Using mobile fNIRS to explore the development of goal-directed action sequence planning in freely moving preschoolers

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Abstract

Measuring the neural correlates of cognition in freely moving preschoolers presents several challenges. The current article describes a proof-of-principle study assessing brain activation in preschoolers while performing a naturalistic action planning task in the wild. Ninety-two children between 3 and 5 years of age built both a Duplo house and a Duplo spaceship. Both building tasks involve the completion of multiple subgoals within the overall goal. The results revealed an increase in oxyhaemoglobin activation in right DLPFC when planning for the next subgoal, as well as in a standard go/no-go inhibition task, suggesting that inhibition may play a special role in selecting subgoals at these ages. More generally, we demonstrate that fNIRS data can be recorded from moving preschoolers and that a multi-modal set-up including optical motion capture can allow the reconstruction of events of interest. Implications of the approach, as well as recommendations to improve data quality of wireless fNIRS in freely moving toddlers, are discussed.

Keywords: fNIRS; preschoolers; naturalistic tasks; action planning; executive functions

Introduction

Planning is a complex set of mental and behavioural operations that brings together, cognitive, emotional and motivation resources to achieve a desired goal via individual actions or action sequences (Shallice, 1982; Friedman & Schonick, 2014). Planning is generally considered to draw upon *Executive Functions* (EF), the cognitive processes that control and regulate goal-directed behaviour (Barkley, 2012, Diamond, 2013; Miyake & Friedman, 2012). Within the EF literature, a common view is that planning (as well as other complex cognitive processes such as reasoning and problem-solving) draws upon simpler or more basic component executive functions including working memory maintenance and manipulation, response inhibition and mental set-shifting (Diamond, 2013; Miyake et al., 2000).

One aspect of planning involves the sequencing of actions to achieve goals. The ability to plan and execute simple action sequences is thought to develop throughout infancy (e.g., Claxton et al., 2003; Lockman et al., 1984; von Hofsten & Rönnqvist, 1988; Zaal & Thelen, 2005), while the planning of more complex actions and action sequences continues to develop through toddlerhood and the preschool years (Schröer et al., 2021; Yanaoka & Saito, 2017, 2019, 2020). However, it is currently unknown how changes in brain activation correlates with these developmental improvements.

A key challenge to existing psychological research, particularly in the context of development, is to leave behind the traditional laboratory studies and investigate cognition, its development and its brain functioning, in more *real-world* or *naturalistic* settings (Dahl, 2017; Matusz et al., 2019; Pinti et al., 2018). This is critical in the case of action planning, because part of the complexity of action planning stems from the fact that actions are embedded within the context that they are planned and executed. Thus, findings from lab-based studies (with restricted degrees of freedom) may not transfer to natural settings (with more open-ended degrees of freedom). The current article reports on a proof-of-principle study that demonstrates that wireless functional near-infrared spectroscopy (fNIRS) can be combined with optical motion tracking to assess action planning in preschoolers moving freely in real-world settings.

Recently, the development of wearable wireless fNIRS systems has allowed brain activity to be imaged in more naturalistic settings (Pinti et al., 2018). Previous work has demonstrated this in adult studies (e.g. Pinti et al., 2015; Balardin et al., 2017). However, additional challenges must be considered such as the larger impact of systemic interference, increases in motion artifacts, and difficulties in recovering the onset of events of interest (Pinti et al., 2018). Generally, brain imaging can be difficult to perform in children as they rarely comply with the restrictions of neuroimaging testing (e.g., sitting still, many trials). However, one recent study has shown that wireless fNIRS could represent a solution to measure fluctuations in neural activity in preschoolers in naturalistic and more engaging virtual environments (Bulgarelli et al., 2023).

fNIRS is particularly promising for investigating the neural correlates of *cognition in the wild* (Hutchins, 1995) in young children because it is relatively resilient to motion artefacts (Lloyd-Fox et al., 2010; Mehnert et al., 2013; Moriguchi & Hiraki, 2013; Pinti et al., 2020). Furthermore, in previous

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adult studies, fNIRS has been combined successfully with sensor-based motion capture (Hamilton et al., 2018; Kubota et al., 2015; Lin & Lin, 2016), suggesting that a combination of fNIRS and motion capture might provide a novel window into the relations between brain, behaviour and cognition in the real-world.

