『江戸川大学紀要』第 34 号（2024 年 3 月） pp.341-350

Does the Stroop task in young children require the prefrontal activation?: a NIRS study

Mikako Ishibashi*, Yusuke Moriguchi**

Abstract

We examined whether children recruit the prefrontal regions during the Shape Stroop task, which is regarded an age-appropriate assessment of inhibitory control. This task consisted of an identification session, where children were asked to point to a small- and big-sized stimuli, and a Stroop session, where children were asked to point to the small-sized stimuli with inhibition of pointing to the big-sized stimuli. We found that (1) children showed marginally worse performances during the Stroop phase than the identification phase at the behavioral level (n=20, M age=35.05 months, SD=5.58), and (2) there was no significant differences in prefrontal region activation between the identification and the Stroop phases at the neural level (n=17, M age=34.53 months, SD=5.84). Our results suggested that the measurements obtained in the Shape Stroop task can vary from those obtained in the Stroop task.

Key words: Shape Stroop task, near-infrared spectroscopy, prefrontal cortex, inhibitory control, young children

Introduction

Executive function (EF) is a higher-order cognitive control process including cognitive flexibility, inhibition, and working memory (Diamond, 2013) and representing a latent psychological construct (Holmboe, Bonneville-Roussy, Csibra, & Johnson, 2018). EF have role for regulation and monitoring higher order cognitive resources, and employed as process that planning, problem solving, and coordinate other cognitive process (Huizinga, Dolan, & van der Molan, 2006; Miyake et al., 2000; Pennington & Ozonoff, 1996; van der Sluis, de Jong, & van der Leij, 2007) although Conceptualization and measurement of EF has varied across studies(Garon, Bryson, & Smith, 2008; Kimberg, D'Esposito, & Farah, 1997). The development of EF is closely related to the functional development of the prefrontal cortex (PFC). Subserved by PFC, EF has emerged from as early as the latter half of the first year of life and dramatically developed from preschool age (2.5–5.5 years) (Bunge & Zelazo, 2006; Fiske & Holmboe, 2019; Diamond, 2002; Holmboe et al., 2010; Moriguchi & Hiraki, 2011). Better EF score predicts intellectual and social competencies, such as school

As of November 30, 2023
* Department of Psychology and Humanities, Edogawa University
** Graduate School of Letters, Kyoto University

performance (Blair & Razza, 2007) and social understanding (Riggs et al., 2006). EF has separable domains, such as (1) response inhibition which is the ability to inhibit the prepotent responses, (2) shifting which is the ability to switch flexibility rules or goals, (3) updating which is monitoring and replacing the information in working memory (Best & Miller, 2010; Diamond, 2002). These domains are statistically different but covaried strongly, referring to as the unity and diversity model (Miyake et al., 2000). Developmental differences in EF have been observed in adults and school-aged children (Miyake et al., 2000; Miyake & Friedman, 2012). For preschool-aged children, the major components of EF remain controversial (Garon, Bryson, & Smith, 2008) because the structure of EF has been considered as unity at a young age (Brydges et al., 2014; Wiebe et al. 2011). It has been suggested that general EF ability rapidly develops through childhood and specific EF abilities have not developed enough to make distinguishable until 9 years of age (Garon et al., 2008).

Although the components of EF in preschool-aged children are still a matter of debate, extensive behavioral research has revealed that inhibitory control, which is the core aspects of EF, dramatically developed from an earlier stage of childhood (Garon et al., 2008; Holmboe et al., 2018). Inhibitory control is the ability to suppress prepotent responses which are not relevant to pursue goal or task (Diamond, 2002). One of the most widely used measurements of children's inhibitory control is the performance of the Day/night task, which is referred to as a Stroop task. Research has shown that the performances of this task improved from 3 to 7 years of age (Gerstadt, Hong, & Diamond, 1994). Moreover, a study has revealed that the components of inhibitory control around 3 years of age have been identified as a two-factors model, which is response inhibition and interference suppression (Gandolfi et al., 2014). Recently, an age-appropriate inhibitory control task has been developed to evaluate the EF skills in early childhood (Holmboe et al., 2008; Johansson et al., 2015; Kovács & Mehler, 2009). For example, simpler Stroop task, namely, Shape Stroop task, has been developed for preschool-aged children (Carlson, Mandell, & Williams, 2004; Garon et al., 2008). In this task, small-sized fruit stimuli embedded in big-sized fruit stimuli were presented. Shape Stroop task is to assess focusing on a subdominant perceptual feature rather than on a dominant perceptual feature (Kochanska, Murray, & Harlan, 2000). Shape Stroop task was loaded on the Conflict-EF which is the ability to respond appropriately facing the conflicting response situation (Bernier et al., 2010). Mostly Stroop task required working memory and set shifting, tapping cognitive flexibility and attention in EF (Carlson, 2005). Shape Stroop task is a battery of EC tasks, and also taps into cool aspect of self-regulation task, which does not tap into emotional elements or immediate rewards under "hot/cool framework (Lin, Liew & Perez, 2019).

