

# Supporting Information

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## SI Text

**Differences in Brain Activation Between Preswitch and Postswitch Phases.** The paired  $t$  test was used to compare the brain activation between the preswitch and postswitch phases. Interestingly, ch 6, 7, and 9 as well as ch 15, 17, and 18 were activated to a larger extent in adult participants during the preswitch phases than during the postswitch phases, whereas 5-year-old children showed the opposite pattern at ch 7 and 15 (paired  $t$  test,  $P < 0.002$ ). There were no differences in activation between the preswitch and postswitch phases at ch 6 in the 3-year-old children.

**Detailed Discussion on the Oxy-Hb Decrease in 3-Year-Old Children.** We found that children in the perseverate group showed a significant decrease in the oxy-Hb levels at ch 7 and 17 during the preswitch phase and at ch 6, 9, and 15 during the postswitch phase ( $P < 0.002$ ).

In both fMRI and NIRS studies, task-related signal decrease is yet to be fully discussed. In particular, we do not have enough data in the ROI of the present study and in young children. Therefore, we have to speculate on the reason on the basis of the existing literature.

The first possibility is that participants may activate brain regions during control phases to a greater extent than in task phases (1). In the current study, during the control phase, children were asked to sort blank cards into an extra tray. This task may be relatively easy for children; therefore, children may have been involved in other mental activities at the same time. During the task phases, the degree of the activation at ch 6 may have been less than the activation during the control phases. However, this possibility may be weakened, given that 3-year-olds in the pass group significantly activated ch 6 during the task phases compared with activation during the control phases.

The second possibility is that the task-related signal decrease in a single region may be attributable to signal increases in other regions, a phenomena referred to as “vascular steal” (1). For activation, some areas may drain blood from the adjacent areas, thus resulting in a decrease in activation in the adjacent areas. In the present study, there is an area (ch 1) that was significantly activated in the children in the perseverate group but not in the children in the pass group. Given that finding, it could be that children in the perseverate group activate other regions during the task phases rather than the inferior prefrontal regions (i.e., ch 6), which may affect their performance in the DCCS tasks.

The third possibility is that demand for attention during a visual stimulus may be responsible for deactivation in the prefrontal regions. Shulman et al. (2) showed that the dorsal and ventral medial prefrontal region was consistently deactivated during 9 goal-directed tasks that used visual stimuli, such as visual search tasks. Similar deactivations in dorsal prefrontal areas were observed in our previous NIRS studies for both children and adults (3, 4). Given the facts, it is likely that children in the perseverate group may have paid attention to the visual features of the cards (i.e., “red color,” “cup”). In fact, in the control phase, there were no visual features (blank cards). This speculation may be consistent with our interpretations for the results; that is, sustained activations in the inferior prefrontal areas might be crucial for successful cognitive shifting in young children. Our interpretation was that inferior prefrontal regions should be “prepared” during the preswitch phase for successful cognitive shifting during the postswitch phase. Specifically, we suggested that children may represent the task structure or rules

(i.e., color, shape) during the preswitch phases and switch the rules during postswitch phases. Children in the perseverate group may have paid attention to the visual feature of the stimuli, as a result of which the children did not prepare the inferior prefrontal regions (i.e., representing the task structure or rules) on the preswitch phase. In the current study, we cannot exclude these possibilities yet.

**Brain Activation of 3-Year-Old Children in the Regions Outside the ROI.** We examined the patterns of brain activation of 3-year-olds in the regions outside the ROI during cognitive shifting tasks to assess whether the brain activation during the DCCS tasks was region specific. We assumed that the brain regions situated most distant from the target regions can be used as control regions. Thus, we defined ch 1 and 2 and ch 11 and 13 as control regions. We found that neither 3-year-olds in the pass group nor those in the perseverate group exhibited significant activation at ch 2 or at ch 11 and 13. In addition, children in the perseverate group exhibited significant activation at ch 1, whereas those in the pass group did not. The results may suggest that the target regions may be selectively activated during a cognitive shifting task, at least within the regions examined in the present study

**Reason Why We Did Not Use the Same Procedure in Adults and Children.** We used the rest phase as a baseline condition for adults and the control phase as a baseline condition for children. We did this because rest phases are generally used as a baseline condition in NIRS studies; the method was applied to adult participants for replicating the findings of previous cognitive shifting studies (5).