The aims of the current study were therefore: (1) to validate an approach to measuring brain activation patterns of executive functions such as inhibition and planning in preschoolers using a standardized inhibition task, (2) to assess the feasibility of using wireless fNIRS in combination with optical motion capture to investigate the neural correlates of "*cognition in the wild*" in preschoolers, and (3) to investigate prefrontal cortex activation in this participant group during naturalistic action planning. We focus on the prefrontal (and motor) cortices as these areas are associated with executive functions (e.g., Aron et al., 2014) and planning (e.g. Kaller et al., 2011; Tanji et al., 2007)

fNIRS

Functional near-infrared spectroscopy (fNIRS) is a neuroimaging method that measures changes in haemoglobin concentration in the brain in a non-invasive way (Hoshi et al., 2005; Pinti et al., 2020). fNIRS uses near-infrared light (700 to 900 nm) that passes through biological tissue. fNIRS systems includes near infra-red light sources and detectors typically housed in a cap. Conventional systems are equipped with long fibre optics to guide and collect light that tether the participant to the device; novel wireless fNIRS instruments have all the optical components located onto the cap and transmit the brain data in real time via a wireless connection to the recording device, allowing the participant to move more freely with minor physical restraints.

fNIRS allows neural activity to be measured because the near-infrared light is absorbed by haemoglobin (Hb) (e.g., Hoshi et al., 2005). When a specific brain area is activated, the blood volume in that specific area changes, characterized by an increase in cerebral blood flow resulting in an increase in oxy-haemoglobin (HbO_2) and an increase in cerebral oxygen metabolic rate resulting in a decrease in deoxygenated haemoglobin (HHb). This is called haemo-dynamic response and is characterized by an increase in HbO_2 and a decrease in HHb (Hoshi et al., 2005; Pinti et al., 2020). Differences in absorption spectra of HbO_2 and HHb enable relative changes in haemoglobin concentration to be estimated using two or more wavelengths of infrared light (e.g., Hoshi et al., 2005; Pinti et al., 2020).

fNIRS uses light emitters and detectors placed on the skull in a cap, and is most sensitive to changes in neural activity close to the scalp (i.e., neocortex: Hoshi, 2005; Pinti et al., 2020). fNIRS is relatively easy to use, comfortable to wear, and relatively resilient to motion artefacts (e.g., Pinti et al., 2020), making it particularly appropriate for use with young children. Typically, fNIRS is used in conjunction with block-design studies with many trial repetitions (e.g., Lloyd-Fox et al., 2010; Pinti et al., 2020). Recently, its feasibility to track brain activity in naturalistic and more unstructured protocols has been investigated (i.e., Pinti et al., 2015).

Methods

Participants

Data from 45 3-year-olds (M = 40.9 months, SD = 3.31, 27F) and 47 5-year-olds (M = 64.2 months, SD = 3.54, 20F) was collected. Four children were not included in the planning analysis due to missing data for the planning task, and 2 children were not included due to refusing to wear the fNIRS cap. Participants were recruited from a university database of volunteer families. All procedures were approved by the local ethics committee, and participation was voluntary.

Procedure and Measures

Participants performed a naturalistic planning task and a standard computer-based inhibition task. The standardised inhibition task was included to confirm that the approach was able to measure brain activation patterns related to executive functions and planning in the specific participant group (i.e., preschoolers). The naturalistic planning task was included to explore differences in brain activation at different points in the action planning process.

Upon arrival and after obtaining informed consent from the caregiver and verbal assent from the child, each participant was fitted with an fNIRS cap, and asked to wear motion capture gloves (see Figure 1A). Small reflective plates were located on the outer surface of the gloves so as to allow motion capture cameras to detect and record the location of the hands and finger joints in 3-D space.

Thirty children of the initial sample completed one planning task. The remaining 60 children completed two planning tasks. Only children with data for both planning tasks were included in planning analysis. For each planning task, an instruction video was shown to the child until they understood the hierarchical goal structure of the task (build a house or spaceship using Duplo) and felt ready to build. Children were then able to build until they felt they were finished. After the planning task(s), the motion capture gloves were removed, and the child was asked to play the inhibition game on a standard computer. Families were reimbursed for their travel costs, and children were given a certificate and a t-shirt. Planning data was coded offline via video recordings of the session (see naturalistic planning task section).

