The Neurobehavioral Relationship between Executive Function and Creativity during Early Childhood

Running title

Executive Function & Creativity

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Abstract

Increasing evidence from behavior and neuroimaging research indicates that executive functions (EFs) are related to creativity. However, most of these studies focused on adult and adolescent populations. The relationship between EFs and creativity is unknown when EFs undergo rapid development during early childhood, due to the preschoolers' marginal skills of expressing their ideas, orally or in writing. Using a non-verbal, open-ended test, the present study examined whether creative thinking was related to cognitive flexibility in young children. Preschool children (N = 26) performed the Dimensional Change Card Sort (DCCS) and the Unusual Box Test (UBT), while their brain activation was recorded using functional near-infrared spectroscopy (fNIRS). We did not find any significant correlation between children' s cognitive flexibility and creative thinking. However, fNIRS analyses showed that children's brain activation in the lateral prefrontal regions was significantly greater during the test phases of the UBT. Additionally, children who strongly recruited their ventrolateral prefrontal regions during the post-switch phases of the DCCS recruited the same regions while performing the UBT. Taken together, these findings suggest that children recruit their lateral prefrontal regions when expressing creative thinking, and that such creative thinking could be partially supported by cognitive flexibility in early childhood.

Keywords: creativity, executive functions, cognitive flexibility, functional near-infrared spectroscopy, childhood

1. Introduction

Creativity is commonly defined as the ability to produce both, novel and useful outcomes (Sternberg & Lubart, 1999; Runco & Jaeger, 2012). It allows us to deal with new problems in this rapidly changing world. Creativity is a basic psychological and cognitive process (e.g., Mednick, 1962; Csikszentmihalyi, 1999), which involves a divergent thinking (DT) phase followed by a convergent thinking (CT) phase (Gabora, in press). Compared to the CT phase, in which only one correct solution is required, DT is likely to be viewed as more "creative" because the goal is to generate multiple, often unconventional ideas in response to a challenging problem (for review, Runco, 2010). Underlying the mental efforts in the DT process, executive functions (EFs), a set of general-purpose control processes that regulate one's thoughts and behaviors (e.g., Diamond, 2013; Garon et al., 2008) have been suggested as relevant (e.g., Mednick, 1962; Cassotti et al., 2016). The present study examined the developmental relationship between DT and EF in young children.

EFs involve cognitive processes such as inhibitory control, cognitive flexibility, and updating information in working memory (Miyake & Friedman, 2012). Among these three components, the role of inhibitory control in creativity has been extensively discussed. Early conceptions of creativity assumed creative individuals to be characterized by a lack of inhibition (Martindale, 1999), which allowed for a broader range of information to come into the working memory to generate remote associations related to existing ideas (e.g., Eysenck, 1993, 1995; Guilford, 1967). Regarding this view, empirical evidence indicates that high-scoring groups in DT tests are associated with low levels of latent inhibition (Carson et al., 2003). More recently, Radel et al. (2015) found that performance in a widely used DT test improved when the inhibitory resources were exhausted, suggesting that "disinhibition" facilitates creativity (Radel et al., 2015). Contrastingly, an increasing number of studies have shown a positive contribution of inhibition in creativity. For example, Benedek et al. (2012) found that inhibition assessed by the random motor generation task was positively correlation with various indicators of creativity, including DT. Benedek et al. (2014) provided additional evidence through a latent variable model approach, revealing that creativity was significantly predicted by updating and inhibiting (Benedek et al., 2014). Similarly, a study showed that highly creative individuals were characterized by better inhibition ability on the Stroop task (Edl et al., 2014).

These above-mentioned conflicting results might be due to the different types of inhibition and creativity tasks used. Indeed, it has been proposed that different levels of cognitive inhibition may functionally correlate with different stages of the creativity process. Specifically, low cognitive inhibition seems to be superior in the early stage, providing a broader range of information to be combined and used as building blocks for novel ideas, whereas high cognitive inhibition contributes to the late stage by switching to a deliberate, analytical mode of information processing to facilitate a novel response (Cheng et al., 2015). This could relate to the perspective that creativity may be related to the flexible modulation of inhibitory control rather than the low or high capacity of inhibition (Zabelina & Robinson, 2010). However, empirical evidence regarding the role of cognitive flexibility is relatively scarce. To our knowledge, the only study investigated the unity and diversity of EFs in creativity found that people in the artistic domains (compared to IT domains) exhibited both, better common EF and enhanced cognitive flexibility (Zabelina et al., 2019). Despite these findings with adults, a study conducted with school-aged children provided behavioral evidence showing that shifting is the most powerful predictor of creativity among EFs (Krumm et al., 2018). Moreover, neuroscience literature provided additional evidence; Goel and Vartanian (2005) found that healthy adults showed increased activation in the prefrontal cortex (PFC) while solving the matchstick problem test (i.e., a creative problem-solving test) compared to when they only verified a given solution. They also proposed that the right ventrolateral prefrontal cortex (VLPFC) is a critical component of the neural mechanism of set-shifts to overcome fixation, resulting in successful performance in this task. Using the same task, developmental neural evidence indicated that middle adolescents, compared to adults, showed more activation in the lateral PFC during successful creative problem solving (Kleibeuker et al., 2013). It is assumed that recruitment in these regions is important for exploration and adaptive flexibility during this development period.

