is this: what have we learned that we didn’t know already from other measures? What is the “value-added” of NIRS for studies of perception and cognition?” (p. 24). In this spirit, this review aims to go beyond questions asked in past reviews, and investigate NIRS as a measure of attention, as well as its capacity to contribute to a more unified understanding of attention in children with atypical development.

2 Purpose of the systematic review and research questions

The purpose of this systematic literature review is to explore the use of functional near infrared spectroscopy (NIRS) to investigate the functional differences in attention in atypical and typical development. It aims to answer the following research questions:

1. What is the evidence for functional differences in attention for children with atypical development?
2. To what extent do attention differences measured by NIRS map on to differences measured by behavioural tasks?
3. Do studies include discussions of theoretical basis of attention or behavioural implications of findings?

3 Method

3.1 Systematic literature review

To uncover relevant research using NIRS to study the atypical and typical development of attention, a systematic literature review was conducted. A systematic literature review is useful as a preliminary mapping and investigation of a specific research question. It includes a precise delineation of a replicable search strategy characterized by clearly stated inclusion and exclusion criteria, a transparent data extraction and synthesization process, and a quality assessment protocol which may rely on multiple raters (Jesson, Matheson & Lacey, 2011; Cronin, Ryan, & Coughlan, 2008).

3.2 Search procedure

The search involved in this systematic review took place in March of 2018 using databases ERIC, PsycINFO, Pubmed and Medline. Databases and search terms were chosen in consultation with a librarian. In PsycINFO and ERIC, a search using the thesaurus function was performed in combination with a free text search. In Pubmed and Medline, free search terms in the advance option were used. Search terms varied slightly across the databases as relevant or suggested related terms differed across the databases. Generally, there were three “MeSh” categories or overarching terms included in each database: “attention”, “functional near-infrared spectroscopy”, and “children OR adolescents.” As mentioned, related or suggested terms varied, but generally included a number of related terms in each of these three overarching categories. Please see Appendix A for the exact terms used in the search protocol. The search yielded 77 results in PubMed, 90 results in Medline, 92 results in PsycInfo and 12 results in ERIC (an educational database). As such, the initial search yielded a total of 271 articles across all four databases. Additionally, after looking at reference lists of previous literature reviews on related topics, 1 additional study was identified and subsequently added.

3.3 Inclusion/exclusion criteria

Inclusion and exclusion criteria were developed to determine which studies to include in the review. To ensure the focus on attention in children with atypical development, only studies which included both an atypically developing and typically developing group were considered.

Additionally, NIRS needed to analyze brain activity, not some other physiological measure such as heart rate. There were no limitations for the time frame, as the technology for NIRS has emerged fairly recently (Vanderwert & Nelson, 2014). The extraction protocol with inclusion and exclusion criteria is shown in Table 1.

Table 1. *Inclusion and exclusion criteria for title and abstract screening.*

Inclusion criteria	Exclusion criteria
Publication type - Articles published in peer reviewed journals - Published in English	- Other publication types/ languages (abstracts, conference papers, theses)
Population - Age range of participants 0-17 - Atypically developing group and typically developing control group	- Studies with only atypically or typically developing cohorts - Above 18 years of age
Measure - NIRS measure related to attention - Inclusion of NIRS details: number of channels, probe analysis, detailed results section	- NIRS used for other physiological measures such as heart rate - NIRS used to measure other dimensions of cognitive function (language, face processing, or other)
Stimulus - Attention-related task/stimuli (Stroop task, working memory task, go/no-go task, response inhibition task, joint attention task, visual/auditory stimuli)	- Non-attention related stimuli or tasks (face processing/recognition, verbal fluency, language, other)
Study Design - Quantitative studies - Case-controlled studies - Randomized-controlled trials - Neuroimaging studies	- Qualitative studies - Case studies - Clinical drug trials - Literature reviews

3.4 Screening procedure – title and abstract level

Articles collected in PsycINFO, Pubmed, Medline, and ERIC were first screened at the title level. After title review of the 90 articles on Medline, 19 were carried forward for abstract review. Next, after a title review of the 92 articles on PsycInfo and after manually removing duplicates, 12 articles were left. Next, after reviewing 12 studies on ERIC, 3 were carried forward for the abstract review. Finally, after screening 77 titles on Pubmed and after duplicates were removed, 19 were brought forward for abstract review. Overall, of the initial 271 studies, 218 studies were excluded based on the above criteria based on titles alone. Generally, studies were excluded for being drug trials, measuring some other cognitive function through NIRS, or including adults. As such, 53 studies were carried forward for abstract review based on the above criteria, and 1 additional study was identified through searching citation lists in relevant past reviews. The screening process is pictured in a flow chart in Appendix B.

For the abstract screening procedure, two raters separately reviewed each of the 54 abstracts to ensure they adhered to the above inclusion criteria. Prior to speaking, both raters separately noted down whether or not each of the studies should be carried forward for full text review based on their interpretation of the inclusion/exclusion criteria, and then compared these notes afterwards. Raters agreed upon 20 articles to be carried forward for review, with 2 out of the 54 articles flagged by both inter-raters for further discussion, therefore yielding an 100% consensus rate. After this discussion, 2 articles were excluded for not using NIRS to measure a dimension of attention. After this process, both raters unanimously recommended 20 articles to be carried forward for full text review.

3.5 Selection process – full text

Inclusion and exclusion criteria were again applied to the entire article in the full-text screening process with two raters. There was a particular focus on the methods section of each article. Of the 20 articles reviewed, 7 were not carried forward for the data extraction process. 4 articles did not have full texts available online; however, three other articles were flagged by both raters as not adhering to the exclusion/inclusion criteria again showing an 100% consensus rate. There was 1 article which focused on short-term memory which was deemed outside of the attention construct; and 2 articles which did not include relevant details related to NIRS data (number of channels, regions of interest). As such, 13 articles were left over for data extraction (see Appendix B for flow chart).

3.6 Data extraction and quality assessment

Data extraction was performed using the protocol shown in Appendix C. Extracted information includes title, author(s)/date, name of journal, country, aim, research questions if applicable, study design, information about the sample (age, total participating N, classification of atypical development, attention dimension, behavioural stimuli/task (specific test, results if applicable), NIRS information (channels, brain regions, oxy-Hb/deoxy-Hb), results, and any noteworthy or incongruent findings or limitations. Two raters independently reviewed the quality of 2 articles and after agreement was found, one reviewer assessed the remaining 11 articles. Quality assessment was performed using the CASP checklist for quantitative research and in particular for case-controlled studies (CASP, 2018, see Appendix D). Good quality denotes >70% of quality fulfilled, moderate quality is >60% fulfilled, and low quality <60% fulfilled. Answers "yes" fulfilled criteria, while "no" or "can't tell" did not. Importantly, some questions in the CASP (2018) checklist included whether or not the results were significant but did not a power calculation or number of participations (N) which presents a limitation. Many of the studies were exploratory, and therefore a lower N and insignificant results do not indicate an incorrect hypothesis. Some NIRS-specific questions were added to the checklist.

3.7 Data analysis

Data were extracted and analyzed qualitatively. An identification number was given to each study. First, in the qualitative analysis, overall general information of the studies was reported and formed into key points in order to form a preliminary understanding of the general rationale for using NIRS in the research of attention in atypical development. To answer research question 1 related to evidence for functional differences in brain regions associated with attention in children with typical/atypical development, results were analyzed, grouped and subsequently reported. To answer research question 2, behavioural measures results and NIRS data were extracted into a table to compare the results side by side. To answer research question

3, themes related to theoretical basis of attention or behavioural implications throughout each article were examined to determine whether they included the topics of interest. Quantitative meta-analysis was not possible as there were no consistent measures used (oxy-Hb and deoxy-Hb, differing number of channels/analysis methods, and different brain regions reported).

