The non-linear development of basic attentional functions and attentional collaborations in primary school children examined with the High Reliability-Composite Attention Test

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Abstract

The development of attentional functions is a fundamental issue of human cognitive development, but the available evidence for its developmental trajectory is inconsistent due to the diversity and low reliability of measurement paradigms. The study examined the development of attentional functions and attentional collaborations in 281 Chinese primary school children (109 girls, 5.98-13.24 years old) using the self-designed High Reliability-Composite Attention Test. Results showed that the executive control continued to develop prior to the age of 10. It further contributed to the linear development of attentional collaborations. Each of these scores exhibited a split-half reliability exceeding 0.82. Therefore, we effectively demonstrated a mechanism for attentional development that revolves around executive control.

Full Text

Preamble

Running title: Reliable developmental trajectories of attention

Abstract: The development of attentional functions is a fundamental issue in human cognitive development, yet available evidence for developmental trajectories remains inconsistent due to the diversity and low reliability of measurement paradigms. This study examined the development of attentional functions and their collaborations in 281 Chinese primary school children (109 girls, aged 5.98–13.24 years) using a self-designed High Reliability-Composite Attention Test. Results showed that executive control continued to develop prior to age 10 and further contributed to the linear development of attentional collaborations.

Each score exhibited split-half reliability exceeding 0.82, thereby demonstrating a mechanism of attentional development that revolves around executive control.

Keywords: attentional development, High Reliability-Composite Attention Test, attentional collaboration, attentional interaction, gender difference

Research Highlights: We combined a steady-state design with a block design, revised the attention network test, and propose a new measurement paradigm. This revision enables more valid and reliable measurement of attentional functions, with reliability results exceeding 0.8, making it suitable as a reliable instrument for attention measurement. The non-orthogonal computational method allowed us to assess for the first time the developmental trajectory of collaborations and interactions between attentional functions. The study sheds new light on developmental mechanisms of attention by emphasizing the pivotal role of executive control and its relationship to other attention functions.

1 Introduction

Attention is a pivotal cognitive function that directs limited cognitive resources toward behaviorally relevant information, shaping what we perceive, think, and do (Bridewell & Bello, 2016; Chun et al., 2011). It has attracted human interest for over 3,000 years (Almeida et al., 2021). To date, no extensively accepted unified theory of attention exists, due to its complexity and multifaceted nature (Wyble et al., 2020). In a highly influential paper, Posner and Petersen divided attention into three networks: alerting, orienting, and executive control (Posner & Petersen, 1990). The alerting network achieves and maintains a state of high vigilance; the orienting network shifts attentional focus toward specific inputs; while the executive control network identifies and resolves conflicts arising from competing mental processes (Xuan et al., 2016). These three networks are linked with distinct neural circuits and neurotransmitter systems, respectively (Xuan et al., 2016). The triple-network theory has undergone rigorous analysis and represents one of the most extensively investigated attention theories in laboratory, developmental, and clinical contexts (Petersen & Posner, 2012).

Attention constitutes one of the most important cognitive abilities for adaptive behavior during childhood and for meeting daily demands in both school and social interactions (Lewis et al., 2017; Posner & Rothbart, 2007). Furthermore, as children enter school age, the impact of attentional disorders such as Attention-Deficit/Hyperactivity Disorder (ADHD) gradually increases, endangering academic performance as well as physical and mental health (Thomas et al., 2015). Due to these far-reaching effects, gaining insight into attentional processes during early development is crucial (Atkinson & Braddick, 2012).

The Attention Network Test (ANT) proposed by Fan and colleagues is a classic and broadly acknowledged paradigm for assessing the efficiency of the three attention networks (Fan et al., 2002). The ANT and its variants have been extensively applied to examine developmental characteristics of attention (Arora et al., 2021). Other paradigms have also been adopted to measure attentional development. For instance, Hrabok et al. (2007) employed the "Help the farmer" task to assess alerting network development, while Goldberg et al. (2001) used the "Covert orienting task" to measure orienting network development. The Go/No-Go task (Lewis et al., 2018), Stroop task (Lyon et al., 2022), and Simon task (Tiego et al., 2020) have been used to evaluate executive control network development. The diverse developmental courses identified by various researchers may be attributed to the different tasks employed in their studies.