Overall, literatures have shown a close relationship between EFs and creativity from both behavioral and neuroimaging evidence with the population over middle childhood. However, it is still unknown whether these two cognitive abilities correlate with each other during their early development.Several studies have shown that EFs develop rapidly along with the maturation of the PFC during early childhood (Diamond, 2002; Moriguchi & Hiraki, 2013). A previous longitudinal study (Moriguchi & Hiraki, 2011) found both developmental improvement in children's performance on a widely used cognitive flexibility task and increased PFC activation during this task between 3 and 4 years old. Furthermore, research on DT have also been conducted throughout the lifespan, and found DT emerges around 2 years of age (Bijvoet-van den Berg & Hoicka, 2014) and increases thereafter with "slumps" and "peaks" during childhood and adolescence (Barbot, 2019). Both line of studies suggest that children develop EF and DT during early childhood, but no studies have examined the possible relationship between them. Therefore, the present study aimed to address this gap in the literature. We chose a new measurement of creativity, namely the unusual box test (UBT) (Bijvoet-van den Berg & Hoicka, 2014), to assess preschoolers' DT ability. This is a non-verbal, open-ended test that has been shown to be a reliable measurement of DT in young children, when compared to the other DT measurements suitable for older children. To assess children's cognitive flexibility, we used the Dimensional Change Card Sort (DCCS) task. Additionally, we also assessed brain activation during the tasks, as the knowledge of neural mechanisms would contribute to understanding individual differences in the DT ability during early childhood.

Based on previous theoretical and empirical backgrounds, we hypothesized that cognitive flexibility positively contributes to children's DT. The predictions for this hypothesis are as follows: (1) the performance of the DCCS task correlates with the performance of the UBT, (2) participants show greater brain activation during the test phases of the UBT as compared to the rest phases, (3) greater brain activation in the PFC correlates with better performance in the UBT, and (4) a correlation between brain activation in the PFC can be observed during the DCCS task and the UBT.

2. Methods

2.1. Participants

Twenty-six preschool children participated in this study (14 males, *mean age* = 69 months, 9 days; *range* = 50 months, 20 days–81 months, 24 days; *SD* = 9 months, 9 days). Of the four participants excluded from the NIRS analysis, two were excluded due to their large body movements, and two due to the experimenter's miss. The children were recruited from nursery schools in Japan and all were Japanese.

2.2. Behavioral assessments

The nursery school's indoor rooms were used for data collection. All actions were videotaped for further analyses. After building rapport, the children first completed the DCCS task and then the UBT. The order of the measures was held constant, and the experiment lasted for 10 minutes for each participant. Both tasks are described below.

The Unusual Box Test (UBT). The unusual box test (Bijvoet-van den Berg & Hoicka, 2014), involves a colorful wooden box of an unusual build (it contains blocks, rings, strings, stairs, a round hole, and a small room), along with a number of objects that are novel to the participants. In this study, we used a metal-spiral egg holder, an unusually shaped wooden toy, a plastic S-hook, a paint sponge, and a foxtail grass cat teaser (Figure 1). Furthermore, to adapt the UBT for use with preschoolers who have greater motor skills than toddlers who participated in a previous study (Bijvoet-van den Berg & Hoicka, 2014), we made the blocks, rings, and strings removable to encourage more different ways of play.

While giving the instructions, the experimenter highlighted the features of each side of the box, and children were then given a chance to turn the box around by themselves. Then, the children were asked to play with a given object and the box until the experimenter instructed them to stop. Each trial started the moment the children took the object from the experimenter and lasted for 60s. Five trials were performed. During the experiment, the children were not asked any specific questions and were allowed to play freely with some toys. When children asked for clarification regarding the use of a given object, the experimenter responded by saying, "I don't know, you can do whatever you want to do."

Actions were coded from the video, and the uniqueness of each action was assessed by the combination of two features: (a) the type of action (e.g., hit, squeeze, guide through), and (b) where the action was performed on the box (e.g., rings, edge of the box, and stairs). For an action to count as a unique action, it needed to be either a different action type, take place on a different box area, or both. Two types of scores were calculated for each child: fluency and originality. The fluency score was the total number of actions the child performed for all five trials combined. . To calculate originality score for each child, each action that a child performed was firstly given an originality score (i.e., 0, 1, 2, 3) based on the index (for full coding scheme, see Bijvoet-van den Berg & Hoicka, 2014), thereafter child could receive the total originality score by adding up all the originality scores of the actions that he or she had performed. Moreover, the coding was assessed for inter-rater agreement.

The Dimensional Change Card Sort (DCCS) task. The Dimensional Change Card Sort (DCCS) task measures cognitive flexibility by having children switch between different rules while sorting cards by color or shape. Children were presented with two sorting trays consisting of the target cards (e.g., a green tree and a red pig, see Figure 1) affixed to the front. Children were then presented with eight trials in the pre-switch phase (20s) where they were asked to sort test cards (e.g., a red tree and a green pig) based on one dimension (e.g., color). Next, children were presented with eight trials in the post-switch phase (20s) where they were asked to switch and use an alternative dimension (e.g., shape). Finally, children were presented with another eight trials in the mixed phase (20s) where they were asked to sort cards in accordance with the experimenter's verbal instruction for each trial (i.e., color or shape)

; the following rule order was fixed based on a previous study (Moriguchi & Shinohara, 2018): POST (the rule for the post-switch phase), POST, PRE (the rule for the pre-switch phase), POST, POST, PRE, POST, and POST. The rule order was counterbalanced across the children, however for each child, the rule order (e.g., color first) during the pre -and post-switch phases was held constant across the two consecutive sessions which used different card stimuli sets. Children's first responses were recored as their performance on each trial of the DCCS task.