4 Results

4.1 Overview of studies

Overall, thirteen articles were included in the full-text review based on the inclusion and exclusion criteria. They included both a typically developing (TD) control group and an atypical group, measured a clearly defined dimension of attention, used a behavioural stimulus or task appropriate to the attention dimension being investigated, and recorded relevant NIRS data, including number of channels, brain regions of interest, and changes in either oxy-Hb or deoxy-Hb, or both. The articles were published between 2009 and 2017 in peer-reviewed, academic journals related to developmental or cognitive psychology, child neurology, psychiatry, neuro-imaging, or neuroscience. For a general overview of basic information related to the studies, see Table 2. A more comprehensive outline of information including the quality assessment scores can be found in Appendix E.

Generally, the studies included school-aged children from 6-16 years of age, with one study (6) focusing on infants. Equally, seven studies (1,2,3,7,9,12,13) measured ADHD and TD, two studies (5,8) measured ADHD, ASD and TD, three studies (4,6,11) measured ASD and TD, and one (10) measured Tourette Syndrome and TD. The number of participants also varied widely, with some studies including 50-65 participants (5,9,12), a majority including 34-45 participants (2,3,6,8,11,13) and other studies including as few as 20-26 participants (1,4,7,10). For the behavioural measures, the ADHD and TD studies measured response inhibition using the Stroop, Go/no-go task or a “to lose” Rock Paper Scissors (RPS) task (1,2,9,13) or working memory using specific working memory tasks (3,7,12). The ASD and TD studies measured attentional control and joint attention using auditory and visual stimuli (4,6,11), while the ASD, ADHD and TD studies also measured response inhibition using the Stroop and Go/no-go tasks (5,8). The Tourette Syndrome and TD study measured response inhibition using the Stroop task (1). In the NIRS measurements, just six studies (1,4,5,6,12,13) included both oxy-Hb and deoxy-Hb data, while seven (2,3,7,8,9,10,11) included oxy-Hb. Last, all studies were interested in regions in the frontal, temporal and lateral cortex, while others had additional interest in the parietal lobes, gyri and sulci (6,9,10).

Table 2. *Overview of studies.*

IN*	Author and Year	Age	N	Atypical Development	Attention Dimension	Task	Oxy/Deoxy-Hb	Brain region
1	Moser et al. (2009)	8-13	24	ADHD	Response inhibition	Stroop	Both	Frontal
2	Negoro et al. (2010)	6-15	37	ADHD	Response inhibition	Stroop	Oxy-Hb	Frontal
3	Schecklmann et al. (2010)	8-15	38	ADHD	Working memory	WM* task	Oxy-Hb	Frontal
4	Funabiki et al. (2012)	10-16	23	ASD	Attentional control	Auditory	Both	Frontal, temporal
5	Xiao et al. (2012)	9-12	51	ASD, ADHD	Response inhibition	Go/no-go Stroop	Both	Frontal
6	Lloyd-Fox et al. (2013)	4-6 (m)	34	ASD risk	Attentional control	Auditory Visual	Both	Frontal, temporal
7	Tsujimoto et al. (2013)	8-12	26	ADHD	Working memory	WM task	Oxy-Hb	Frontal
8	Yasemura et al. (2014)	8-11	36	ASD, ADHD	Response inhibition	Stroop; RST*	Oxy-Hb	Frontal
9	Monden et al. (2015)	6-15	60	ADHD	Response inhibition	Go/no-go	Oxy-Hb	Frontal, parietal
10	Yamamuro et al. (2015)	7-10	20	Tourette Syndrome	Response inhibition	Stroop	Oxy-Hb	Frontal
11	Zhu et al. (2015)	6-10	40	ASD	Joint attention	Auditory Visual	Oxy-Hb	Frontal
12	Arai et al. (2016)	7-13	65	ADHD	Working memory	WM task	Both	Frontal
13	Ishii et al. (2017)	6-10; 11-16	45	ADHD	Response inhibition	RPS* task	Both	Frontal

*IN – Identification number *WM – Working memory *RST – Reverse Stroop task *RPS – Rock paper scissors

4.2 Main NIRS findings

Table 3. *Evidence for functional differences based on NIRS data.*

IN	Authors, Year	Atypical Development	Attention dimension	Hb	Main finding
1	Moser et al. (2009)	ADHD	Response inhibition	Both	↑Deoxy-Hb in ADHD *after* Stroop*
2	Negoro et al. (2010)	ADHD	Response inhibition	Oxy-Hb	↑Oxy-Hb in TD in during Stroop
3	Schecklmann et al. (2010)	ADHD	Working memory	Oxy-Hb	No difference
4	Funabiki et al. (2012)	ASD	Attentional control	Both	Differences reported; unclear whether ↓ or ↑ oxy- or deoxy-Hb
5	Xiao et al. (2012)	ASD, ADHD	Response inhibition	Both	↓Oxy-Hb in ASD and ADHD during Go/no-go*; none in Stroop
6	Lloyd-Fox et al. (2013)	ASD risk	Attentional control	Both	↓Oxy-Hb in ASDr in temporal cortex in auditory/visual
7	Tsujimoto et al. (2013)	ADHD	Working memory	Oxy-Hb	↑Oxy-Hb in ADHD in right PFC during distractor WM task
8	Yasemura et al. (2014)	ASD, ADHD	Response inhibition	Oxy-Hb	No difference in Stroop; ↓Oxy- Hb in ADHD in right PFC in RST
9	Monden et al. (2015)	ADHD	Response inhibition	Oxy-Hb	↓Oxy-Hb in ADHD in right PFC during Go/no-go task*
10	Yamamuro et al. (2015)	Tourette syndrome	Response inhibition	Oxy-Hb	↓Oxy-Hb in Tourette S in left dlPFC during Stroop task*
11	Zhu et al. (2015)	ASD	Joint attention	Oxy-Hb	↓Oxy-Hb in ASD in left PFC in joint attention task*
12	Arai et al. (2016)	ADHD	Working memory	Both	No significant correlation between age and Oxy-Hb in ADHD; ↑Oxy-Hb in TD in bilateral lateral PFC during WM task
13	Ishii et al. (2017)	ADHD	Response inhibition	Both	Younger ADHD children ↑Oxy-Hb during to lose task Older ADHD children ↓Oxy-Hb

*Differences — Atypical and typical *Stroop — Incongruent *Go/no-go — Inhibition

The above table presents the evidence related to research question 1: What is the evidence for functional differences in attention for children with atypical development?

Attention Deficit Hyperactivity Disorder (ADHD) — Using the Stroop test to detect response inhibition, Moser et al. (2009) found that deoxy-Hb increased in ADHD participants *after* the incongruent condition in the right dlPFC but did not report any significant changes in oxy-Hb and no changes *during* the task. Negoro et al. (2010) found increased oxy-Hb in the left inferior PFC during the Stroop task in typically developing children compared to ADHD children, suggesting that ADHD is characterized by hypo-activity in this brain region during response inhibition. Monden et al. (2015) found decreased oxy-Hb in the right IFG (inferior frontal gyrus) and MFG (middle frontal gyrus) in the right PFC in ADHD participants during the Go/no-go task, also implying that differences in attention are characterized by hypo-activity. Monden et al. (2015) included the parietal lobes in their regions of interest, but group differences in this region were not apparent from the results section. Last, studying children aged 6-16, Ishii et al. (2017) found increased oxy-Hb in younger ADHD children and decreased oxy-Hb in older ADHD children in left dlPFC during the to lose task. Thus, here, ADHD differences in younger children are characterized by hyperactivity, while in older children they are characterized by hypo-activity. Each of the aforementioned studies found differences that are mostly characterized by hypo-activity but report different brain regions and findings that are difficult to interpret, as noted by Vanderwert and Nelson (2014).