In regards with children' brain development, density of neuronal layer of the PFC begin to decrease between two and seven, and synaptic density in the PFC reaches the highest value at 3.5 years of age with decreasing through adolescence (Huttenlocher & Dabholkar, 1997). A study revealed that the performance of the Shape Stroop task has improved after two years of age (Kochanska, Murray, & Harlan, 2000). Children should point to the target stimuli while they inhibit to point non-target stimuli, which is the dominant response in this situation.

Recently, using near-infrared spectroscopy (NIRS), extensive studies have examined the neural basis of inhibitory control in children, showing that PFC is functionally activated when engaging in inhibitory control tasks (Chevalier et al., 2019; Koch, Miguel, Smiley-Oyen, 2018; Moriguchi & Hiraki,

2011). Specifically, a study showed that significant activation in the left lateral prefrontal regions were seen in both children at seven years of age and adults during the Stroop task, although the hemodynamic response occurred later in children than in adults (Schroeter et al., 2004). Moreover, with the improvement of the Stroop performance, activation in the dorsolateral prefrontal cortex significantly increased with age, indicating that significant brain activation can be elicited by resolution of Stroop interference in the Stroop task (Schroeter et al., 2004).

However, the neural basis of the performance of the EF task in preschool-aged children especially with 2–3 years of age has not been sufficiently studied. The behavioral performance of the Shape Stroop task has been adapted at aged two, but no neural activation has been provided.

In this study, we examined both behavioral and neural activation to examine the validity of the Shape Stroop task in children aged 2–and 3–year–old. The NIRS technique was used to monitor cerebral hemodynamics by measuring changes in the attenuation of near-infrared light passing through the tissue. NIRS is a non-invasive technique and does not require affixing the body and is widely accepted for examining the neural correlates of the EF task in children (Huppert et al., 2009; Masataka, Perlovsky, & Hiraki, 2015; Moriguchi & Hiraki, 2011; 2013). In this study, two- and three-year-old children were instructed to perform the Shape Stroop task. Children required to inhibit pointing to the prepotent response. We also measured the temporal changes in the local concentrations of oxyhemoglobin (oxy-Hb), deoxyhemoglobin (deoxy-Hb), and total hemoglobin during the Shape Stroop task by using NIRS. Given that the significant activation in the left lateral prefrontal regions was seen in children who engaged in the Stroop task (Schroeter et al., 2004), we hypothesized that the significant activation in the prefrontal region can also be seen in the Shape Stroop phase than in the identification phase.

Methods

Participants

Thirty-three typically developing children [*M* age=33.42 months, *SD*=5.62, 18 girls, *range*=26.00 – 42.00 months] participated. All but one participant was right-handed. Larger sample size exists with older children adapting the same NIRS equipment of our study (e.g., Moriguchi et al., 2015), however, to the best of our knowledge, they have not been examined in young children. We referred to the sample size by the similar age range examining on young children's executive function using NIRS (*n*=28, *M* age=3.5 years; Buss et al., 2014; *n*=26, *M* age 2.5 years; Kerr-German et al., 2022). 13 out of 33 children were excluded; several were because of fussiness, refusal to wear the NIRS probe, and refusal to engage in the task (*n*=10). Moreover, three children were excluded because they had already selected the card before the experimenter's instructions. Thus, twenty children's data were used in the behavioral analysis (*M* age=35.05 months, *SD*=5.58, 11 girls, *range*=26.00 – 42.00 months).