The dependent measures of this task were successful switches. Specifically, children need to switch rules five times during each session. First, children who performed more than 90% correct in both of the pre-switch and post-switch phases received 1 point for the successful switch between these tow phases. (Towse et al., 2000). The other four switches occurred during the mixed phase; children received 1 point once successfully switched from the rule for the post-switch to the rule for the pre-switch (or vise versa). Finally, the ratio of successfully switching out of the five switches was calculated for each session, and the mean percentage of successful switching across the two sessions were used as the justification for children's performance on the DCCS task.

2.3. fNIRS data acquisition

Functional near-infrared spectroscopy (fNIRS) measurements were performed throughout the DCCS task and UBT. Temporal changes in the concentrations of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in the frontal regions were recorded using a 16-channel fNIRS unit (OEG-16; Spectratech Inc., Tokyo, Japan). The fNIRS probe included 12 optodes which were fixed to a headband that could be mounted on the hairless frontal lobe . After positioning headband to children's forehead, the Calibration work would be implemented for about 25 seconds to confirm if the sensors are mounted appropriately, so that it is able to get biological signals within the value of Cal Upper Limit (2000) and Cal Lower Limit (100). The temporal resolution at each channel was approximately 0.1 second.

The region of interest (ROI) was located near F3/4 (dorsolateral) and F7/8 (ventrolateral) according to the International 10/20 system. This was based on previous studies that showed these areas to be activated during DCCS tasks (Moriguchi et al., 2015). To increase the signal-to-noise ratio, data were averaged into right (channels 2, 4, and 5) and left dorsolateral prefrontal regions (DLPFC) (channels 11, 13, and 14), right (channels 2, 4, and 6), and left ventrolateral prefrontal regions (VLPFC) (channels 12, 13, and 14, Figure 1). Data from channels straddled two regions, that is, channels 4 and 13 were weighted at a level of 0.5, in both regions (Matsuda & Hiraki, 2006). We measured changes in oxy-Hb and deoxy-Hb in the lateral prefrontal regions during the rest and task phases, and analyzed the fNIRS data using OEG-16 software V3.0 (Spectratech Inc., Tokyo, Japan) and Python 3.6.4. To remove physiological artifacts that might contaminate NIRS signals, we separated the NIRS signal into functional (i.e., brain activation) and systematic (i.e., physiological noise) components, based on a negative or positive linear relationship between oxy-Hb and deoxy-Hb changes (Yamada et al., 2012). Only functional components were used for subsequent analyses.

3. Results

3.1. Behavioral results

Table 1 shows the descriptive statistics for the fluency and originality scores of the UBT, as well as the performance on each of the three phases of the DCCS task. The mean and the range scores of the UBT suggested individual differences, which was consistent with a previous study (Bijvoet-van den Berg & Hoicka, 2014). No age effects were found in the UBT (Pearson's $r = 0.065$, $p = 0.75$), but age differences were observed in the DCCS task. Children's age was positively correlated with the ratio successful switching (Pearson's $r = 0.44$, $p = 0.024$). Five randomly chosen videos (20%) were coded for agreement. Cohen's kappa showed good inter-rater agreement (Cohen's $\kappa = .814$). When there was a disagreement, the original coder's coding was used. Additionally, the fluency and originality scores were highly intercorrelated (Pearson's $r = 0.96$, $p < 0.01$). However, these two UBT scores were not significantly correlated with successful switching of the DCCS task.

3.2. fNIRS results

Results for oxy-Hb and deoxy-Hb were consistent after separating fNIRS signals into functional and systematic components; therefore, we reported the oxy-Hb results as follows.

First, the significance of the possible differences between changes in oxy-Hb concentration for the rest and test phases in the UBT was determined using one-tailed Student's *t-test* for each region. As multiple comparisons were conducted, we applied a 0.013 (0.050/4) alpha level of significance. The results revealed greater activation of all the lateral prefrontal regions during the task phases than during the rest phases. Particularly, greater activation of the left DLPFC ($t(22) = -4.566$, $p < 0.001$), right DLPFC ($t(22) = -3.995$, $p < 0.001$), left VLPFC ($t(22) = -2.685$, $p = 0.007$), and right VLPFC ($t(22) = -4.523$, $p < 0.001$) during the task phase have been seen. These results revealed that the children recruited their lateral prefrontal regions during UBT.

Next, we analyzed the neurobehavioral correlations of UBT. As both fluency and originality scores were normally distributed, we used Pearson correlation analysis to examine this correlation. The results did not indicate any correlations between children's performance during UBT and brain activation in the PFC.