Several other studies investigated ADHD and working memory (WM). Schecklmann et al. (2010) found no difference between TD and ADHD groups in WM during a working memory task from the NIRS data due to confounding factors. Tsujimoto et al. (2013) find increased oxy-Hb in the right PFC in ADHD children during a working memory task, indicating that for WM, ADHD is characterized by frontal hyper-activity. Arai et al. (2016) found that oxy-Hb in the bilateral lateral PFC increases with developmental age in typically developing children during WM tasks, but that there is no relationship between oxy-Hb increase and age in ADHD. These results suggest that WM in ADHD is characterized by hypo-activity in the lateral PFC, which contradicts the findings of Tsujimoto et al. (2013).

Autism Spectrum Disorder (ASD) — Other studies investigate ASD and attentional control and joint attention in children using auditory and visual stimuli. Funabiki et al. (2012) reported differences in auditory attention in the ‘ignore’ condition of the task in the prefrontal cortex but not auditory cortex. However, the authors do not report decreases or increases in oxy-Hb or deoxy-Hb in the PFC, making the overall significance of the study difficult to justify, as previously noted by Vanderwert and Nelson (2014). The authors write "the unawareness of autistic participants could be interpreted as due to inattention rather than cortical dysfunction" (Funabiki et al., 2012, p. 522) but provide no theoretical basis for what might differentiate 'inattention' from cortical dysfunction. Lloyd-Fox et al. (2013) found a decrease in oxy-Hb in infants at high-risk for autism in the temporal cortex during exposure to social visual and auditory stimuli, suggesting that differences in attentional control in ASD is characterized at least in part by hypo-activity in the temporal cortex, suggesting a lack of cortical specialization to social stimuli in infants at high risk for autism in the first six months of life. Similarly, investigating joint attention, Zhu et al. (2015) found decreased oxy-Hb in the left PFC during a joint attention task, indicating hypo-activity. These studies also implicate different brain regions as well as different age groups, but while Zhu et al. (2015) and Lloyd-Fox et al. (2013) reported hypo-activity in the temporal and prefrontal areas of the brain, there is a need for more research on these questions.

ADHD and ASD — Studies by Xiao et al. (2012) and Yasemura et al. (2014) investigate response inhibition in ASD, ADHD and TD groups. Xiao et al. (2012) find decreased oxy-Hb in the left PFC in ADHD and ASD groups as compared to TD in the Go/no-go task but not in the Stroop task. Although the study is in line with previously outlined work regarding response inhibition and the Go/no-go task in ADHD (9), it contradicts findings of attentional differences during the Stroop task (2). However, Yasemura et al. (2014) also find no significant differences between ASD, ADHD and TD groups during the Stroop task, but find decreased oxy-Hb in ADHD in the right PFC during a reverse Stroop task (RST). Additionally, Yasemura et al. (2014) cite no statistical differences between ASD and the other groups based on the NIRS data.

Tourette Syndrome — Finally, Yamamuro et al. (2015) find decreased oxy-Hb in the left PFC during the Stroop task, showing that Tourette Syndrome is at least in part characterized by hypo-activation in this brain region during tasks involving response inhibition. A significant limitation of this study is that 5 of 10 children had co-morbid ADHD in the Tourette's group.

4.3 Behavioural measures results and NIRS findings

Behavioural and NIRS results are outlined in Table 4. For an overview of each of the behavioural measures, see Appendix F.

Table 4. *Behavioural measures results and NIRS findings.*

IN	Authors, Year	Attention Dimension	Behavioural results*	Main NIRS finding
1	Moser et al. (2009)	ADHD	P* — No difference RT* — ADHD slower	↑Deoxy-Hb in ADHD in right dlPFC *after* Stroop
2	Negoro et al. (2010)	ADHD	P — No difference RT — Not reported	↑Oxy-Hb in TD in inferior PFC during Stroop
3	Schecklmann et al. (2010)	ADHD	P — No difference RT — No difference	No difference in NIRS during WM task
4	Funabiki et al. (2012)	ASD	ASD group recalled more words in ignore condition	Differences reported; unclear whether ↓ or ↑ oxy- or deoxy-Hb
5	Xiao et al. (2012)	ASD, ADHD	P — ↑ error in ADHD/ASD RT — ASD and ADHD slower in Go/no-go; no difference in Stroop	↓Oxy-Hb in ASD and ADHD in left PFC during Go/no-go; no difference in Stroop
6	Lloyd-Fox et al. (2013)	ASD risk	Not applicable for auditory and visual stimuli	↓Oxy-Hb in ASDr in temporal cortex in auditory/visual
7	Tsujimoto et al. (2013)	ADHD	P — ↑ error in ADHD RT — No difference	↑Oxy-Hb in ADHD in right PFC during distractor WM task
8	Yasemura et al. (2014)	ASD, ADHD	No difference in Stroop; P — ↑ error in ADHD RT — No difference	No difference in Stroop; ↓Oxy- Hb in ADHD in right PFC in RST
9	Monden et al. (2015)	ADHD	P — No results reported RT — No results reported	↓Oxy-Hb in ADHD in right PFC during Go/no-go task*
10	Yamamuro et al. (2015)	Tourette syndrome	P* — ↑error TS (age) RT* — Not reported	↓Oxy-Hb in Tourette in left dlPFC during Stroop task*
11	Zhu et al. (2015)	ASD	Not applicable for auditory and visual stimuli	↓Oxy-Hb in ASD in left PFC in joint attention task

12	Arai et al. (2016)	ADHD	P — ↑ Errors in ADHD RT — Not reported	No correlation between age and Oxy-Hb in ADHD; ↑Oxy-Hb in TD during WM task
13	Ishii et al. (2017)	ADHD	P — Young, no difference; Older, ↑ errors in ADHD RT — Not reported	Young ADHD children ↑Oxy-Hb during task Older ADHD children ↓Oxy-Hb

*Behavioural results – group difference *P – performance error *RT – Reaction time

Table 4 shows behavioural and NIRS results side by side, and pertain to research question 2: To what extent do attention differences measured by NIRS map on to differences measured by behavioural tasks?

One study (9) left out behavioural results entirely, and two studies (2,10) discussed the correlation between age and behavioural performance but not group (atypical and typical) differences). Additionally, studies which use exclusively auditory/visual stimuli and do not include eye-tracking do not have measure of behaviour (6,11). However, a study (4) by Funabiki et al. (2012) used a post-test involving word recall, and therefore this is reported in Table 4 as the behavioural measure. However, NIRS was not used during this test and it is therefore excluded.

The remaining studies (1,3,5,7,8,12,13) cover ADHD and ASD. A single study (3) found no differences in either behavioural or NIRS data. Two studies (5,13) found that behavioural measures overlapped with NIRS findings in both error rate and reaction time (RT). A number of other studies also found increases error rates which overlapped with NIRS differences (7,8,12) but either did not record RT or did not find RT- differences. One study (1) found slower RTs in ADHD but no NIRS differences during the behavioural task. As such, based on the above results, it is difficult to confirm that behavioural differences reliably overlap with neurophysiological differences, suggesting the need for more a robust investigation of this question.

4.4 Theoretical basis and behavioural implications

The below table examines research question 3: Do studies include discussions of theoretical basis of attention or behavioural implications of findings?

Table 5. *Theoretical basis of attention or behavioural implications of findings.*

Discussion topics:	IN*:	1	2	3	4	5	6	7	8	9	10	11	12	13
Theory of attention/ attention dimension				X		X							X	
Behavioural implications of differences*					X		X							

*Differences — NIRS differences *IN — identification number

The above table shows that few studies (3,5,12) included a theoretical basis of attention, seldom (4,6) discuss behavioural implications of neurophysiological differences. Two studies (3, 12) included a reference to Baddeley's model of working memory in varying degrees of detail, one (12) referred to attention as a limited capacity system, and one (5) referred to a theoretical model of response inhibition. Each of the studies (4,6) which alluded to behavioural implications investigated areas in both the auditory and prefrontal cortex in children with ASD (4) or infants at risk for ASD (6).