In the NIRS analysis, of the 20 children' data, we further excluded an additional three participant data; two children engaged in the task but failed to complete the session and one child was left-handed. Thus, seventeen children's data were used in the NIRS analysis (*M* age=34.53 months, *SD*=5.84, 11 girls, *range*=28.00 – 41.00 months). The purpose of the study was explained

verbally and in a written document for the children's parents. Under the Declaration of Helsinki, informed consent for the children to participate from the parents was obtained. This study was approved by the Ethics Committee of Kyoto University.

Shape Stroop task

All procedures were conducted in a playroom at Kyoto University. During the experiment, the children's parents sat next to the children, and they were allowed to interact; however, their parents were requested not to help their child. The children's behaviors during the session were recorded by a video camera placed in the room.

The stimuli and procedure used in this study followed the original research (Kochanska et al., 2000). Three colored printed images of fruits (apple, banana, and orange) were used. Each stimulus consisted of a big size (20 x 28 cm) and a small size (7 x 10 cm).

Primarily, with presenting the printed images over the table, the experimenter instructed how to identify each size of fruits ("This is a big apple, and this is a small apple"). After the experimenter confirmed that the child understood to identify them, the measurement of NIRS was initiated. The procedure consisted of the identification phase and Stroop phase. Each trial consisted of a rest (15 s), identification session (15 s), a rest (15 s), and Stroop session (15 s). The study consisted of six trials. During the rest sessions, no stimuli were presented, and the child was instructed to sit still. During the identification session, 3 big- and 3 small-sized stimuli were presented, and the child was required to point to one of the big- and small-sized stimuli ("Which is the big banana?" "Which is the small banana?"). In line with the procedure of the Shape Stroop task (Crivello et al., 2016), if the child did not answer correctly or did not show any response, the experimenter encouraged the child to point the stimuli and gave the correct answer if necessary.

Children were asked two questions for big and small stimuli, respectively. The score was given only when the child pointed to the correct stimuli at his/her first attempt before the experimenters' prompt. The range of the correct responses was from 0 to 12 for a total of six trials. The dependent measure was the percentage of the number of correct responses.

In the Stroop session, three big–sized stimuli were presented with small sized–stimuli. That is, the small fruit stimulus was placed on the big fruit stimulus or on different kinds of fruit stimuli. For example, the small banana stimulus was placed on the big apple stimulus. Then, the experimenter asked the child to point to the small fruit ("Show me the small banana"). In this task, the child needed to inhibit the prepotent response, which was pointing to the big fruits. At this time, no feedback was provided. Children were given only one question for each trial. The number of correct responses to pointing to the small fruits were counted. The range of the score was from 0 to 6 for total trials. The dependent measure was the percentage of the number of correct responses. The order of the presentation of the stimuli was randomized across participants. Children required to point to the small stimuli and must inhibit pointing to the big stimuli, which was the prepotent response in this situation.

In addition to correct responses, the reaction time (RT) was also measured. RT was measured from the time the experimenter's instruction until the child pointed to the correct stimuli. We only recorded observations if the child pointed to the correct stimuli at his/her first attempt before the

experimenters' prompt.

NIRS recordings

NIRS measurement (OEG-SpO2; Spectratech Inc., Tokyo, Japan) was performed during the Stroop tasks. NIRS probes that had 16 channels with 12 optodes were placed on the children's prefrontal regions. The temporal changes in the local concentrations of oxyhemoglobin (oxy-Hb), deoxyhemoglobin (deoxy-Hb), and total hemoglobin were measured. Multichannel NIRS unit consisted of 12 optodes and 16 channels with the two-wavelength region of 770 nm and 840 nm. The distance of optodes between emitters and detectors was 3 cm apart and the temporal resolution at each channel was approximately 81 ms, following the previous study (Moriguchi & Shinohara, 2019), which were adapted to the same NIRS equipment with our study. In line with the International 10/20 system, the region of interest was located near F3/4 (channel 2, 4, 5, and channel 11, 13, 14) and F7/8 (channel 3, 4, 6 and channel 12, 13, 15), which corresponded to Brodmann areas 9/46 and 45/47. As NIRS is relatively low, spatial resolution, channels 2, 4, 5, and 11, 13, 14 were defined as roughly the right and left dorsolateral prefrontal regions (DLPFC). Additionally, channels 3, 4, 6, and 12, 13, 15 roughly corresponded to the right and left ventrolateral prefrontal regions (VLPFC) (See figure 1).