Beyond the varied paradigms for measuring attentional functions, most studies exhibit relatively low reliability. In the original study (Fan et al., 2002), test-retest reliability coefficients for alerting, orienting, and executive control networks were 0.52, 0.61, and 0.77, respectively, when two sessions were conducted in adults within a single day. MacLeod et al. (2010) analyzed 15 studies using the ANT in adults and revealed average split-half reliabilities of 0.20, 0.32, and 0.65 for alerting, orienting, and executive control networks, respectively. The child version of the ANT exhibited even lower reliability. For example, Ishigami and Klein (2014) found test-retest reliabilities of 0.16, -0.25, and 0.22 for alerting, orienting, and executive control networks, respectively, in children aged 6–8 years. Draheim et al. (2019) argued that unstable subject states, speed-accuracy trade-offs, and the inability to separate single psychological components from measurement indicators constitute the main reasons for low reliability in reaction time (RT)-based measurements.

Due to diverse paradigms and low reliabilities, developmental trajectories of attentional functions are inconsistent across studies. Some studies have found that the alerting network attains stability by age seven or nine (Abundis-Gutierrez et al., 2014; Rueda et al., 2004), while others argue it continues developing into late childhood or even young adulthood (Boen et al., 2021; Posner et al., 2020; Suades-Gonzalez et al., 2017). Similarly, the orienting and executive control networks have been observed to stabilize around age six or seven (Lewis et al., 2018; Posner et al., 2020; Suades-Gonzalez et al., 2017), yet other research indicates their development may extend beyond age seven (Boen et al., 2021; Federico et al., 2017; Pozuelos et al., 2014). These studies highlight diverse developmental trajectories of attentional functions, particularly during primary school years.

In the current study, we aimed to assess developmental trajectories of attentional functions using a measurement paradigm with high validity and reliability. Our novel paradigm was adapted from the classic ANT to ensure high validity. Furthermore, we adopted the steady-state block design to ensure high reliability in measuring attentional functions (Gao et al., 2019; Wang et al., 2016). The steady-state block design presents the same experimental condition at a fixed frequency to reduce fluctuating expectations between trials and avoid mutual interference between experimental conditions (Zhang et al., 2023). Therefore, it provides a stable and predictable environment for subjects and can effectively isolate each attentional function and their collaborations (Wang et al., 2015). We further adopted the non-orthogonal method to avoid inter-network interference. Evidence indicates significant differences in results obtained through orthogonal versus non-orthogonal methods, with the latter proving superior for obtaining single measurements (McConnell & Shore, 2011; Wang et al., 2014).

Through these methodological improvements, we aimed to address issues concerning subject state stability and cognitive component purity that influence measurement reliability (Draheim et al., 2019). Overall, we provided a High Reliability-Composite Attention Test (HR-CAT) and measured with certainty the developmental courses of coordination and interaction among attentional networks beyond the efficiency of each individual network in primary school children.

2.1 Participants

Subjects were recruited from a primary school situated in the urban-rural interface of Sichuan Province, where they resided in residential premises. All children were of Han ethnicity. The research content and potential conflicts of interest were fully disclosed to all subjects and their guardians. The research protocol was conducted in strict accordance with the Helsinki Ethical Agreement, and informed consent was obtained from both children and guardians. All participants signed a written informed consent form approved by the Ethics Committee of the Institute of Brain and Psychological Sciences, Sichuan Normal University, prior to initiating the experiment.

Data were collected between October 2020 and June 2021. A total of 281 children, including 109 girls, participated in the study, with a mean age of 9.48 years (range: 5.98–13.24 years). Four children were excluded from further analysis due to failure to complete the experiment. All participants were right-handed, had normal or corrected-to-normal vision, and none were color-blind. Children with prior history of mental retardation, brain trauma, neurological disease, physical impairment, or learning disabilities were excluded.

2.2 Materials and Procedure

As shown in Figure 1 [Figure 1: see original paper], the task contained eight blocks, each representing one task condition [i.e., alerting (A), baseline (B), executive control (E), orienting (O), alerting and executive control collaboration (AE), alerting and orienting collaboration (AO), executive control and orienting collaboration (EO), and common collaboration (AEO)]. Each block consisted of 24 trials. The overall task lasted approximately 15 minutes.