5 Discussion

Research involving attention and NIRS in children with atypical development often cites compromised neuronal- activity or cortical dysfunction as the theoretical basis underlying differences, whether they be characterized by increases or decreases in oxy-Hb and deoxy-Hb. Moreover, it is difficult to compare the results as both oxy- or deoxy-Hb are not consistently included. When using behavioural tests alongside NIRS measurements, some studies do not report the behavioural results at all, and few investigate the relationship between the behavioural and NIRS results. However, of the studies that do investigate and report behavioural data alongside NIRS data, particularly in the case of response inhibition, behavioural results occasionally map on to cortical differences (or lack thereof) measured by NIRS, providing preliminary support for the validity of these tests and strengthening their importance in overall investigations of attention. Only three studies include a theoretical basis of the attention dimension, and just two include a discussion of the behavioural implications of their findings. Ultimately, this review underscores the findings of Vanderwert and Nelson (2014) in an earlier systematic review, who cite the difficulty of interpreting NIRS results in larger behavioural and developmental contexts. However, the following sections will not focus primarily on the methodological issues related to this issue, as has been done in earlier reviews, but investigate the implications of the above results in the context of research questions 1, 2 and 3.

5.1 Evidence and characterizations of functional differences

Research question 1: What is the evidence for functional differences in attention for children with atypical development?

This review underscores the notion that there is conflicting evidence for attentional differences based on NIRS findings. However, unpacking findings related to functional differences and neuronal activity is complex. First, it is important to mention that it is not surprising that ADHD is characterized differently than ASD or Tourette Syndrome. As mentioned earlier in this review, each of these disorders is characterized by distinct attentional challenges although occasionally in similar brain regions. What’s more concerning, however, are the inconsistencies within single disorders. Multiple brain regions were implicated across studies and in some cases, it is unclear whether the authors set out to investigate the regions reported or only reported the significant or noteworthy results, excluding insignificant results which may contradict other research. While there may be a general trend towards hypo-activity for response inhibition in ADHD (Negoro et al., 2010; Ishii et al., 2017; Monden et al., 2015; Yasemura et al., 2014; Xiao et al., 2012), different brain regions are reported or left out, and other studies show no difference (Moser et al., 2009). Results for working memory in ADHD are less clear, and show hypo- activity (Arai et al., 2016), hyper-activity (Tsujimoto et al., 2013) and no difference (Schecklmann et al., 2010). In ASD, prefrontal hypo-activity is shown in school-aged children with ASD (Zhu et al., 2015) and infants at risk for ASD (Lloyd-Fox et al., 2013), while other results are unclear (Funabiki et al., 2012). Finally, a single study showed hypo-activity in Tourette Syndrome (Yamamuro et al., 2015). Given the exploratory nature of NIRS research, this is not entirely unexpected. However, the results would be more useful if authors report explicitly if their findings confirm or deny previous research in *each* region of interest or channel-clustered area.

Additionally, it is important to note that it is not necessarily surprising that both hyper- and hypo- activity are reported in different parts of the brain. However, the lack of standardization across brain regions of interest and number of channels makes it difficult to conclude whether some findings contradict or support others. A solution to this issue has already been reported by Aslin (2012) and Vanderwert and Nelson (2014), who underscore the importance of standardizing NIRS methodology to include a set number of channels and/or regions of interest to be associated and reported on in all cognitive dimensions being studied. Standardization of methodological approaches would increase the relevance of single NIRS studies and allow their findings the ability to either confirm or deny previous research through replication, thereby contributing to an overall understanding of attention in typical and atypical development.

NIRS research has the potential to be an incredibly useful measure of attention with some promising preliminary evidence in the dimension of response inhibition but conflicting evidence in the areas of working memory, attentional control, and joint attention. More focus on replicating and confirming specific claims in previous findings rather than isolated exploratory studies looking at varying brain regions may strengthen the overall use of NIRS as a neurophysiological measure.

5.2 Behavioural measures results and NIRS measures

Research question 2: Do attention differences measured by NIRS reliably map on to differences measured by behavioural tasks?

There are varying degrees to which behavioural results map on to NIRS findings based on the attention dimensions considered. For an overview of each of the behavioural tasks, please see Appendix E. In certain cases, only visual/auditory stimuli are used in studies investigating social and joint attention in ASD by Zhu et al. (2015), Lloyd-Fox et al. (2010), and Funabiki et al. (2012), and therefore it is not possible to determine whether behavioural results overlap with neurophysiological differences. Although, Funabiki et al. (2012) use a recall test after exposing children with ASD, NIRS was not deployed during this test.

Studies which did use behavioural tasks such as the Stroop, RST, RPS, Go/no-go and working memory tasks did not consistently measure both performance (number of errors) and reaction time (RT). This presents another area where the methodology may be standardized so as to have an easier time comparing the results of different studies. However, introducing both reaction time and performance introduces more conditions for behavioural results to *not* overlap with NIRS findings, which is a potential bias towards negativity. For instance, if one study includes both reaction time and performance alongside NIRS data, and only performance maps on to NIRS data but not reaction time, does this count as behavioural differences overlapping with NIRS differences or not? To contrast this, if a study which only reports/measures reaction time but not performance error finds differences alongside NIRS data, by having one less condition, they are potentially able to more easily demonstrate this overlap. This discrepancy in the results reported by studies was not originally anticipated and therefore presents a limitation to the original research question which must be kept in mind throughout this discussion.

First, there is not enough evidence to determine whether working memory behavioural tasks map on to functional differences, as only three studies were used. Schecklmann et al. (2010) found no differences in either NIRS or behavioural working memory tests, Tsujimoto et al. (2013) found increased oxy-Hb and increased error in ADHD in children with working memory task, while Arai et al. (2016) found increased oxy-Hb in TD during the task but increased error in ADHD. Tsujimoto et al. (2013) found a correlation between error rate and oxy-Hb data, suggesting that children with poorer performance showed greater prefrontal oxygenation. This finding is important, at it strongly suggests that the proportion of error can be correlated to *higher* levels of oxy-Hb, countering previous discussions of atypical dysfunction as generally characterized by hypo-activity. However, these findings are hard to reconcile with those of Arai et al. (2016), who found that increased error was associated with decreased oxy-Hb, even though both studies use spatial working memory tasks and similar brain regions. This leads to an important question: how are we to categorize differences reflected at behavioural levels which are not reflected or agreed upon at the neurophysiological level? For now, it is sufficient to suggest that more research must be done in this are to close these important gaps in our understanding.

In response inhibition, the Go/no-go task was used in 2 studies, the Stroop task and/or the Reverse Stroop task (RST) was used in 5, and a ‘to lose’ rock paper scissors (RPS) task was used once. It is difficult to comment on whether differences observed by the Go/no-go task map on to NIRS differences, as Monden et al. (2015) did not report behavioural results leaving only one study by Xiao et al. (2012) which used both the Stroop and Go/no-go task. However, these results are interesting, as the authors found no NIRS *or* behavioural differences during the Stroop task, but NIRS *and* behavioural differences in both ASD and ADHD as compared to TD children in the Go/no-go task. The authors write, “these deferential results obtained from the Go/No-go and Stroop tasks support the viewpoint of Casey (2002)” (p. 5). To summarize, Casey et al. (2002) posit that response inhibition is comprised of three subcategories: stimulus selection, response selection and response execution and that perhaps these recruit different cognitive processing systems. In the Stroop task, individuals must ignore semantic meanings but name ink colour, suggesting that individual must inhibit the meaning of the word to name the colour in which it is printed; on the other hand, in the Go/no-go task, individuals must inhibit an engrained tendency to carry out a response (Xiao et al., 2012). Each of these tests, the authors argue, measure different subcomponents of response inhibition. Interestingly, Moser et al. (2009) also weigh in on the differences between these two behavioural measures. They write, “performance in the Stroop paradigm matures at approximately 17–19 years of age, whereas maturation occurs earlier in more basic inhibition tasks, such as the Go/no-go (12 years of age) and stop signal task (13–17 years of age). Conducting imaging studies with these tasks opens a window into the impaired neurodevelopment of executive functions” (p. 190). These are interesting observations with regards to development which might be kept in mind for future investigations of the developmental trajectories of response inhibition.