Finally, we examined whether brain activation during the two tasks was correlated. We conducted Pearson correlation analyses separately, to examine whether brain activation in the PFC showed a correlation between UBT and each of the three phases of the DCCS task. The results showed no significant correlations between brain activation during the UBT and the pre-switch phase and between brain activation during the UBT and brain activation during the mixed phase. However, positive correlations of brain activation in both the left and right VLPFC between the UBT and the post-switch phase of the DCCS task were obtained. Particularly, brain activation during the UBT and the post-switch phase of the DCCS task were highly correlated in the left VLPFC (Pearson's $r = 0.61$, $p = 0.0025$), and moderately correlated in the right VLPFC (Pearson's $r = 0.43$, $p = 0.045$).

4. Discussion

In this study, we aimed to examine whether (1) the behavioral performance on the two tasks was correlated, (2) children show greater brain activation in the PFC during the test phases of the UBT compared to the rest phases, (3) children's behavioral performance on UBT was correlated with their brain activation in the PFC, and (4) the neural activation in the PFC during the two tasks was correlated. From children's behavioral performance, we did not find any significant correlations between the two tasks, a finding inconsistent with our hypothesis. However, using fNIRS to monitor brain activation during the DCCS task and the UBT, we observed the similarity in cognitive processes between the two tasks. Moreover, we did not find performance-related activation in the PFC when the children were performing UBT.

Children's performance suggests individual differences in the UBT, and the high correlation between fluency and originality scores supports the view that increased fluency can lead children to be more original (e.g., Mednick, 1962). Moreover, greater brain activation in the PFC during the test phases of the UBT (compared to the rest phases) revealed that children recruited the PFC when they freely played with the unusual box and the given objects. That is to say, even in the absence of task goals set by the experimenters like other classical DT tests, children have a tendency to set themselves appropriate challenges and control over their activities during spontaneous and self-initiated play. However, the neurobehavioral correlation of this task has not yet been confirmed. This might be due to individual differences in motor performances during play. Since the task is time-limited, among children who recruited their PFC regions to play in more different ways, those with slower motor performance could not have had enough time to demonstrate a large number of performances.

Although the two scores of UBT did not have significant correlations with successful switching of the DCCS task, the fNIRS results indicated that children who strongly recruited their VLPFC regions during the post-switch phase of the DCCS task recruited the same regions during the UBT. According to previous studies using the DCCS task, the VLPFC is suggested to contribute to flexible shifting from one rule to the next (Moriguchi & Hiraki, 2009). According to this view, children might recruit this region to try to change their way of playing based on different features of the box and the given objects.

Our results are partially consistent with those of adult and adolescent studies that showed greater brain activation in the PFC during creative problem-solving tasks and DT tests (Goel & Vartanian, 2005; Kleibeuker et al., 2013). However, the strong recruitment of PFC regions did not result in better performance, which could be considered a characteristic in this development period.

The present study is the first to examine the correlation between cognitive flexibility and creativity during early development. Despite the strengths of the current work, some limitations are worth noting. First, most neuropsychological studies on creativity in adult population examine the engagement of EFs by comparing the differences between conditions (e.g., condition requiring the engagement of DT or not) or differences between successful and unsuccessful performance. In the present study, such a comparison was omitted because of limited neural studies conducted with young children (e.g., the time limitation). Second, due to the young age group of our participants, we chose fNIRS rather than other standard modalities such as fMRI and EEG. Thus, our neurological analysis and the associated results are limited to the bilateral prefrontal regions of the brain. Thus, we believe that there is a need for future studies to assess other brain and prefrontal regions during the DT test. Third, we only used UBT to measure creativity. Future studies could examine the relation between cognitive flexibility and performance on other verbal measurements, or examine the neural-behavioral correlation on other creativity measurements.

The present study aimed to examine the role of cognitive flexibility in creativity in early childhood. Using a performance-based measurement thought to be more comfortable for preschoolers to express their thoughts, our fNIRS results indicated that children’s cognitive flexibility is engaged in their divergent thinking during play. While the current work sheds new light on the neural mechanisms underlying creativity in early childhood, we encourage future research to further investigate the emergence and developmental trajectories of creativity during this developmental period.

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Tables

Table 1: Descriptive Statistics of UBT and the DCCS task (N= 26).

Variables	Mean	SD	Range
Performance on the DCCS task:			
Percentage of correct responses during the pre-switch phase	0.97	0.11	0.50-1.00
Percentage of correct responses during the post-switch phase	0.98	0.03	0.88-1.00
Percentage of correct responses during the mixed phase	0.86	0.14	0.38-1.00
Ratio of successful switching	0.70	0.31	0.20-1.00
DT ability measures::			
Fluency	15.69	6.61	3-30
Originality	19.65	11.35	3-48

Table 2: Examples of Actions Performed for UBT and Their Originality Score (N = 26).