At the onset of each trial, a black line segment appeared at the center of the screen as a fixation point for 1.1 seconds. The line segment had a length of 3 mm and a width of 1 mm. The line segment remained for 0.2 seconds under B, E, O, and EO conditions, or transitioned to a red cue for 0.2 seconds under A, AE, AO, and AEO conditions. A "click" sound accompanied the red cue to increase alertness. Afterward, the line segment remained for 0.2 seconds, forming a fixed cue-target interval. The target, comprising five arrows, was then presented for 1.7 seconds or until a response was recorded. The arrows were presented at the center of the screen, with the third arrow overlapping the line segment, or displayed at the top or bottom of the line segment. Each arrow measured 3 mm in length and 2 mm in width, with a combined length of 20 mm for all five arrows. The vertical distance from fixation was 26 mm when arrows were presented at the top or bottom of the line segment. Finally, a fixation point was presented, ensuring each trial lasted 3.2 seconds.

The program ran on a 14-inch laptop with a gray background. The Psychology Toolbox embedded in MATLAB was used for programming, stimulus presentation, and timing control. Before the experiment, each participant completed 24 practice trials to familiarize themselves with the procedure. The experiment was conducted in a dimly lit office, with subjects seated comfortably 60 cm from the screen.

FIGURE 1. Illustration of the highly reliable composite attention test. Each task was conducted trial-by-trial in an independent block. A: alerting; B: baseline; E: executive control; O: orienting.

2.3 Indicators of Attentional Networks

The mean and median RT for all correct trials, as well as accuracy for each condition, were calculated. In trials with error responses or RTs exceeding the mean RT ± 2.5 standard deviations (SD), RTs were replaced with the median RT for that condition. This operation retained all trials and enabled assessment of split-half reliability, which depended on random trial selection. Subsequently, the median RT of each condition was recalculated and used to compute attentional network indices.

We adopted four potential methods to calculate attentional network indicators, dividing them into three categories: efficiency of single attentional networks, coordination between attentional networks, and directional influence between attentional networks.

The first method entailed direct subtraction of two RTs. For instance, the efficiency of a single attentional network was defined by the difference between the RT for that network and the RT for the baseline condition. The efficiencies of A, E, and O were shown by equations (1)-(3). The RT in each equation represented the mean RT for a given condition for each subject.

Similarly, coordination between attentional networks was characterized by the difference between the RT for a collaborative condition and the RT for the baseline condition. The efficiencies for AE, AO, EO, and AEO collaborations were shown by equations (4)-(7).

Furthermore, directional influence between attentional networks was defined as the change in efficiency of the current attentional network when additional networks were introduced. This change was expressed by the difference in RTs between conditions. The twelve directional influences between attentional networks were shown by equations (8)-(19). The M→N notation in these equations refers to the directional influence of M on N.

Considering that individuals exhibit varying baseline reaction speeds, we used ratio scores as another method to define the aforementioned efficiencies (Wang et al., 2015). The ratio score was defined as the rate of change of the aforementioned efficiency relative to the baseline or original condition (e.g., A, A→E, and O→AE in equations (20)-(22)).

To avoid the trade-off between speed and accuracy in traditional RT-based attentional scores, we further adopted the balanced composite score (BIS) (Liesefeld & Janczyk, 2019) to calculate each attentional score. The BIS formula is shown in equation (23).

In this equation, ACC represents accuracy while RT refers to the median RT for a given condition for each subject. The Z value denotes the location of an individual's score within the distribution of scores for all subjects. A superior BIS equates to greater accuracy and faster RT, thereby indicating better performance. The BIS could be calculated using either the original score or the ratio score obtained in the first two methods, yielding four types of scores: original score, ratio score, original BIS, and ratio BIS.

2.4 Reliability of Attentional Scores

The split-half reliability of the nineteen attentional scores (e.g., in equations (1)-(19)) was evaluated using Monte Carlo simulation in MATLAB 2022b software (MathWorks, U.S.A). Specifically, the 24 trials of each block were randomly divided into two halves 10,000 times. Attentional scores were calculated for each half separately, and Pearson's correlation between the two scores was computed across all subjects. Split-half reliability was defined as the mean of the 10,000 correlation coefficients.

All four types of attentional scores (each with 19 items) underwent reliability analysis. Two (original, ratio) by two (non-BIS, BIS) repeated measures ANOVA and paired-samples t-tests in SPSS Statistics Software 25 (IBM, U.S.A) were used to determine the optimal method for calculating attentional scores. The attentional scores computed using the best method were used for further analyses.

2.5 Developmental Trajectories of Attentional Functions

SPSS Statistics Software 25 was used to test developmental trajectories of attentional functions. Linear and quadratic fittings were conducted, with age as the independent variable and attentional scores as the dependent variable, to investigate whether attentional functions exhibit linear or quadratic developmental trends.