However, we were unable to use the procedure for younger children, because it is difficult for young children to “rest.” In the rest phases, participants are instructed to sit still or to gaze at a particular static stimulus. However, even when instructed to do so, young children tend to move. These movements can affect the measurement of brain activation as measured by NIRS systems. NIRS is not as sensitive to motion artifacts as other methods, such as fMRI, electroencephalography, and magnetoencephalography. Nevertheless, quick head motions can be detected as sharp changes in hemoglobin signals in NIRS systems. Moreover, in our previous study, school-aged children were given a rest phase, during which they were instructed to gaze quietly at a cross (4). However, 7 of 20 children had to be excluded from the analyses because of the motion artifact. Because even school-aged children were unable to conform to the requirements of the rest phase, it is likely that preschool children will also be unable to do so and may create more motion artifacts. Thus, we used control phases as a baseline in children. In the control phase, children were asked to sort the blank cards, by which we assumed that the children would exhibit lesser “quick head motions.” We found that only one 5-year-old child and two 3-year-old children were rejected. Additionally,  $\approx 9\%$  of the data for 5-year-olds and 5% for 3-year-olds were excluded from the analyses (see *Experimental Procedures*). The results indicated that our procedure may be successful.

**Spatial Resolution in NIRS Systems.** Spatial resolution in NIRS systems can be characterized in terms of lateral (width) and depth resolution, both of which are dependent on the placement of emitters and detectors (Fig. 1B).

First, we describe the lateral spatial resolution. In NIRS systems, the near-infrared light is injected into the head from an

emitter and is scattered by the tissues of the brain; the resultant beam is detected by a detector distant from an emitter. One pair of an emitter and a detector creates a single channel, which is often defined as the midpoint between an emitter and a detector (6). The lateral spatial resolution corresponds to the distance between channels. The emitters and detectors were placed within a 2-cm distance. Accordingly, the distance between channels (i.e., lateral spatial resolution) was about 1.4 cm. A recent study suggested that the area of the brain surface that contributes to the NIRS measurement (e.g., oxy-Hb) can be approximately as wide as the emitter-detector spacing and that it extends 1 cm laterally when the distance between optodes is 4 cm (7). This implies that each channel has some overlapping areas. Thus, in the present study, we defined ch 6, 7, and 9 and ch 15, 17, and 18 as right and left inferior prefrontal regions, respectively. Overall, the lateral spatial resolution in NIRS systems is inferior to the resolution in fMRI.

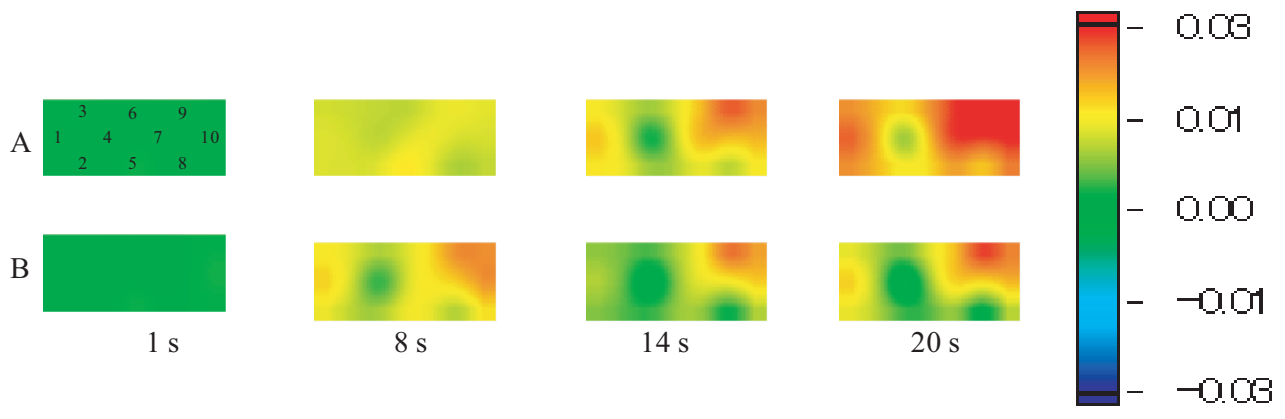
Recently, a simultaneous measurement was conducted to assess the validity of the spatial resolution in NIRS systems. Research using PET and NIRS suggested that the same brain areas may be seen as activated or deactivated in adults (8, 9). For example, Hoshi et al. (9) showed that the level of oxy-Hb measured by NIRS decreased in the frontal area, in which regional cerebral blood flow, as measured by PET, decreased during mental arithmetic tasks. Additionally, fMRI studies with NIRS systems have been conducted (10, 11). Strangman et al. (10) simultaneously measured a motor task by using fMRI and NIRS and found that the blood oxygen level-dependent signal

measured by fMRI showed significant correlations with the oxy-Hb, deoxyhemoglobin, and total hemoglobin measured by NIRS.