NIRS data were analyzed using OEG-16 software V3.0 (Spectratech Inc., Tokyo, Japan) and Python 2.7.13 (https://www.python.org/). The data rejection process was followed by the previous study (Moriguchi et al., 2015), which were adapted to the same NIRS equipment with our study. First, motion artifacts using video recording were checked and revealed no data rejection with only minor motions, which was 1% of data. Then, we subsequently pre-processed the individual data for the NIRS signal of each channel were filtered with the moving average and the base line correction was performed with a linear fitting. The NIRS signal was separated into functional signals (i.e., brain activation) and systematic signals (i.e., physiological noise), and only functional signals (brain

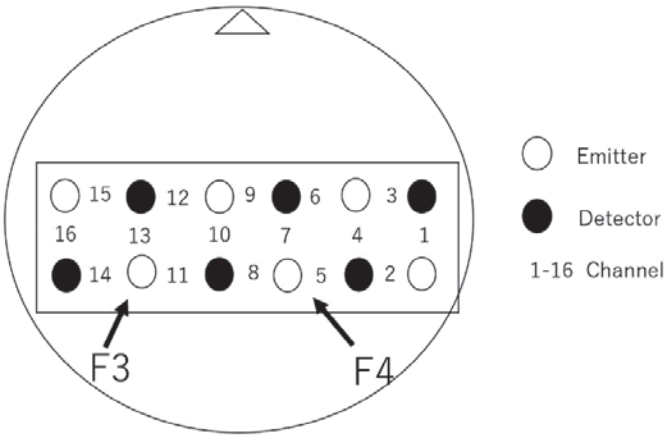

Figure1. The NIRS probe was attached to the prefrontal area. One emitter optode and one detector optode was consisted of each channel. The region was located near F3/4 (channel 2, 4, 5, and channel 11, 13, 14) and F7/8 (channel 3, 4, 6 and channel 12, 13, 15), respectively.

activation) was used for the analyses. We then excluded three standard deviations (± 3SD) away from their mean. We adapted the previous study examining in young children' prefrontal region (Kajiume et al., 2013; Moriguchi, & Shinohara, 2018; Tsujii et al., 2009; Yanaoka, Moriguchi, & Saito, 2020).

The oxy-Hb signal was found to be most sensitive to changes in cerebral blood flow, which was a strong correlation with the blood oxygen level–dependent (BOLD) signal in the prefrontal regions (Strangman et al., 2002).

Analysis

We first conducted behavioral analysis to see the performance of the identification phase and Stroop phase. Then, to examine whether changes in oxy-Hb of the prefrontal regions differed between identification and Stroop task we conducted three-way ANOVA with session (Identification vs. Stroop), phase (rest vs. test), and region (right DLPFC vs. left DLPFC vs. right VLPFC vs. left VLPFC) as within factors. As the dependent variables was the difference in the average changes in oxy-Hb during the rest and task phases.

Results

Behavioral results

The percentage of the number of correct responses of the identification phase was 80.00% (*SD*=25.28; range=25.00% - 100%), and the Stroop phase was 71.67% (*SD*=32.04; range=0% - 100%). Paired *t*-test showed that there was a marginal difference between the percentage of the number of correct responses for the identification and the Stroop phase ($t(19)=1.74$, $p=.10$, $r=0.37$).

In line with the previous study (Macdonald et al., 2014), our study compared the baseline (i.e., identification phase) with Stroop phase. The average of the RT for identification phase was 1377 ms (*SD*=671.41; range=660–2833 ms) and the average of the RT for the Stroop phase was 1731 ms (*SD*=1062.33; range=715–4738 ms). A paired t-test showed marginal differences between the average of the RT for the identification phase and for the Stroop phase ($t(19)=-1.73$, $p=.10$, $r=0.37$).