Naturalistic planning task: Children were instructed to build a Duplo house and Duplo spaceship with a specified goal hierarchy to assess naturalistic action sequence planning (Schröer et al., 2021). Each building consisted of a main goal, and several subgoals each in turn consisting of several action steps. Each subgoal used different coloured blocks, which were placed in separate boxes. Children could re-watch the instruction video until they felt confident to start building. Whether the child knew the goal of the task and action

sequence subgoal colours was checked verbally prior to the child commencing (see Schröer et al., 2021). Offline coding of each child's action sequences consisted of locating *branch points*, where a child switched from one subgoal to another, and *within subgoal steps*, where the child remains within the same subgoal (Schröer et al., 2021). The time point for the action in the analysis was the moment when the child pressed the button to open the boxes to obtain a block for the new subgoal (i.e. branch point) or a block for the same subgoal (within subgoal steps) (Schröer et al., 2021). The contrast between branch points and within subgoal trials is of particular relevance as adults show increased action selection time at branch points compared to within subgoal trials (Arnold et al., 2017; Ruh et al., 2010), and this is thought to reflect planning (and hence increased cognitive control) at branch points (Ruh et al., 2010).

Movements in the planning task were recorded at 120 Hz using 16 near-infrared cameras in a 3D optical motion capture system (Vicon, UK). However, the motion capture data were not used in the current analysis, which focusses on the fNIRS data to explore brain activation in freely moving preschoolers.

Standardised inhibition task: Children also completed the BAT task, a child-friendly computerised version of the go/no-go task, in a block design. This task was administered to ensure that the fNIRS set-up was able to detect differences in prefrontal cortical activation. This task requires response inhibition, which is associated with activity in the prefrontal cortex (see., e.g., Aron et al., 2014). Children sat at a standard PC and were asked to press the space bar if they saw a bat (go-trails, 75%), but not if they saw a cat (no-go trials). The task consisted of 12 blocks (6 Go blocks, and 6 Mixed blocks), and each Go block consisted of 9 to 11 trials with only bats. Each Mixed block consisted of 5 go-trials (bats) and 5 no-go trials (cats) in a random order. A rest period between blocks lasted 8 to 12 seconds.

Figure 1: (A) a child wearing the motion capture gloves and fNIRS cap and (B) the optode arrangement with sources in red, detectors in blue, and channels in yellow on head mesh computed from an MRI template of a 5-year-old. The channels of interest covered the prefrontal cortex bilaterally.

fNIRS data acquisition: Concentration changes of oxygenated (HbO_2) and deoxygenated haemoglobin (HHb) during both the planning and inhibition task were recorded using a 46-channel wireless system (Brite 24, Artinis, the Netherlands; Figure 1A). Optodes were located bilaterally over prefrontal cortex and motor areas (Figure 1B). The NIRS probe consisted of 18 sources emitting light at 760 nm and 850 nm, and 16 detectors equally divided over both hemispheres with a source-detector distance of 25 mm. Data were sampled at 25 Hz.

Given that our goal was to investigate the neural correlates of executive functions, we focused our analyses on the 26 channels covering the left and right prefrontal cortex.

fNIRS data processing: Raw fNIRS data at the two wavelengths were first inspected to identify noisy channels to