Actions	Descriptions of the actions	N (performed the action)	Originality Scores of the action

Turn	The object is turned around.	21	0
Hang on the ring	The object is attached to the ring and let go so that it hangs on the ring.	15	0
Place on the block	The object is placed on the block and let go so that it stands on its own for a while.	14	0
Guide through the round hole	While holding the object it is guided through the round hole without stopping.	10	1
Stick to the side of the box	The object is sticked to the side of the box, and let go so that it hangs on the box (only the side with rings and blocks could be sticky in the present study).	9	1
Drop in to the room	The object is held above the room, and then let go.	8	1
Jump on the stairs	Within a two-second period of time and for two or more times in a row, the object is placed on the stairs, then lifted in the air higher than needed for walking. During the placing of object, it is kept hold of.	4	2
Hang on the block	The object is attached to the block and let go so that it hangs on the block.	4	2
Guide through the rope	While holding the object it is guided through the rope without stopping.	2	2
Walk on the edge of the box	Within a two-second period of time and for two or more times in a row, the object is placed on the edge of the box. During the placing of the object, it is kept hold of.	1	3
Roll over the block	The object is rolled over the block, either holding it or letting it go.	1	3
Stick to the ring	The object is sticked to the ring, and let go so that it hangs on the ring.	1	3

SUPPORTING ONLINE MATERIAL

1. Supporting Analyses
2. Supporting introduction
3. Supporting Figure Legends

1. Supporting Analyses

We also conducted the correlational analyses after children were classified into younger and older group based on mean ages. Results did not show any significant neurobehavioral correlations during both of the DCCS task and the UBT in the younger group (i.e., children under 72 months). In the older group, however, there is a negative correlation between children’s originality score and their brain activation in the right DLPFC during the UBT (Pearson’s $r = -0.58$, $p = 0.029$).

The analyses revealed that less activation in the right DLPFC was associated with better performance on the UBT in older children (above 72 months). DLPFC has been found to play a key role in maintaining and storing information, which automates the process of rule induction. Less recruiting the DLPFC could help to “loosen the rules”, which gives children more freedom to play in different ways, so that they could better perform on the UBT. However, this relationship was not observed in younger group. This might because children this age experience relatively lower mental fixation and fewer learned rules, so that their behavioral performance were not related to the brain activation in the region which correspond to cognitive goal/rule maintenance.

2. Supporting Introduction

Functional near-infrared spectroscopy (fNIRS) is an optical technique which is non-invasive for measuring the hemodynamic response to neural activity, like functional magnetic resonance imaging (fMRI). Several studies suggested fNIRS hemodynamic measures to be correlated with the gold standard fMRI BOLD signal in cognitive tasks (Scarapicchia et al., 2017), but when it comes the paradigms that require actions performed in a natural environment, optical techniques using flexible fibers which can tolerate a degree of motion artifact shows the notable advantage (Minagawa-Kawai et al., 2008). Although electroencephalography (EEG) shares this advantage as fNIRS over fMRI, the electrophysiological signal is relatively weak that it needs many repetitions of stimuli events to average out noise. More importantly, as the signal acquisition of EEG is the sum of potential postsynaptic neurons over a large are of the cortex, its ability to localize the focus of activity is generally poorer than fNIRS (Minagawa-Kawai et al., 2008). To this end, we chose a 16-channel fNIRS unit (OEG-16; Spectratech Inc., Tokyo, Japan) to record temporal changes in the concentrations of oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb) in the frontal regions.

3. Supporting Figure Legends

Figure S1. The neurobehavioral correlation of the UBT and the DCCS task. ***(A)*** neurobehavioral correlation of the UBT (N = 23). ***(B)*** neurobehavioral correlation of the pre-switch phase ***(C)*** post-switch phase and ***(D)*** mix phase of the DCCS task (N = 22). Correlation coefficients with a white background are the insignificant ones.

Figure S2. The behavioral and neural correlation between the UBT and the DCCS task. ***(A)*** behavioral correlation (N = 26) ***(B)*** neural correlation between the UBT and the three phases of DCCS (N = 22). Correlation coefficients with a white background are the insignificant ones.

Notes: Fluency = The total number of distinct actions performed in the UBT. Originality = Final originality score in the UBT. Pre = Percentage of correct responses during the pre-switch phase of the DCCS task. Post = Percentage of correct responses during the post-switch phase of the DCCS task. Mix = Percentage of correct responses during the mixed phase of the DCCS task. Switching = Ratio of successful switching.