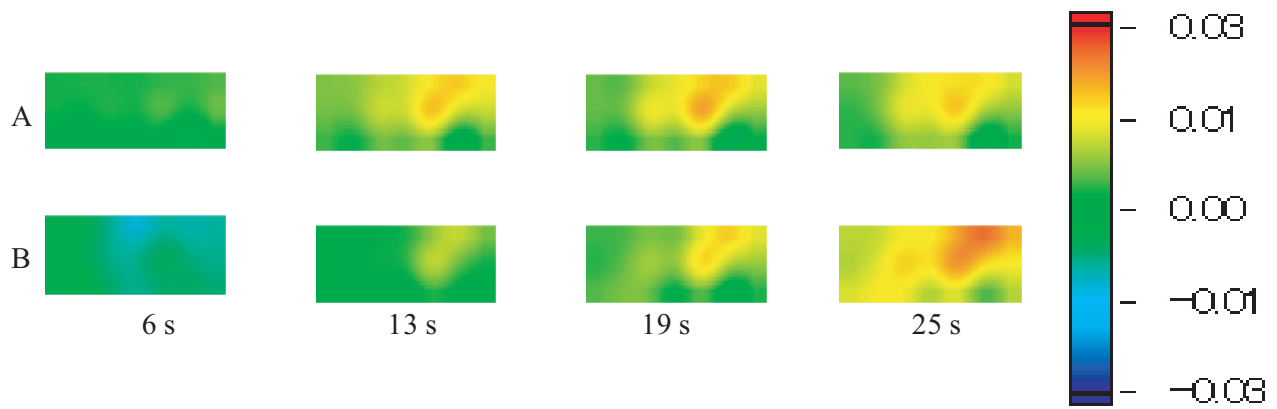
Second, the depth spatial resolution should be considered. NIRS systems examine brain activation in the upper areas of the cerebral cortex. For example, a theoretical study in adults has shown that the measurement area is confined to an upper area of the cortical gray matter if the emitter and detector are separated by a distance of 3 cm (7). This is because of the fact that the near-infrared light is predominantly absorbed by the brain tissue hemoglobin at  $\approx 10\text{--}30$  mm below the scalp; the depth may vary depending on the NIRS system used (12, 13). Recent simultaneous measurement studies have shown that the best correlation between the NIRS signal and parameters in other imaging method, such as PET (8) and fMRI (14), was at a depth of  $\approx 1\text{--}1.5$  cm from the scalp.

There is little evidence regarding the issue in young children. In the present study, we placed emitters and detectors at a 2-cm distance from each other, which is consistent with the conditions used in previous studies on infants (6, 15). A 2.5-cm distance separating the emitter and detector provides a penetration depth of 1.25 cm in adults (12). The gray matter is measured even when distances between optodes is 2 to 2.5 cm, as proved in a previously conducted study on adults (16). In addition, it has been suggested that near-infrared light travels to a greater depth in infants' brains than in adults' brains because of the differences in scalp thickness (17). Given these facts, it is highly likely that our NIRS system is effective for measuring activation in different parts of the brain in young children.

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**Fig. S1.** Dynamic topogram of the changes in oxy-Hb in the right inferior prefrontal cortex of an adult during the DCCS task. Averaged data during the task phase for a typical subject are shown at 1, 8, 14, and 20 s after the task onset (0 s). (A) The preswitch phase. (B) The postswitch phase.



**Fig. S2.** Dynamic topogram of changes in oxy-Hb in the right inferior prefrontal cortex of a 5-year-old child during the DCCS task. Averaged data during the task phase for a typical subject are shown at 6, 13, 19, and 25 s after the task onset (0 s). (A) The preswitch phase. (B) The postswitch phase.

**Table S1. The number of children who exhibited significant oxy-Hb change in the right inferior prefrontal cortex during the preswitch and postswitch phases**

	5-year-old children	3-year-old children (pass)	3-year-old children (perseverate)
Both phases	7	6	0
Preswitch only	2	0	2
Postswitch only	2	2	2
Neither phase	0	1	2