NIRS results

To examine whether the activation of the prefrontal regions differed in Identification and Stroop session, the mean changes in oxy-Hb in the prefrontal regions during the Stroop task were measured. A three-way ANOVA with session (Identification vs. Stroop), phase (rest vs. test), and region (right DLPFC vs. left DLPFC vs. right VLPFC vs. left VLPFC) as within factors were performed. No significant main effect of the session [$F(1, 16)=0.19$, $p=.67$, $\eta^2=0.01$], the phase [$F(1, 16)=0.30$, $p=.59$, $\eta^2=0.02$], and the region [$F(3, 48)=0.10$, $p=.96$, $\eta^2=0.01$]. However, interactions between the session and region were marginally significant [$F(3, 48)=2.39$, $p=.08$, $\eta^2=0.13$]. No other significant interactions were found (See Figure 2).

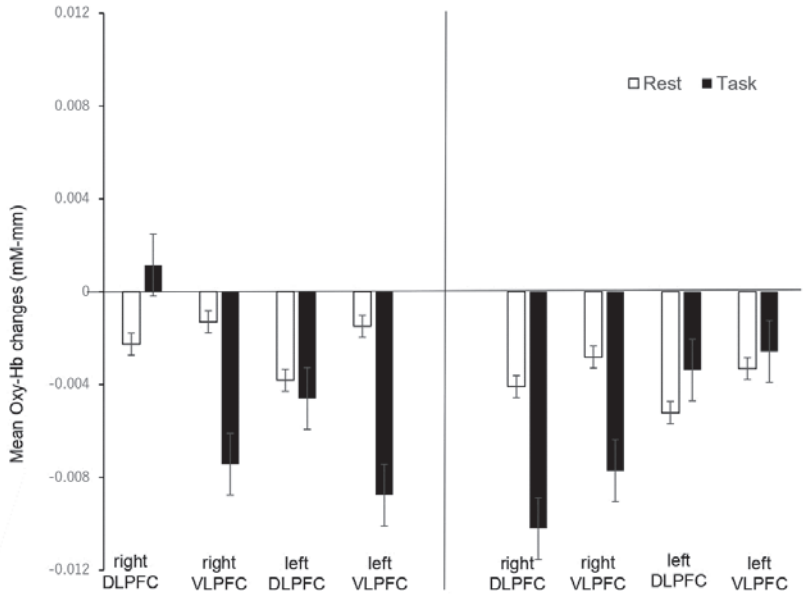

Figure 2 Mean oxy-Hb changes within the lateral prefrontal areas (Right DLPFC [channels 2, 4, 5], Left DLPFC [channels 11, 13, 14]) and the inferior prefrontal areas (Right VLPFC[channels 3,4,6], Left VLPFC[channels 12,13,15]) during the rest and task phases of the Identification session and Stroop session in the Shape Stroop task. Error bars represent standard error

Discussion

In this study, we examined whether 2–and 3–year–old children engaged in the lateral prefrontal regions during the Shape Stroop task. We hypothesized that the significant activation in the prefrontal region can be seen in the Shape Stroop phase than in the identification phase. To this end, we analyzed the percentage of the number of correct responses, and the reaction time to the correct responses as the behavioral measures. Also, the temporal changes in the local concentrations of oxyhemoglobin (oxy-Hb) during the Shape Stroop task by using NIRS were analyzed. For the behavioral performance, marginal differences in the percentage of correct responses and the reaction time to the correct response between the identification phase and Stroop phases were found. For the brain measures, although interactions between the session and region were marginally significant, no significant differences in the session (Identification vs. Stroop), phase (rest vs. test), and region (right DLPFC vs. left DLPFC vs. right VLPFC vs. left VLPFC) were found.

As the performance of the Stroop session in our participants was worse than that of the identification session, the children's inhibitory control skill can be needed in the session of the Stroop. A past study revealed that the performance in the baseline (i.e., identification phase) in children aged 5 to 8 was significantly better than in the Stroop (Macdonald et al., 2014). Such findings can partially support the results. However, these marginal findings need to be interpreted

cautiously.

In contrast our hypothesis, we found no significant activations in the lateral prefrontal regions during the task phases compared to rest phases in both identification and Stroop sessions. The effect size was small in our data, which states that the null results were not due to the sample size. Thus, our results showed that no significant differences in prefrontal cortical activation during the Shape Stroop task were observed, suggesting that the engaging in the Shape Stroop task may not be related to the activation of the prefrontal region in children. Considering the evidence that significant activation in the left lateral prefrontal regions was seen in children who engaged in the Stroop task (Schroeter et al., 2004) suggesting that the measurements obtained in the Shape Stroop task can vary from those obtained in the Stroop task.