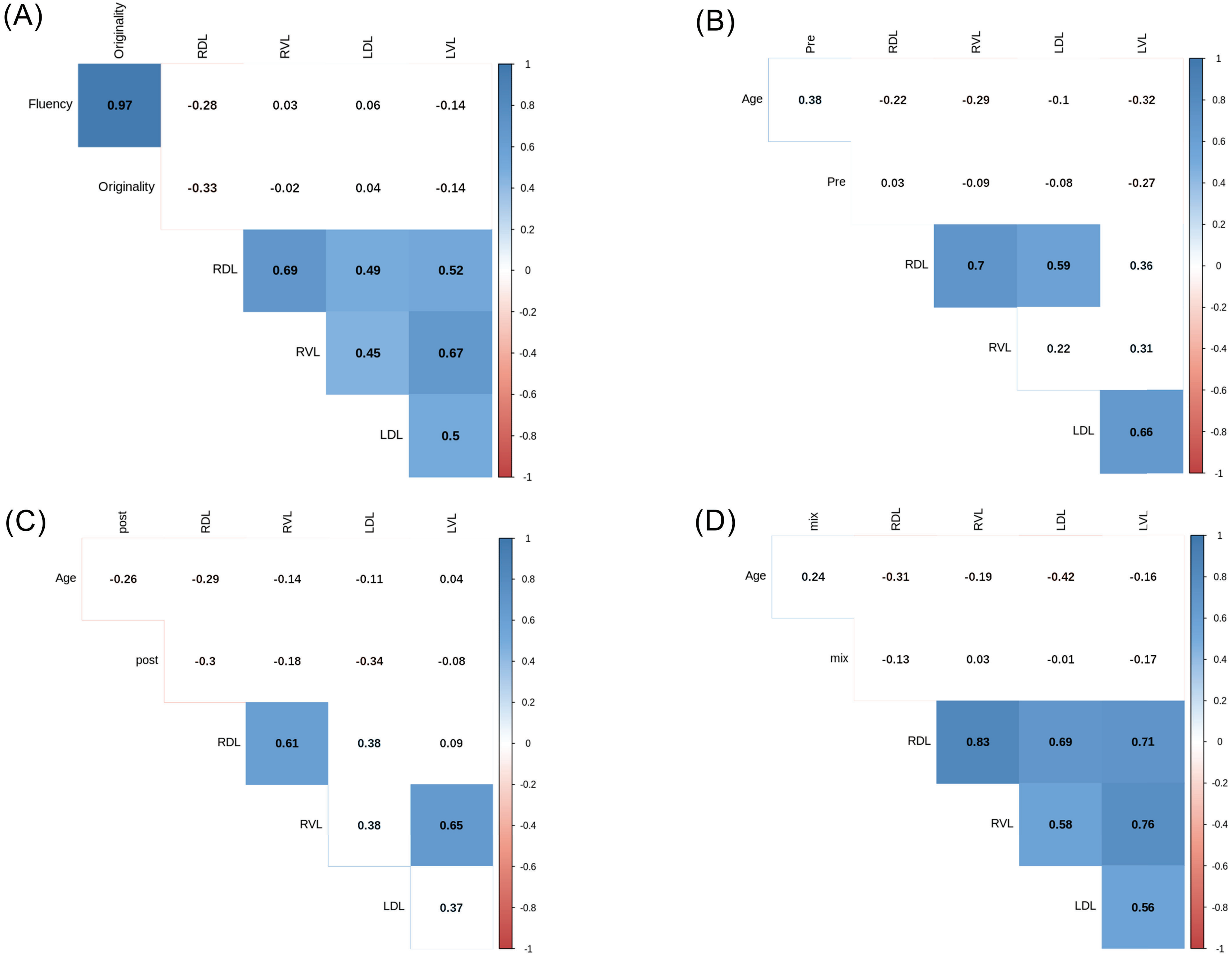
RDL = Brain activation in the right dorsolateral prefrontal regions during the UBT. RVL = Brain activation in the right ventrolateral prefrontal regions during the UBT. LDL = Brain activation in the left dorsolateral prefrontal regions during the UBT. LVL = Brain activation in the left ventrolateral prefrontal regions during the UBT.

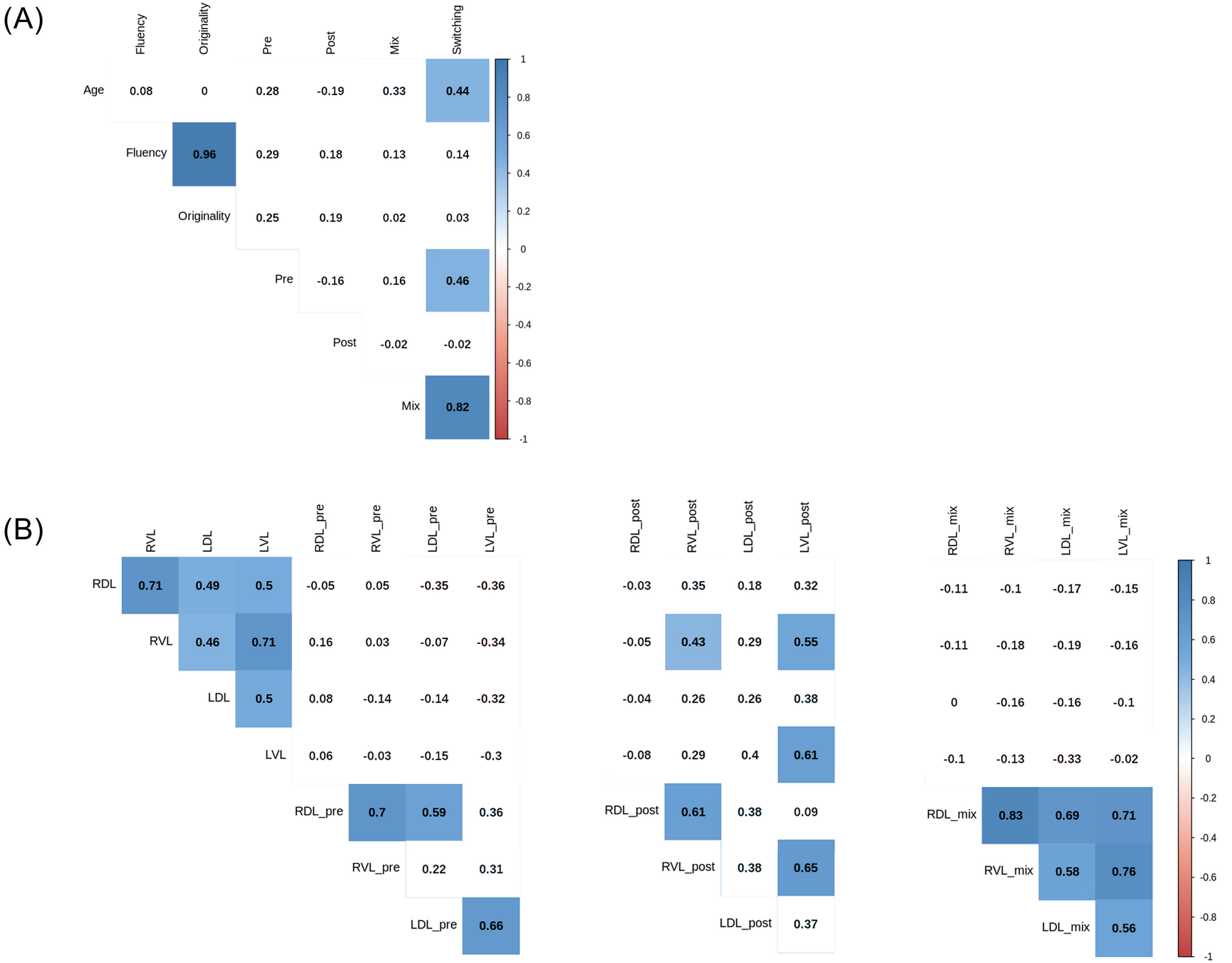
RDL_pre, RDL_post, RDL_mix = Brain activation in the right dorsolateral prefrontal regions during the pre-switch phase, post-switch phase and the mix phase of the DCCS task relatively. RVL_pre, RVL_post, RVL_mix = Brain activation in the right ventrolateral prefrontal regions during the pre-switch phase, post-switch phase and the mix phase of the DCCS task relatively. LDL_pre, LDL_post, LDL_mix = Brain activation in the left dorsolateral prefrontal regions during the pre-switch phase, post-switch phase and the mix phase of the DCCS task relatively. LVL_pre, LVL_post, LVL_mix = Brain activation in the left ventrolateral prefrontal regions during the pre-switch phase, post-switch phase and the mix phase of the DCCS task relatively.