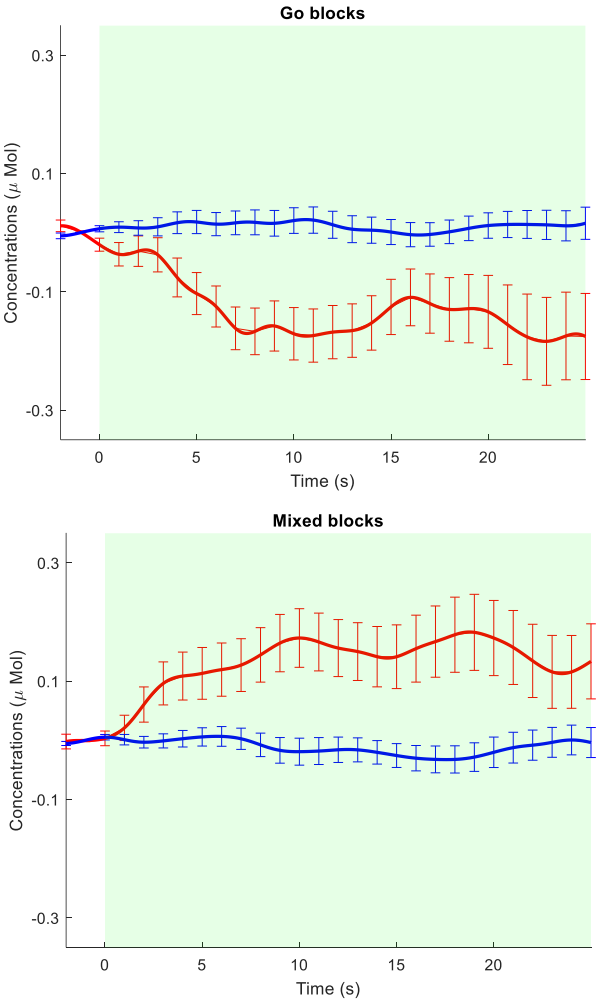

Figure 2: Block-averaged (means±sd) hemodynamic response of left DLPFC for Go (top) and Mixed (bottom) conditions. Oxygenated hemoglobin (HbO_2) is shown in red and deoxygenated hemoglobin (HHb) in blue.

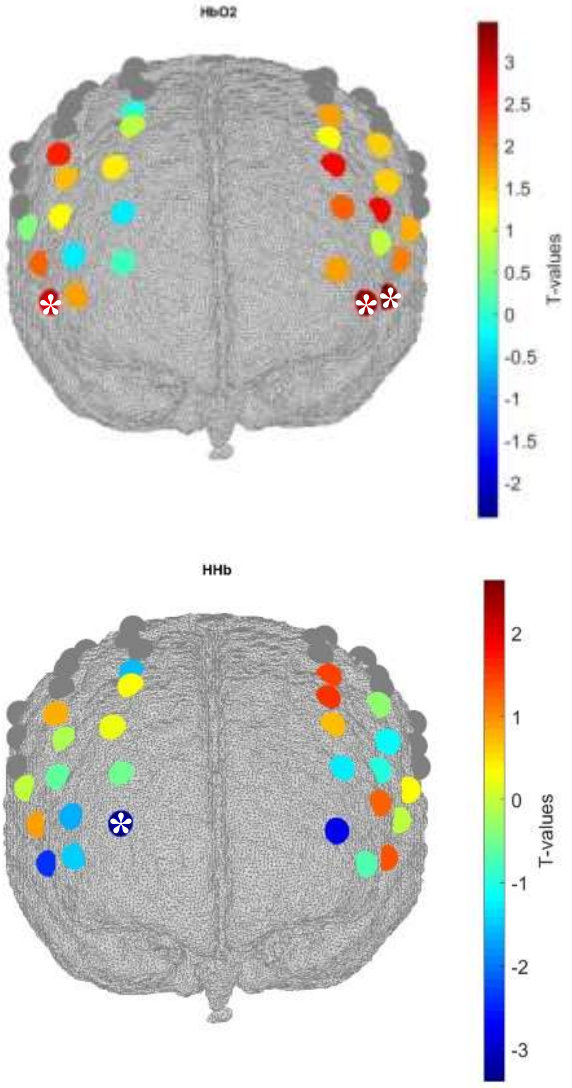

Figure 3: The significant contrasts (with *) in preschoolers between Mixed blocks and Go blocks of the BAT response inhibition task for HbO_2 (top) and HHb (bottom). Images show optode sites as viewed looking at the brain from the front. The left side of the image therefore corresponds to the right side of the brain.

be excluded from further analyses. These included channels which exhibited detector saturation, severe motion artifacts, no heart-beat component, or severe interference from motion tracking (Pinti et al., 2018). Raw intensity signals were then converted into changes in optical density, corrected for motion artifacts and band-pass filtered. The modified Beer-Lambert law was then applied to gather the concentration changes in HbO_2 and HHb (Bulgarelli et al., 2023).