Indeed, several reports have been argued whether the age-appropriate task can reflect EF skill in children. Although the age-appropriate EF task has been developed (Diamond, 1985; Holmboe et al., 2008; Johansson et al., 2015; Kovács & Mehler, 2009; Wass, Porayska-Pomsta, & Johnson, 2011), the validity of the task has been doubted (Holmboe et al., 2018) as the observed task performance of preschool children is yet to be investigated sufficiently (Wiebe et al., 2011).

Thus, from our results, the Shape Stroop task may not qualitatively the same task in the Stroop task (e.g., Schroeter et al., 2004). The validity of the Shape Stroop task needs to be further evaluated to explore and combine multiple EF-related tasks. Although the regions of interest are determined by the 10/20 system which corresponds to the Broadman areas (Okamoto et al., 2004), we should take into account the methodological limitation about the estimation of the cortical localization. In addition, children' language abilities needed to be considered especially with this age range. In addition, we should compare the performance in the frontal robe with more older ages in order to justify the validation of our results.

In conclusion, the performance of the Shape Stroop task may not be associated with the activation of the lateral prefrontal regions, which suggested that the Shape Stroop task can vary from those obtained in the Stroop. Further studies with larger sample sizes and multiple tasks need to be done to validate our findings.

References

1. Bernier, A., Carlson, S. M., & Whipple, N. (2010). From external regulation to self - regulation: Early parenting precursors of young children's executive functioning. *Child Development, 81*(1), 326–339.
2. Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development, 81*(6), 1641–1660.
3. Blair, C., & Razza, R. P. (2007). Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development, 78*(2), 647–663.
4. Brydges, C. R., Fox, A. M., Reid, C. L., & Anderson, M. (2014). The differentiation of executive functions in middle and late childhood: A longitudinal latent-variable analysis. Intelligence, 47, 34–43. doi: org/10.1016/j.intell.2014.08.010
5. Buss, A. T., Fox, N., Boas, D. A., & Spencer, J. P. (2014). Probing the early development of visual working memory capacity with functional near-infrared spectroscopy. *Neuroimage, 85*, 314–325. doi: org/10.1016/j.neuroimage.2013.05.034
6. Bunge, S. A., & Zelazo, P. D. (2006). A brain-based account of the development of rule use in childhood. *Current Directions in Psychological Science, 15*(3), 118–121. doi: org/10.1111/j.0963-7214.2006.00419.x
7. Carlson, S. M., Mandell, D. J., & Williams, L. (2004). Executive function and theory of mind: stability and prediction