Before pre- and post-switch phase, experimenter gave the instruction about the sorting rule (e.g. “We are going to play a color game. In the color game, all the green ones go here, and all the red ones go there”) while pointing the related tray.

Minagawa-Kawai, Y., Mori, K., Hebden, J. C., & Dupoux, E. (2008). Optical imaging of infants' neurocognitive development: recent advances and perspectives. *Developmental neurobiology*, *68*(6), 712–728. https://doi.org/10.1002/dneu.20618

Scarapicchia, V., Brown, C., Mayo, C., & Gawryluk, J. R. (2017). Functional Magnetic Resonance Imaging and Functional Near-Infrared Spectroscopy: Insights from Combined Recording Studies. *Frontiers in human neuroscience*, *11*, 419. https://doi.org/10.3389/fnhum.2017.00419


(A)
Originality
RDL
RVL
LDL
LVL
Fluency
0.97
-0.28
0.03
0.06
-0.14
Originality
-0.33
-0.02
0.04
-0.14
RDL
0.69
0.49
0.52
RVL
0.45
0.67
LDL
0.5
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
(B)
Pre
RDL
RVL
LDL
LVL
Age
0.38
-0.22
-0.29
-0.1
-0.32
Pre
0.03
-0.09
-0.08
-0.27
RDL
0.7
0.59
0.36
RVL
0.22
0.31
LDL
0.66
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
(C)
post
RDL
RVL
LDL
LVL
Age
-0.26
-0.29
-0.14
-0.11
0.04
post
-0.3
-0.18
-0.34
-0.08
RDL
0.61
0.38
0.09
RVL
0.38
0.65
LDL
0.37
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
(D)
mix
RDL
RVL
LDL
LVL
Age
0.24
-0.31
-0.19
-0.42
-0.16
mix
-0.13
0.03
-0.01
-0.17
RDL
0.83
0.69
0.71
RVL
0.58
0.76
LDL
0.56
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1



	Fluency	Originality	Pre	Post	Mix	Switching
Age	0.08	0	0.28	-0.19	0.33	0.44
Fluency		0.96	0.29	0.18	0.13	0.14
Originality			0.25	0.19	0.02	0.03
Pre				-0.16	0.16	0.46
Post					-0.02	-0.02
Mix						0.82

	RVL	LDL	LVL	RDL_pre	RVL_pre	LDL_pre	LVL_pre
RDL	0.71	0.49	0.5	-0.05	0.05	-0.35	-0.36
RVL		0.46	0.71	0.16	0.03	-0.07	-0.34
LDL			0.5	0.08	-0.14	-0.14	-0.32
LVL				0.06	-0.03	-0.15	-0.3
RDL_pre					0.7	0.59	0.36
RVL_pre						0.22	0.31
LDL_pre							0.66

	RDL_post	RVL_post	LDL_post	LVL_post
RDL	-0.03	0.35	0.18	0.32
RVL	-0.05	0.43	0.29	0.55
LDL	-0.04	0.26	0.26	0.38
LVL	-0.08	0.29	0.4	0.61
RDL_post		0.61	0.38	0.09
RVL_post			0.38	0.65
LDL_post				0.37

	RDL_mix	RVL_mix	LDL_mix	LVL_mix
RDL	-0.11	-0.1	-0.17	-0.15
RVL	-0.11	-0.18	-0.19	-0.16
LDL	0	-0.16	-0.16	-0.1
LVL	-0.1	-0.13	-0.33	-0.02
RDL_mix		0.83	0.69	0.71
RVL_mix			0.58	0.76
LDL_mix				0.56