For the inhibition task, HbO_2 and HHb were block averaged across trial repetitions for the Go and Mixed conditions. Only blocks with at least 50% accuracy were included. The area under the curve (AUC) was calculated on the block-averaged haemodynamic responses in a time window 10-18s post stimulus onset and used for the group level statistics. Channel-wise one-sample t-tests were run on the group AUCs for HbO_2 and HHb individually; in particular, we compared the amplitude changes in the Mixed blocks versus the Go blocks. Results were corrected for multiple comparisons by False Discovery Rate using the Benjamini-Hochberg procedure (Benjamini & Hochberg, 1995).

For the planning task, given the event-related design, we employed a general linear model (GLM) approach using a haemodynamic response function with time derivative to fit the HbO_2 and HHb time course of each channel. The design matrix modelled brain activity time-locked to critical points of interest in the child's stream of actions. In particular, 4 regressors were built to consider non-overlapping blocks of 20s based on visual inspection of the responses: (1) prior to the start of branch point actions; (2) prior to the start of within subgoal actions; (3) after the start of branch point actions; (4) after the start of within subgoal actions. This was done to assess whether there were differences in brain activity when planning the action as opposed to when the action was being executed. Beta values were estimated and used to compare the 20 s before the start of branch points versus the 20 s before the start of within subgoal trials ((1) vs (2)), and the 20 s after the start of branch points versus the 20 s after the start of within subgoal trials ((3) vs (4)). Beta-values were entered into group level channel-wise one-sample t-tests.

Results

The house and spaceship construction tasks revealed similar behaviour (i.e., outcome behaviours of fulfilling the main goal, following the instructed subgoal structure and avoiding use of distractor objects did not differ significantly across the tasks). We concentrate analysis on the fNIRS data.

Data quality: Compliance with wearing the cap was high (96.7% of the sample). However, a substantial amount of data was corrupted by the infrared light from the motion tracking cameras interfering with the fNIRS detectors. On average per channel in the naturalistic planning task, 20 participants had good enough data quality (*range* = 12 to 38, *SD* = 7.20). In general, participants showed an average of 45.1% of channels suitable for analysis (*range* = 7.7% to 84.6%, *SD* = 20.4%). Data quality was considered satisfactory given that the data were collected from moving toddlers.

Response inhibition task: Children showed good behavioural performance, with an average error rate of 18.2% (*SD* = 17.5%) on the inhibition task. Error rate was significantly correlated with age in months ($r(87) = -.594$, $p < .001$). Thus, the error rate in the inhibition task declined with age.

For the analysis of the fNIRS data from the BAT task, we compared the HbO_2 and HHb amplitude changes in Mixed blocks to Go blocks. Significant changes in HbO_2 amplitude surviving False Discovery correction for multiple testing were found in a channel in left Broca's area ($t(62) = 3.47$, $p = .001$), a channel in the left DLPFC ($t(52) = 3.30$, $p = .002$;

Figure 2) and a channel in right Broca's area ($t(41) = 3.00$, $p = .004$; Figure 3). In addition, there was a significant change in HHb amplitude found in a channel in the right frontopolar area ($t(42) = 3.39$, $p = .002$), again corrected for multiple comparisons. No other significant effects were found in HHb after correction for multiple testing. These results suggest that our current mobile fNIRS setup is sufficiently sensitive to capture brain activation patterns associated with executive functions in standard computer-based tasks.

Planning task: There was a significant increase in activation in HbO_2 in the right DLPFC prior to branch points compared to prior to within-subgoal steps ($t(37) = 2.99$, $p = .005$, Figure 4). However, this channel did not remain significant when controlling for multiple testing using the False Discovery procedure (Benjamini & Hochberg, 1995). There were no significant differences for the contrast after the start of within-subgoals vs. after the start of branch points.