The Stroop task only showed results in attentional differences in a few studies even though the age varied from 6-15 years old, suggesting that it may not be the most appropriate measure of response inhibition. Additionally, the differences only occasionally mapped on to the NIRS results. For instance, Negoro et al. (2010) found no differences in performance error but hypo-activity in ADHD during the task, suggesting that functional differences exist which cannot be observed at the behavioural level (at least on the basis of performance error). Moser et al. (2009) found individuals with ADHD to have slower reaction times in Stroop, but no differences in performance error and no functional differences *during* the task. To contrast these, Yasemura et al. (2014) found no difference in the Stroop task in either performance or reaction time, but also found no differences at the neurophysiological level. Last, Yamamuro et al. (2010) found evidence of functional differences and increased error during the Stroop task. Taken together, these findings suggest that previous reviews indicating the use of the Stroop task to record behavioural differences in response inhibition (Schwartz and Verhaeghen, 2008) may need to be revisited.

In an interesting experimental design using younger and older age groups, Ishii et al. (2017) used a rock paper scissors task (where the purpose is to lose) to measure response inhibition. In the younger children with ADHD, they found no differences in performance error, but increased oxy-Hb, whereas in the older children with ADHD they found increased errors and *decreased* oxy-Hb. Although these results are difficult to interpret, the authors findings and discussion suggests that mechanisms involved in response inhibitions are still developing before the age of 10, and that only later in childhood do ‘atypical’ behaviours associated with response inhibition appear as significant. However, the authors do not comment on how the behavioural and NIRS findings overlap beyond this. In the future, further investigation of these findings is needed as well as a potential introduction of longitudinal NIRS designs.

An earlier question in this section asks: how are we to understand differences at the behavioural level which are not reflected at the neurophysiological level. Here, the opposite can also be applied. How are we to understand neurophysiological differences which are not reflected at the behavioural level? Another may also be added: how are we to understand neurophysiological characterizations of atypical attentional development which change over time? These questions may only be speculative for the moment but highlight the need for more of such questions to be asked in NIRS research, as well as the potential of NIRS to strengthen the validity of behavioural measures.

5.3 Theoretical basis and behavioural implications

Research question 3: Do studies include discussions of theoretical basis of attention or behavioural implications of findings (beyond 'cortical dysfunction')?

Studies rarely included a theoretical basis of attention or behavioural implications of the NIRS findings. Only three studies included a theoretical basis of attention or an attention dimension. Schecklmann et al. (2010) included a brief discussion related to Baddeley's (2003) model of working memory but did not find NIRS evidence to support differences in the dlPFC which was thought to be the neural correlate of the central executive. Arai et al. (2016) also briefly referred to Baddeley's (2003) model of working memory as well as attention as a limited capacity system but did not discuss how their findings in light of these theories. Xiao et al. (2012) included a brief discussion of Casey's (2002) theory of response inhibition, which proved to be important as they were able to measure response inhibition at the behavioural and neurophysiological levels using the Go/no-go task but not the Stroop task. Casey's (2002) theoretical account of response inhibition having subcomponents was supported by Xiao et al. (2012), particularly for evidence of differences in the response selection or execution processes, thereby underscoring the potential of NIRS research to strengthen theoretical models of attention as well.

NIRS research might begin to incorporate implications for behaviour and intervention in discussions of their findings. Only 2 studies include discussions of behavioural implications of their findings, by Funabiki et al. (2012) and Lloyd-Fox et al. (2013). Lloyd-Fox et al. (2013) found hypo-activity in the temporal cortex when children at high-risk for ASD or with ASD were exposed to social stimuli, while Funabiki et al. (2012) did not report prefrontal cortical NIRS data but stated that differences in the PFC were found. Moreover, Funabiki et al. (2012) write that differences in auditory processing can be attributed to inattention rather than functional impairments in the auditory (temporal) cortex. Although the results of Funabiki et al. (2012) are unclear, their larger point regarding the behavioural implications is important. If their conclusions are correct (and they need to be confirmed in future research), difficulties at the behavioural level in ASD children are due to prefrontal dysfunction related to attentional difficulties, rather than auditory processing. In turn, and again if true, this suggests that support for children with ASD should operate under the assumption that difficulty in these interactions can be ameliorated through focus on increasing attentional control, rather than targeting auditory processing. This is an important difference which has profound implications for designing interventions.

These findings may make sense in the context of development. As the PFC is the last brain structure to develop (Kolb et al., 2012), perhaps functional differences in individuals at risk for autism are at first found in the auditory cortex and *later* impact functioning in the PFC. Related are the results of Ishii et al. (2017). Although Ishii et al. (2017) did not report on the behavioural implications of their results, their findings may contribute to understandings of development and behaviour. As mentioned previously, in younger children (6-10 years of age), they found that ADHD was characterized by increased oxy-Hb, whereas in older children (11-15 years of age) it was characterized by *decreased* oxy-Hb. The authors do not comment on why functional differences are at first characterized by hyperactivity and later by hypo-activity, but it may have important implications for brain development as well as behaviour. Indeed, part of the challenge here is that knowledge in this area is still developing, and as such uniting behaviour with neurophysiological levels is still a challenge in the field (Vanderwert & Nelson, 2014).

Indeed, not much is known about the specific behavioural implications of either hyper-or hypo- activity or if they have differing behavioural implications at all. In some ways, the above behavioural implications posited by Funabiki et al. (2012) in ASD are easier to make, as they deal with brain regions whose associated behaviours are more clearly separated (the prefrontal cortex and auditory cortex). It is more difficult to determine behavioural implications where only the prefrontal region is concerned, as the associated behaviours (generally referred to as executive functions) are so closely intertwined. As has been shown in this review and others, atypical attentional processing is usually associated with hypo-activity, or less selective neural responses as compared to control groups (Lloyd-Fox et al., 2010; Fassbender & Schweitzer, 2006), but how this is understood at a theoretical level beyond a lack of cortical connectivity is unclear. Equally, how these findings translate to specific behaviours is still under explored. Fassbender and Schweitzer (2006) note that atypical attention can be characterized by neuronal hyper-activity, or more oxygen consumption than control groups. This was also shown in the above review, particularly with the correlation of increased error and oxygenation in atypical development by Tsujimoto et al. (2013). It may be easier to link neuronal hyper-activity to theoretical accounts of attention as well as the resulting behavioural implications. Increases in oxy-Hb could denote more attentional resources deployed, and as such increased mental effort. Based on the disrupted executive processing systems of disorders such as ADHD, ASD, and Tourette Syndrome, there may be less attentional resources available to recruit the regions necessary for specific tasks. To support this, Fassbender and Schweitzer (2006) note the existence of 'compensatory' activation in ADHD, in which other brain structures over-engage to compensate for this dysfunction. Compensatory activation may also be a response to cognitive fatigue (Fassbender & Schweitzer, 2006) and was cited by the study by Moser et al. (2009). Ultimately, both the theoretical and behavioural implications of neuronal hyper-activity in atypical development have been articulated, while much less is known about neuronal hypo-activity in atypical development, indicating the need for more research on this topic.