from ages 2 to 3. *Developmental Psychology, 40*(6), 1105–1122. doi: org/10.1037/0012-1649.40.6.1105
8. Carlson, S. M. (2005). Developmentally sensitive measures of executive function in preschool children. *Developmental Neuropsychology, 28*(2), 595–616.
9. Chevalier, N., Jackson, J., Roux, A. R., Moriguchi, Y., & Auyeung, B. (2019). Differentiation in prefrontal cortex recruitment during childhood: Evidence from cognitive control demands and social contexts. *Developmental Cognitive Neuroscience, 36,* 100629. doi: org/10.1016/j.dcn.2019.100629
10. Crivello, C., Kuzyk, O., Rodrigues, M., Friend, M., Zesiger, P., & Poulin-Dubois, D. (2016). The effects of bilingual growth on toddlers' executive function. *Journal of Experimental Child Psychology, 141*, 121–132. doi: org/10.1016/j.jecp.2015.08.004
11. Diamond, A. (1985). Development of the ability to use recall to guide action, as indicated by infants' performance on AB. *Child Development*, 868–883. doi.org/10.2307/1130099
12. Diamond, A. (2002). *Principles of Frontal Lobe Function*. Stuss, D. T. & R.T. Knight (Eds.), Oxford Univ. Press, New York, pp. 466–503.
13. Diamond, A. (2013). Executive functions. *Annual Review of Psychology, 64, 13*5–168. doi: org/10.1146/annurev-psych-113011-143750
14. Fiske, A., & Holmboe, K. (2019). Neural substrates of early executive function development. Developmental Review, 52, 42–62. doi: org/10.1016/j.dr.2019.100866
15. Gandolfi, E., Viterbori, P., Traverso, L., & Usai, M. C. (2014). Inhibitory processes in toddlers: a latent-variable approach. *Frontiers in Psychology, 5*, 381. doi: org/10.3389/fpsyg.2014.00381
16. Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: a review using an integrative framework. *Psychological Bulletin, 134*(1), 31–60. doi: org/10.1037/0033-2909.134.1.31
17. Gerstadt, C. L., Hong, Y. J., & Diamond, A. (1994). The relationship between cognition and action: Performance of children 3 1/2–7 years old on a Stroop-like day-night test. Cognition, 53(2), 129–153.
18. Huizinga, M., Dolan, C. V., & Van der Molen, M. W. (2006). Age-related change in executive function: Developmental trends and a latent variable analysis. *Neuropsychologia*, *44*(11), 2017–2036.
19. Holmboe, K., Bonneville‐Roussy, A., Csibra, G., & Johnson, M. H. (2018). Longitudinal development of attention and inhibitory control during the first year of life. *Developmental Science, 21*(6), e12690. doi: org/10.1111/desc.12690
20. Holmboe, K., Fearon, R. P., Csibra, G., Tucker, L. A., & Johnson, M. H. (2008). Freeze-Frame: A new infant inhibition task and its relation to frontal cortex tasks during infancy and early childhood. *Journal of Experimental Child Psychology, 100*(2), 89–114. doi: org/10.1016/j.jecp.2007.09.004
21. Holmboe, K., Nemoda, Z., Fearon, R. M., Csibra, G., Sasvari-Szekely, M., & Johnson, M. H. (2010). Polymorphisms in dopamine system genes are associated with individual differences in attention in infancy. *Developmental Psychology, 46*(2), 404–416. doi: org/10.1037/a0018180
22. Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain. Applied Optics, 48(10), 280–298. doi: 10.1364/ao.48.00d280
23. Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology, 387*(2), 167–178. doi: org/10.1002/(SICI)1096-9861(19971020)387:2<167::AID-CNE1>3.0.CO;2-Z
24. Johansson, M., Marciszko, C., Gredebäck, G., Nyström, P., & Bohlin, G. (2015). Sustained attention in infancy as a longitudinal predictor of self-regulatory functions. *Infant Behavior and Development, 41,* 1–11. doi: org/10.1016/j.infbeh.2015.07.001
25. Kajiume, A., Aoyama-Setoyama, S., Saito-Hori, Y., Ishikawa, N., & Kobayashi, M. (2013). Reduced brain activation during imitation and observation of others in children with pervasive developmental disorder: a pilot study. *Behavioral and Brain Functions, 9*(1), 1–5.
26. Kimberg, D. Y., D'Esposito, M., & Farah, M. J. (1997). Effects of bromocriptine on human subjects depend on working memory capacity. *Neuroreport, 8*(16), 3581–3585.
27. Koch, J. K. L., Miguel, H., & Smiley-Oyen, A. L. (2018). Prefrontal activation during Stroop and Wisconsin card sort tasks in children with developmental coordination disorder: a NIRS study. *Experimental Brain Research, 236*(11), 3053–3064. doi: org/10.1007/s00221-018-5358-4
28. Kochanska, G., Murray, K. T., & Harlan, E. T. (2000). Effortful control in early childhood: continuity and change, antecedents, and implications for social development. Developmental Psychology, 36(2), 220–232. doi: org/10.1037/0012-1649.36.2.220
29. Kovács, Á. M., & Mehler, J. (2009). Cognitive gains in 7-month-old bilingual infants. *Proceedings of the National Academy of Sciences, 106*(16), 6556–6560. doi: org/10.1073/pnas.0811323106
30. Lin, B., Liew, J., & Perez, M. (2019). Measurement of self-regulation in early childhood: Relations between laboratory and performance-based measures of effortful control and executive functioning. *Early Childhood Research Quarterly, 47*, 1–8.