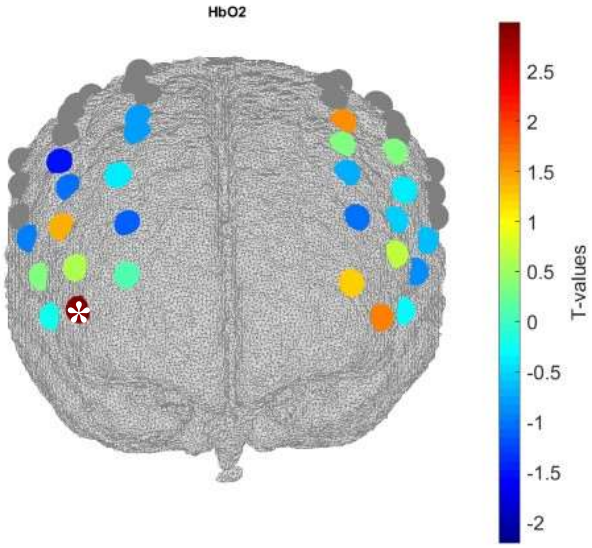

Figure 4: The significant contrasts (with *) in preschoolers between branch points and within subgoal steps prior to the start of the action for HbO_2. As in Figure 3, the left side of the image corresponds to the right side of the brain.

Discussion

In the current manuscript, we aimed to (1) validate our set-up of assessing brain activation patterns of executive functions using a standardised inhibition task, (2) assess the feasibility of investigating the neural correlates of *cognition in the wild* in preschoolers, and (3) to investigate the involvement of PFC in naturalistic action planning in preschoolers.

Regarding our first aim, we demonstrated that there were significant activations in left Broca's, left DLPFC and right Broca's areas showing increases in brain activation in Mixed blocks compared to Go blocks. This is in agreement with previous studies in children that found the involvement of left and right DLPFC during go/no-go tasks (Wu et al., 2023; Zhou et al., 2022). It was suggested that right DLPFC might be related to implementation of control, while left DLPFC might be related to conflict monitoring (Zhou et al., 2022).

We also found increased brain activation in right DLPFC at branch points when the next subgoal had to be planned in our planning task. However, this did not survive correction for multiple comparisons. At branch points, children have to recall and plan the next subgoal, as well as suppress any actions that are not necessary for the next subgoal, such as playing with other Duplo blocks. The DLPFC has already been suggested as being essential in action planning, especially in action sequences (Kaller et al., 2011; Tanji et al., 2007), and in monkeys, DLPFC activation reflects forthcoming movements in multistep actions (Mushiake et al., 2006). Importantly, patients with lesions in right DLPFC show planning impairments (Burgess et al., 2000). All of this and our current results suggest that the DLPFC is involved in action planning as early as preschool years.

Both in our inhibition task as well as our planning task, we found common activations in right DLPFC. Thus, it might be that response inhibition is particularly important at branch points, as a dominant response of executing the previous subgoal action or playing with distractor objects may have to be inhibited. Furthermore, it may also be that both processes involve a commonality such as implementation of control (Zhou et al., 2022), which has been suggested to reflect activation in right DLPFC.

Most of the effects reported in our study were only significant in HbO_2 and not in HHb. This is common occurrence within studies using fNIRS, as HbO_2 is the signal with larger contrast and higher signal-to-noise ratio compared to HHb, which often requires a larger sample size for detection (Hakim et al., 2022).

On a more general level, this study demonstrates the feasibility of using wearable fNIRS with freely moving preschoolers to investigate the development of planning and executive functions in naturalistic settings. We used a mobile and wireless fNIRS system in combination with an optical motion capture system to investigate brain activation patterns during free action planning in young children. While we found some significant brain activation associated with increased planning at *branch points* when the switch from one subgoal to another had to be made (Ruh et al., 2010), none survived correction for multiple testing. Thus, this study suggests that it is feasible to use of wireless fNIRS to investigate brain activation patterns of cognition in the wild in toddlers, although it is still more challenging than investigating brain activation patterns in standardized tasks. The analyses also demonstrated larger drop-out rates for the freely moving naturalistic planning task (45.1% included on average) compared the standardised computerised inhibition task (56.7% included on average). At the same time, some limitations need to be addressed. Below, we provide some recommendations that can improve the overall quality of fNIRS data recorded in such contexts.