5.4 Suggestions for future research

NIRS research is a recent and emerging field and has made some important contributions to our overall understanding of child development. It is also a very useful measure which is more accessible than fMRI and has made large strides in the past decade. As the measure is so new, the lack of consistency within the literature is not entirely surprising. As noted by past reviews as well as the current review, NIRS research has shown promise for uncovering functional neurophysiological markers for behavioural differences, as well as an initial probing into the biomarkers of certain disorders (Vanderwert & Nelson, 2014; Aslin, 2012; Minakawa-Kawai, 2008; Lloyd-Fox et al., 2010). However, the present review has uncovered some potential areas of future research for the field. First, NIRS researchers should work to standardize the use of the methodology with respect to number of channels, brain regions of interest, and/or channel-clustered analyses. However, as has been shown throughout this review, NIRS research is complex and not easily generalizable or replicable given the amount of details involved in the tool as well as behavioural tasks or stimuli. Next, research may be more explicit about examining the overlap between behavioural and neurophysiological differences. Future research may work to incorporate both a theoretical basis of attention as well as behavioural implications and therefore contribute to a more cohesive understanding of attention. Last, NIRS research has potential to investigate developmental trajectories of attention, as in the case of Ishii et al. (2017) as well as untangle highly co-morbid conditions, such as ADHD and TS which was a challenge for Yamamuro et al. (2015). As the field continues to grow, these areas offer opportunity for exploration.

5.5 Methodological challenges and limitations of the review

This review faced methodological challenges and demonstrates some important limitations. First, studies did not all include the same brain regions of interest in their discussions, and it difficult to determine whether they only included significant results (thereby contradicting other studies) or only analyzed certain regions. Studies also analyzed NIRS data by region or channel cluster making it difficult to reconcile these results. Additionally, the present review was not able to analyze data quantitatively for this reason, and as such an important limitation is that it is difficult to empirically confirm whether NIRS is an appropriate measure of attention. Studies also did not include all dimensions of behavioural results such as performance and reaction time, and as such it was difficult to compare the results across studies. Another important limitation of the review is that it did not include an in-depth investigation of the effect of medication. Some studies instructed participants to stop medication 24 hours before the test while others instructed for 48 hours, which may have important implications for the results as noted by Schecklmann et al. (2010).

6 Conclusion

Functional near-infrared spectroscopy has shown some preliminary evidence to support the existence of neurophysiological differences in some dimensions of attention — namely response inhibition in children with ADHD. However, more research is needed to support differences in other dimensions, including response inhibition in Tourette's Syndrome, working memory in ADHD, as well as attentional control and joint attention in ASD. Additionally, more research might begin to include other instances of atypical attention, such as the one study of Tourette Syndrome, as well as children with other neurodevelopmental disorders or other impairments which may impact attention. This review underscores previous reviews (Aslin, 2012; Vanderwert & Nelson, 2014) and suggests standardization of methodology as well as more longitudinal approaches to research to provide more robust evidence for biomarkers of disorders or neurophysiological differences. Overall, NIRS shows preliminary promise as a measure of attention in children with atypical development. In addition, this review has highlighted the disconnect between conceptions of attention at theoretical, behavioural and neurophysiological levels and underscored the potential of NIRS as a way of bridging these gaps. First, it investigated the overlap between behavioural and NIRS differences, and found that only a few behavioural measures overlap with the NIRS differences, suggesting an important potential focus in future NIRS research. Next, it explored whether studies included a theoretical basis of attention or the behavioural implications of the findings and found that only a small number of studies (3 and 2, respectively) did so. Although making behavioural inferences from neurophysiological data is somewhat difficult as much is still unknown, studies which included these discussions may have a much larger impact in terms of practical support for children with attentional difficulties. Ultimately, this review uncovers the need to strengthen our understandings of how theoretical, behavioural and neurophysiological conceptualizations of attention come together and underscores the fact that more research using NIRS to study attention in children with atypical development is needed.

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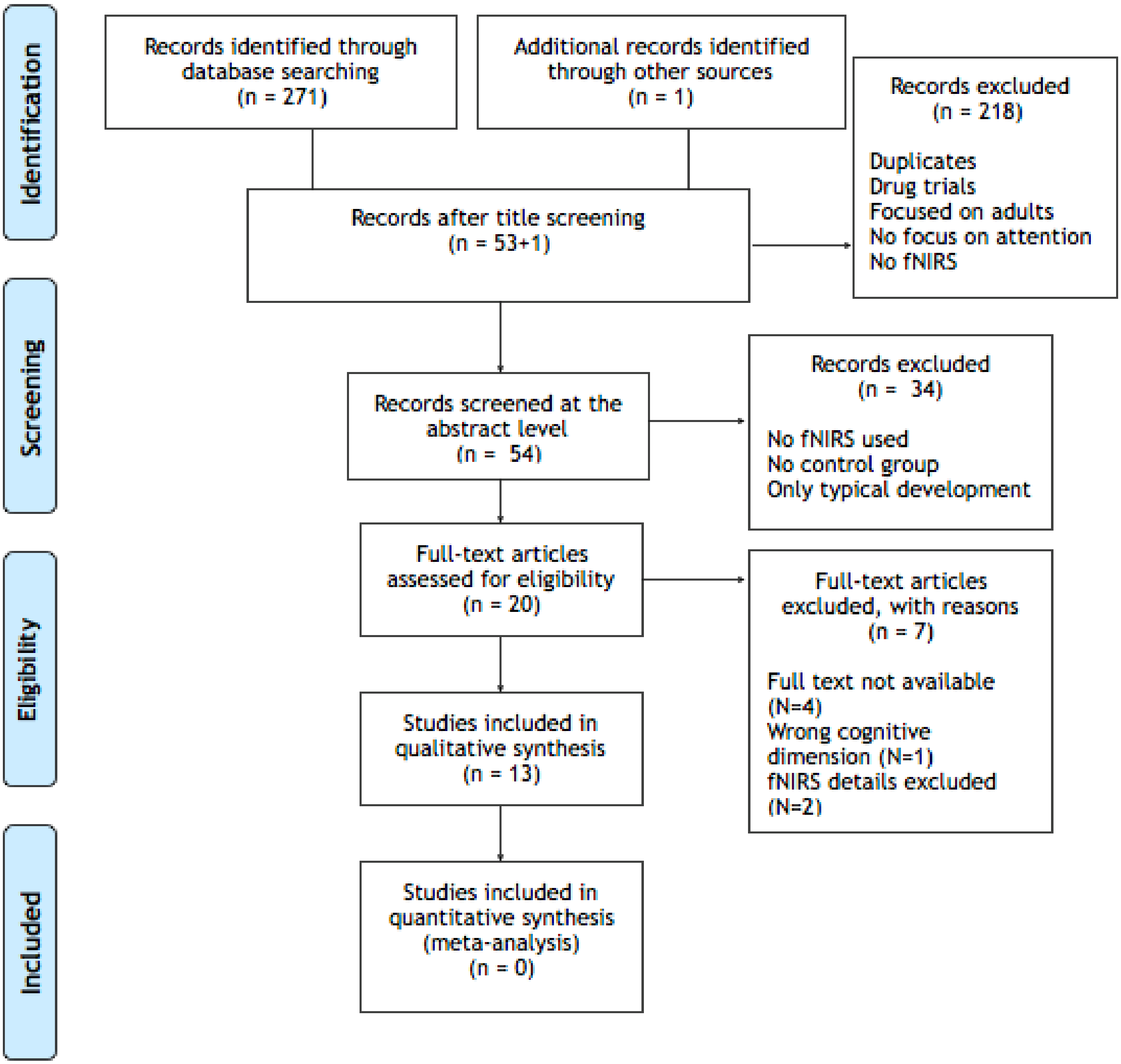
Appendix A. *Search terms (taken from Pubmed search).*

((attention [Title/Abstract] OR “sustained attention”[Title/Abstract] OR vigilance[Title/Abstract] OR “vigilant attention”[Title/Abstract] OR “paying attention”[Title/Abstract]) AND (Near Infrared Spectroscopy[Title/Abstract] OR fNIRS[Title/Abstract] OR functional near infra*[Title/Abstract] OR Optical Topography[Title/Abstract] OR Diffuse Optical Imaging[Title/Abstract]) AND (Infan*[Title/Abstract] OR newborn*[Title/Abstract] OR new-born*[Title/Abstract] OR perinat*[Title/Abstract] OR neonat*[Title/Abstract] OR baby[Title/Abstract] OR baby*[Title/Abstract] OR babies[Title/Abstract] OR toddler*[Title/Abstract] OR minors[Title/Abstract] OR minors*[Title/Abstract] OR boy[Title/Abstract] OR boys[Title/Abstract] OR boyhood[Title/Abstract] OR girl*[Title/Abstract] OR kid[Title/Abstract] OR kids[Title/Abstract] OR child[Title/Abstract] OR child*[Title/Abstract] OR children*[Title/Abstract] OR schoolchild*[Title/Abstract] OR schoolchild[Title/Abstract] OR school child[Title/Abstract] OR school child*[Title/Abstract] OR adolescen*[Title/Abstract] OR juvenil*[Title/Abstract] OR youth*[Title/Abstract] OR teen*[Title/Abstract] OR under*age*[Title/Abstract] OR pubescen*[Title/Abstract] OR pediatrics[mh] OR pediatric*[Title/Abstract] OR paediatric*[Title/Abstract] OR peadiatric*[Title/Abstract])).