31. Macdonald, J. A., Beauchamp, M. H., Crigan, J. A., & Anderson, P. J. (2014). Age-related differences in inhibitory control in the early school years. *Child Neuropsychology, 20*(5), 509–526. doi: 10.1080/09297049.2013.822060
32. Masataka, N., Perlovsky, L., & Hiraki, K. (2015). Near-infrared spectroscopy (NIRS) in functional research of prefrontal cortex. *Frontiers in Human Neuroscience, 9*, 274. doi: org/10.3389/fnhum.2015.00274
33. Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. Current directions in Psychological Science, 21(1), 8–14. doi: org/10.1177/0963721411429458
34. Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. doi: org/10.1006/cogp.1999.0734
35. Moriguchi, Y., & Hiraki, K. (2011). Longitudinal development of prefrontal function during early childhood. *Developmental Cognitive Neuroscience, 1*(2), 153–162. doi: org/10.1016/j.dcn.2010.12.004
36. Moriguchi, Y., & Hiraki, K. (2013). Prefrontal cortex and executive function in young children: a review of NIRS studies. *Frontiers in Human Neuroscience, 7,* 867. doi: org/10.3389/fnhum.2013.00867
37. Moriguchi, Y., & Shinohara, I. (2019). Socioeconomic disparity in prefrontal development during early childhood. *Scientific Reports, 9*(1), 1–8. doi: org/10.1038/s41598-019-39255-6
38. Moriguchi, Y., Sakata, Y., Ishibashi, M., & Ishikawa, Y. (2015). Teaching others rule-use improves executive function and prefrontal activations in young children. *Frontiers in Psychology, 6*, 894. doi: org/10.3389/fpsyg.2015.00894
39. Okamoto, M., Dan, H., Sakamoto, K., Takeo, K., Shimizu, K., Kohno, S., ... & Dan, I. (2004). Three-dimensional probabilistic anatomical cranio-cerebral correlation via the international 10–20 system oriented for transcranial functional brain mapping. *Neuroimage, 21*(1), 99–111. doi: org/10.1016/j.neuroimage.2003.08.026
40. Pennington, B. F., & Ozonoff, S. (1996). Executive functions and developmental psychopathology. *Journal of child psychology and psychiatry, 37*(1), 51–87.
41. Riggs, N. R., Greenberg, M. T., Kusché, C. A., & Pentz, M. A. (2006). The mediational role of neurocognition in the behavioral outcomes of a social-emotional prevention program in elementary school students: Effects of the PATHS curriculum. *Prevention Science, 7,* 91–102.
42. Schroeter, M. L., Zysset, S., Wahl, M., & von Cramon, D. Y. (2004). Prefrontal activation due to Stroop interference increases during development—an event-related fNIRS study. *Neuroimage, 23*(4), 1317–1325. doi: org/10.1016/j.neuroimage.2004.08.001
43. Strangman, G., Culver, J. P., Thompson, J. H., & Boas, D. A. (2002). A quantitative comparison of simultaneous BOLD fMRI and NIRS recordings during functional brain activation. *Neuroimage, 17*(2), 719–731. doi:10.1006/nimg.2002.1227
44. Tsujii, T., Yamamoto, E., Masuda, S., & Watanabe, S. (2009). Longitudinal study of spatial working memory development in young children. *Neuroreport, 20*(8), 759–763.
45. Van der Sluis, S., De Jong, P. F., & Van der Leij, A. (2007). Executive functioning in children, and its relations with reasoning, reading, and arithmetic. *Intelligence, 35*(5), 427–449.
46. Wass, S., Porayska-Pomsta, K., & Johnson, M. H. (2011). Training attentional control in infancy. *Current Biology, 21*(18), 1543–1547. doi: org/10.1016/j.cub.2011.08.004
47. Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A., Chevalier, N., & Espy, K. A. (2011). The structure of executive function in 3-year-olds. *Journal of Experimental Child Psychology, 108*(3), 436–452. doi: org/10.1016/j.jecp.2010.08.008
48. Yanaoka, K., Moriguchi, Y., & Saito, S. (2020). Cognitive and neural underpinnings of goal maintenance in young children. *Cognition, 203*, 104378.

Acknowledgment

This research was supported by a grant from CODER (CENTER OF DEVELOPMENTAL EDUCATION AND RESEARCH) to the first author and the JSPS KAKENHI Grant Number 18H01083 to the second author. We thank the parents and children who participated in this study. Additionally, we sincerely thank Tomomi Takahashi for her help.