First, we would suggest using a tight-fitting cap. Initially, we used a slightly larger cap size (54 cm) to maximize participants' comfort. However, this made the cap fit too loose, with frequent optical decoupling as the children moved. Later, we replaced it with a 52 cm cap, which was sufficient to cover our whole sample as we did not find much variability in head size. Data quality improved significantly (from 35.7% of participants included to 45.1% of the participants included, on average for all the channels).

Second, statistical power can be improved by increasing the number of trials that are occurring naturally in the target behaviour. It can be difficult to design naturalistic tasks with a block-design structure, as real-world demands do not follow such a controlled design. Naturalistic tasks are more likely to be event-related designs, which are known to be noisier than block designs and require a larger number of events. This can be difficult to implement in real-world-like experiments (Pinti et al., 2023). To overcome these issues, in the current study, we tried to combine two tasks with a similar hierarchical goal structure to increase the number of branch points and within subgoal trials: building a house and building a spaceship. We made this decision because it was difficult to increase the length of the study to increase the number of trials. However, with a different but related task that is comparable in behaviour, we were able to increase the number of trials without increasing the drop-out rate too much while keeping the children engaged. We only had to exclude 2 participants that had no data for the second data planning task when both tasks were assessed.

Third, the combination of a wireless and wearable fNIRS device with 3D optical motion capture should be considered. While the video recorded from the optical motion capture system allowed us to reconstruct the timeline of events of interest, the optical motion capture system used in this study also uses near-infrared light in the same wavelength range of fNIRS systems. However, the use of, for example, video-based or sensor-based motion tracking might prevent this potential problem of interference, and we would recommend this option for future studies.

Fourth, despite the fact that fNIRS is relatively resilient to motion artefacts (e.g., Lloyd-Fox et al., 2010; Mehnert et al., 2013; Moriguchi & Hiraki, 2013; Pinti et al., 2020), movement in the planning task could have resulted in a large number of noisy channels. However, in this instance, motion artefact correction techniques provide opportunities to improve data quality. Indeed, poor data quality is a well-known challenge in studies using naturalistic settings and tasks with unrestrained movement in adults. One possible corrective would be the use of an orientation sensor that can assess acceleration in 3D space in combination with gyroscope orientation in 3D space on the fNIRS cap (inertial measuring unit; de Almeida Ivo et al., 2021). This can later be used to model artefacts associated with the movements in GLM-based analyses. It is important that this inertial measuring sensor is located on the cap to capture the head movement. However, currently the weight of the sensor and the lack of space on the child-size cap made this method impossible to use in the current proof-of-principle study.

Fifth, the GLM analysis used a haemodynamic response function (HRF) with time derivatives based on adult profiles. The HRF might change over infancy and toddlerhood, as the vascular system, glia cells and neurons underlying this response undergo maturation during this period (Issard & Gervain, 2018). Future studies could use a standardised task to create individualised HRFs for each participant to use in the corresponding GLM analysis.

Finally, fNIRS data can also be strongly impacted by systemic physiological changes; these are likely to become even stronger when participants are freely moving. Experimental setups should thus include methods to minimise such interference, for example by combining fNIRS with monitors of systemic physiology or adding short separation channels to the array (Yucel et al., 2021). However, additional care should be taken when adding extra hardware on children as the equipment might become too heavy or might interfere with their natural behaviour (Pinti et al., 2023).

These considerations notwithstanding, this study has contributed to our knowledge of the neural substrates of executive functioning in young children and their development. Our results suggest that action planning abilities are mediated by DLPFC as early as preschool age, as in adults. It also seems that switching from one subgoal to the next recruits subregions of PFC that also support response inhibition, such as right DLPFC, indicating that inhibitory control might be involved. Finally, our study confirms the importance of naturalistic and engaging tasks when testing young children; these can be more beneficial than standard computer-based tasks to keep the children engaged, allowing developmental researchers to design longer experiments with a larger number of trials and hence greater statistical power.

In summary, we have reported on a proof-of-concept study demonstrating that. wireless and wearable fNIRS can be used to investigate cognition in the wild (Hutchins, 1995) and its development in freely moving preschoolers. We have provided some suggestions to improve data quality, and large samples are recommended in order to have sufficient power for analysis. Optimizing these paradigms and methods will afford a window into the development of *cognition in the wild*.

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