Appendix B. *Flow chart of search procedure (PRISMA, Moher et al., 2009).*



Appendix C. *Data extraction protocol, full-text screening.*

General Information	Authors Year Title Journal Country
Background information, study purpose and research questions	Theoretical background Target population Definition of attention dimension Operationalization of atypical development Study rationale and purpose Research question(s), if applicable
Sample	N, age, gender, diagnosis Sampling procedure, if applicable
Methodology	Number of NIRS channels Regions of interest, where applicable Stimulus Use of oxy-Hb data, deoxy-HB data, or both
Results	Outcome measures Data analysis Results Overlap of behavioural and NIRS data

Discussion	Limitations Theoretical implications of findings Practical behavioural implications
Quality assessment	Score on the Quality Assessment Protocol High/Medium/Low Quality

Appendix D. *Quality Assessment Protocol, CASP (2018) case control study and added questions.*

Section A		Yes, no, can't tell	Comments
	1. Did the study address a clearly focused issue? 2. Did the authors use an appropriate method to answer their question? 3. Were the cases recruited in an acceptable way? 4. Were the controls selected in an acceptable way? 5. Was the exposure accurately measured to minimize bias? 6a. Aside from the experimental intervention, were the groups treated equally? 6b. Have the authors taken account of the potential confounding factors in the design and/or in their analysis?		
Section B			
	7. Is there a significant treatment effect? (in this case treatment is atypical development) 8. Is the estimate of the treatment effect precise? (are the behavioural or NIRS results clearly reported) 9. Do you believe the results?		
Section C			

	10. Can the results be applied to the local population? 11. Do the results of the study fit with other available evidence?		
Added questions	12. Do the authors discuss theoretical basis or behavioural implications? 13. Do they measure both oxy- and deoxyHb?		

N.B. There are significant limitations to this checklist, including a lack of focus on number of participants, power calculation, and a lack of consideration of the exploratory nature of many of the studies.

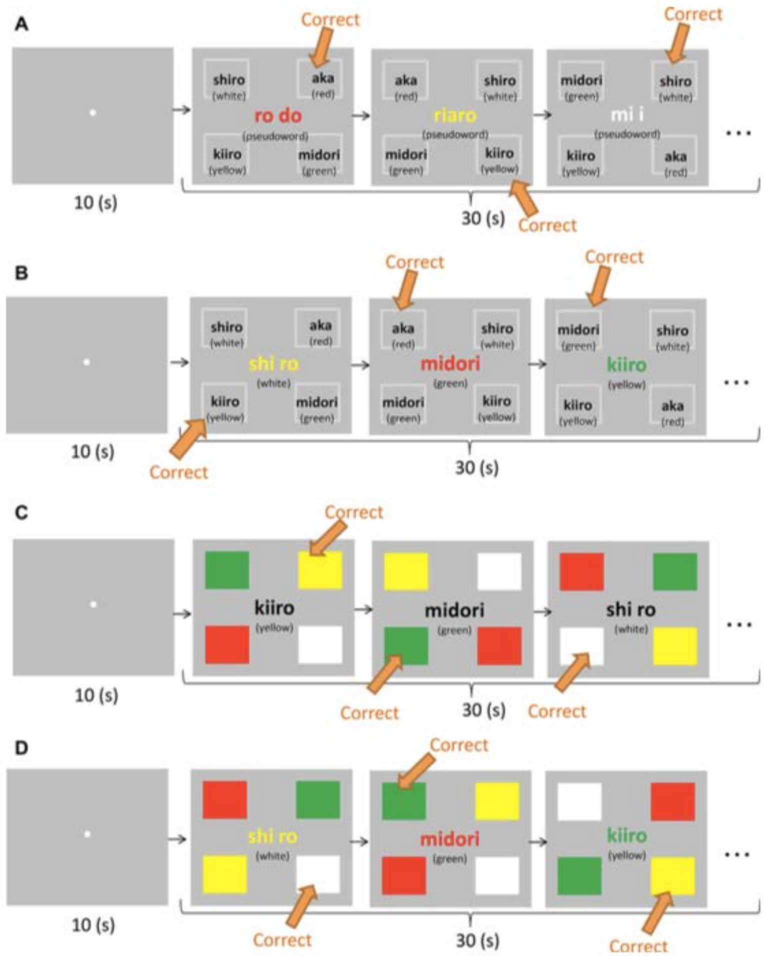
Appendix E. *Overview and quality assessment score of the studies included in the analysis.*

IN*	QAS*	Country	Age	AD*	Attention Dimension	Task	Channels*
1	64% (medium)	Switzerland	8-13	ADHD	Response inhibition	Stroop	2 x 2
2	71% (high)	Japan	6-15	ADHD	Response inhibition	Stroop	24
3	57% (low)	Germany	8-15	ADHD	Working memory	WM task	52
4	57% (low)	Japan	10-16	ASD	Attentional control	Auditory	32
5	71% (high)	China	9-12	ASD, ADHD	Response inhibition	Go/no-go, Stroop	16
6	86% (high)	UK	4-6m	ASD risk	Attentional control	Auditory, visual	26
7	71% (high)	Japan	8-12	ADHD	Working memory	WM task	10
8	64% (medium)	Japan	8-11	ASD, ADHD	Response inhibition	Stroop, RST	16
9	64% (medium)	Japan	6-15	ADHD	Response inhibition	Go/no-go	30
10	64% (medium)	Japan	7-10	TD	Response inhibition	Stroop	24
11	64% (medium)	China	6-10	ASD	Joint attention	Joint attention	22
12	64% (medium)	Japan	7-13	ADHD	Working memory	WM task	16
13	71% (high)	Japan	6-10, 11-16	ADHD	Response inhibition	To lose RPS task	22

*QAS - Quality assessment score *AD – Atypical development *Channels - NIRS

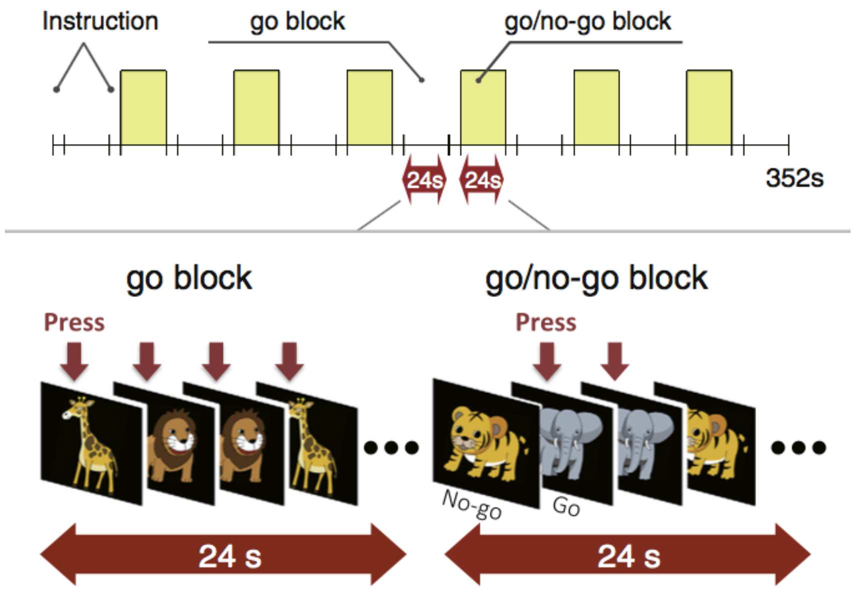
Appendix F. *Examples of behavioural tasks.*