此文稿由 Numbers 表格导出。所有表格均已转换为 Excel 工作表。每张 Numbers 工作表上的所有其他对象都已放置在单独的工作表中。请注意其中的公式计算可能与 Excel 不同。

Numbers 表格工作表名称	数字表格名称	Excel 工作表名称
Tables		
	Table S1(A). The number of children who performed the action (the combination of the type of action and where the action was performed) and the originality score of the action (in brackets).	Tables - Table S1(A). The numbe
	Table S1(B) Other actions	Tables - Table S1(B) Other acti

Table S1(A). The number of children who performed the action (the combination of the type of action and where the action was performed) and the originality score of the action (in brackets).

Type of actions	Round hole	Edge of round hole	Square room	Side of square room	Stairs	Blocks	Rings	Strings	Rope	Edge of Box	Side of Box	Whole Box	No Box
Walk					**2** (2)					**1** (3)			
Jump			**3** (2)		**4** (2)	**1** (3)				**3** (2)			
Hit		**1** (3)		**1** (3)	**2** (2)	**5** (2)				**3** (2)	**4** (2)	**1** (3)	
Touch		**2** (2)		**2** (2)	**1** (3)	**3** (2)	**12** (1)	**4** (2)			**2** (2)		
Roll			**1** (3)		**4** (2)	**1** (3)							
Turn												**1** (3)	**21** (0)
Drop	**11** (1)		**8** (1)				**7** (1)						
Guide through	**10** (1)						**10** (1)		**2** (2)				
Hold in place					**3** (2)	**3** (2)				**4** (2)			
Place			**1** (3)		**10** (1)	**14** (0)	**7** (1)		**6** (1)	**3** (2)			
Move over		**2** (2)	**2** (2)	**2** (2)	**7** (1)	**9** (1)	**1** (3)	**6** (1)		**4** (2)	**4** (2)		**1** (3)
Pull													
Push												**1** (3)	
Throw against													**2** (2)
Squeeze				**1** (3)	**8** (1)	**4** (2)				**1** (3)		**1** (3)	**22** (0)
Extend													**4** (2)
Manipulate								**1** (3)					**3** (2)
Separate													**21** (0)
Cover						**1** (3)							
Hang		**5** (2)				**4** (2)	**15** (0)	**1** (3)	**7** (1)	**8** (1)	**3** (2)		
Stick						**7** (1)	**1** (3)				**9** (1)		
Shake													**5** (2)
Spin													**1** (3)
Take off						**2** (2)	**7** (1)	**1** (3)					
Take and play						**7** (1)	**4** (2)	**1** (3)		**2** (2)			**1** (3)
Connect							**4** (2)						

***Table S1(B).* Other actions performed**

Description of ther new actions	N (performed the action)	Originality score of the action
Using the given object to stick with the ring and then take off it	2	2
Squeeze the object on one’s	1	3
Manipulate the strings to make a ball	1	3
Gather two parts of the object to one through the ring	1	3

***Table S2.* Description of Action used in the Unusual Box test**

Actions	Description
Walk	Within a two-second period of time and for two or more times in a row, the object is placed on (part of) the box. During the placing of the object, it is kept hold of.
Jump	Within a two-second period of time and for two or more times in a row, the object is placed on (part of) the box, then lifted in the air higher than needed for walking. During the placing of object, it is kept hold of.
Hit	The object hits the box.
Touch	The object touches the box.
Roll	The object is rolled over the surface of the box, either holding it or letting it go.
Turn	The object is turned around.
Drop	The object is held above the place where it will land, and then let go.
Guide through	While holding the object it is guided through (part of) the box without stopping.
Hold in place	The object is placed on (part of) the box. During the placing of the object it is kept hold of.
Place	The object is placed on part of the box and let go so that it stands on its own for a while.
Move over	While holding the object, it is guided on part of the box and then moved over its surface.
Pull	(Part of) the box/object is pulled toward the participant.
Push	(Part of) the box/object is pushed away from the participant.
Throw against	The object is thrown against the box.
Squeeze	The object is squeezed, using thumb and index finger.
Extend	The object is extended, using hands.
Manipulate	The object is manipulated in order to play with parts of the box.
Separate	The object is separated into two parts.
Cover	Part of the box is covered by the object.
Hang	The object is attached to the box (e.g., by manipulating the object) and let go so that it hangs on the box.
Stick	The object is sticked to the box, and let go so that it hangs on the box (only the side with rings and blocks could be sticky in the present study)
Shake	The object is held in the hand(s) and moved quickly from one side to the other.
Spin	The object is spun in the hands.
Take off	The object is used to take removable parts (blocks, rings or strings) off the box.
Take and play	Removable parts (blocks, rings or strings) were taken from the box by hand(s) in order to play with the given object or the box.
Connect	The object is used to connect two separated parts of the box (e.g., make a bridge between two blocks).

*code actions even if the object isn't used but the box is (e.g., hand walking on part of box)
*code actions even if the box isn't used but the object is (e.g., rolling the object on the table)
*code none if neither the object or box is used
*make a comment attached to the actions which were performed without box or objects