Stroop Task and Reverse Stroop task (Yasemura et al., 2014)



In Yasemura et al.'s (2014) variation of the Stroop task, participants must quickly select among 4 words displayed in each corner to match the word in the center of the screen. There are two conditions: neutral and incongruent. In the neutral task, participants must choose the corner word which matched the font colour of the central word (which in this case was not a real word). In the incongruent condition, the central word is the name of a colour but written in a different colour, and participants must press the *font* colour of the word in the corner. The Reserve Stroop task involves a neutral and incongruent condition as well, but this time, during the incongruent condition participants had to choose the color (corner word) which matched the *meaning* of the central word.

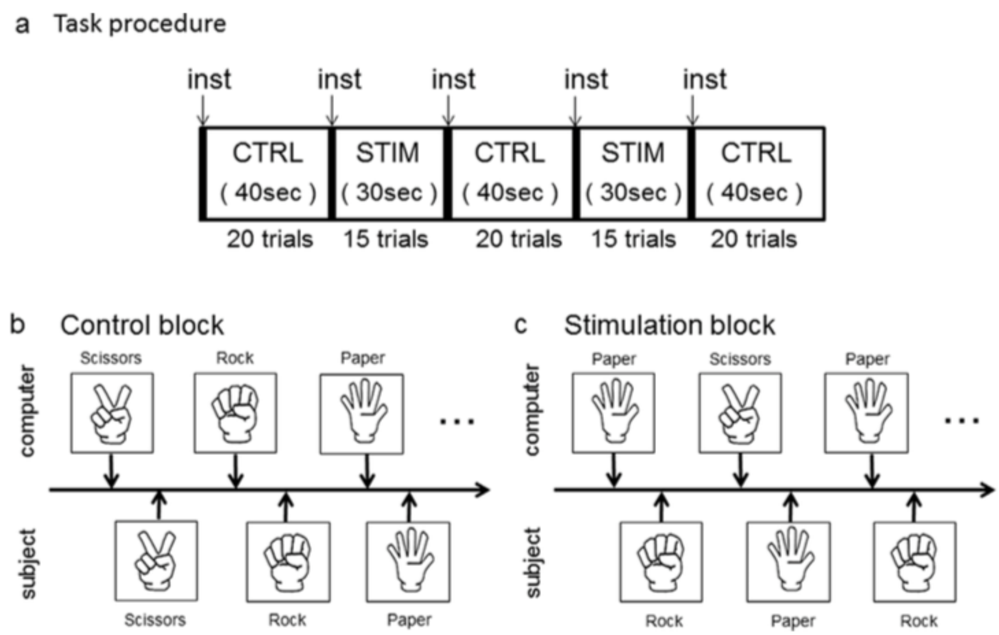
Go/no-go task (Monden et al., 2015)



In Monden et al. (2015), the Go/no-go task consisted of target blocks involving "go" (press the button) and "no-go" (don't press the button) where a series of pictures are shown. In the "go" blocks, participants were instructed to press during each picture that was shown. In the Go/no-go block, participants were instructed to press for elephants, but not for tigers, for example. See participant playing the game with NIRS measure on, below.

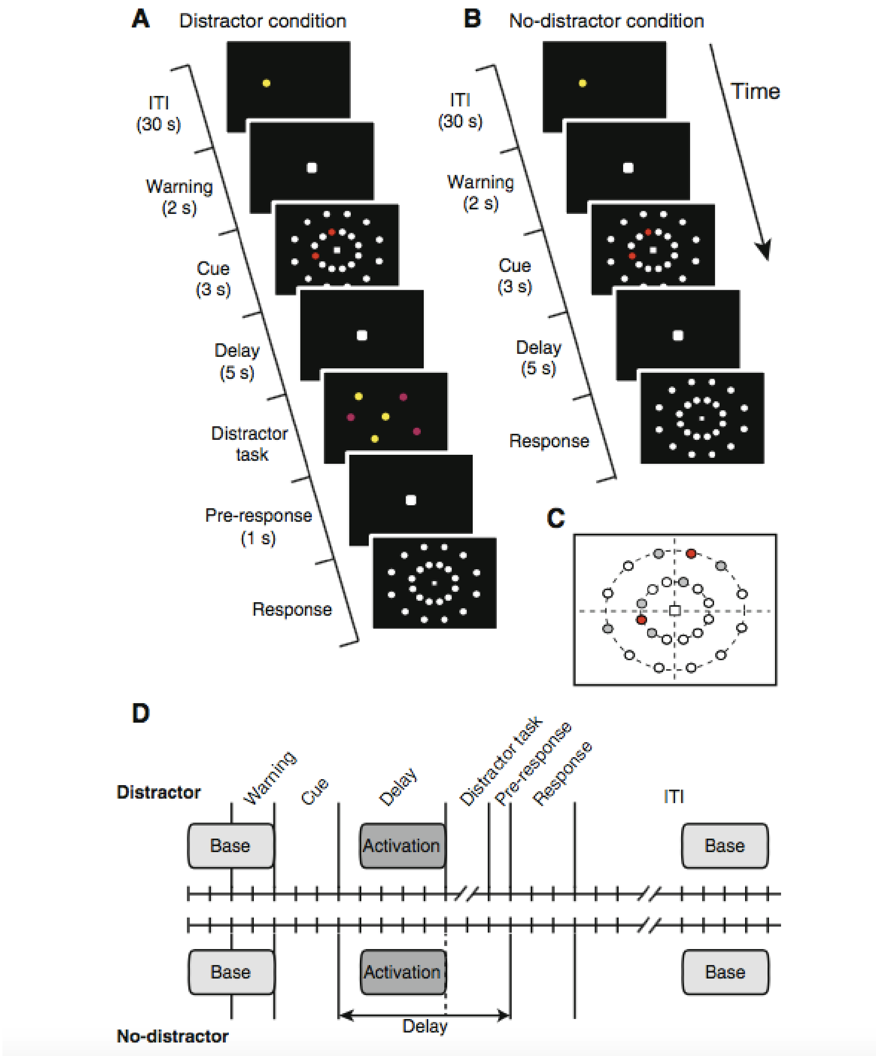
Source: Monden et al. (2015)

Rock Paper Scissors task (Ishii et al., 2017)



For Ishii et al (2017), the purpose of the Rock Paper Scissors task was to purposely lose the game. In the same as the traditional game, rock beats scissors, scissors beat paper, and paper beats rock. Participants were instructed to present the hand signal for either rock, paper or scissors after the computer screen presented one of these symbols. Participants used their own hands and not a button on the screen.

Working memory task (Tsujimoto et al., 2013)



In the study by Tsujimoto et al. (2015) a variation of a visuospatial working memory task was used. In this test, there were two conditions: distractor and non-distractor. In the distractor condition, participants had to touch yellow dots among a variety of other colours and moving dots. “When each subject touched all three dots successfully, the task proceeded to the preresponse delay (1 s), followed by a response period. In this period, 24 white dots were presented at the same locations as the cues, and the children reported the positions at which the red dots had been presented prior to the delay period by touching the two dots sequentially” (p. 681). In the non-distractor condition, the same structure was followed but with no distractor task.