2.6 Gender Differences in Attentional Function Development

We also tested gender differences during attentional function development. Data were analyzed using Stata Statistical Software 17 (StataCorp., U.S.A). Attentional scores demonstrating significant developmental trends served as dependent variables, with age as the independent variable. Gender was set as the grouping variable (b0: girl group, b1: boy group). The bootstrap method was used to test significance of between-group differences (Cleary, 1999). The null hypothesis, H0: d0 = 0, implies no significant difference in estimated coefficient values between groups. The empirical p-value, obtained through bootstrapping, represents the probability of observing the actual coefficient difference between groups. The procedure was as follows: (1) Pool samples from boy and girl groups, assuming group sizes of n1 and n2, respectively, with N = n1 + n2; (2) In each simulation round, randomly select two groups (boys: n1, girls: n2) from the N; (3) Determine coefficients for each group and calculate their difference (di); (4) Repeat steps 2 and 3 k times (k=1000) to obtain the empirical p-value, comparable to traditional test p-values, by calculating the percentage of di (i=1, 2,…, k) greater than the actual coefficient difference d0. If more than 95% of di values exceeded d0, the empirical p-value was less than 0.05, signifying a gender difference.

Multiple comparisons in the above analyses were corrected at $p < 0.05$ using the Bonferroni method (Bland & Altman, 1995).

3 Results

The majority of children (277 out of 281) completed the experiment successfully, with mean accuracy exceeding 94% for each condition and median RT ranging from 535–882 ms (see Table 1).

TABLE 1. RT and accuracy for eight attentional conditions

<table>
<tr><th>Attentional index</th><th>RT (ms, median±SD)</th><th>Accuracy (%, mean±SD)</th></tr>
<tr><td>A</td><td colspan="2">535.67$±100.98|97.41±6.11||<i>B</i>|599.25±114.10|97.78±7.13||<i>E</i>|694.27±126.23|97.28±</td></tr>
</table>

3.1 Split-Half Reliability

ANOVA showed significant main effects of BIS (F(1, 18) = 13.91, p = 0.002, ^{2}p = 0.45) and ratio (F(1, 18) = 21.77, $p < 0.001$, ^{2}p = 0.55). The interaction between BIS and ratio was also significant (F(1, 18) = 22.96, $p < 0.001$, ^{2}p = 0.56). Specifically, original BIS exhibited higher reliability coefficients than ratio BIS (t(18) = 4.77, $p < 0.001$, Cohen's d = 1.09), whereas no significant difference was observed between original score and ratio score (t(18) = 0.74, p = 0.469, Cohen's d = 0.17). Overall, the original BIS method exhibited the highest reliability coefficients for almost all scores (see Table 2).

TABLE 2. Split-half reliability of basic attentional functions and their relationships

Attention index	Original BIS	Ratio BIS	Original score	Ratio score
Attentional efficiency				
Attentional collaboration				
Attentional interaction				

3.2 Developmental Trajectories of Attentional Functions

For basic attentional functions, only the E score showed a significant non-linear developmental trajectory ($R^2 = 0.056$), with an inflection point at age 10 (see Fig. 2 [Figure 2: see original paper]), suggesting continuous development of executive control before age 10. The EO collaboration exhibited a significant non-linear developmental trajectory that could also be accounted for by a linear trend. Developmental trajectories of the interactions E→O, E→A, and EO→A could be explained by linear trends, with non-linear trends also showing significance. For the quadratic trends of EO, E→O, E→A, and EO→A development, inflection points appeared at ages 11.6, 11.91, 12.25, and 12.38, respectively, suggesting development extends into higher primary school grades. Remaining scores did not exhibit either linear or non-linear trends after multiple comparison correction.

Since all aforementioned variables contained E, we regressed out E and re-performed fitting analysis. Results showed only the linear developmental trend remained significant, whereas the quadratic trend dissipated.

FIGURE 2. Developmental trends of basic attentional functions and attentional collaborations

3.3 Gender Differences in Attentional Functions

Observed improvements in attentional scores with age showed no discernible differences in developmental trends between boys and girls (see Table 3). Both boys and girls contributed to development of EO, E→A, and E→O. Boys made specific contributions to EO→A development. Overall, no significant gender differences emerged for attentional function development.

TABLE 3. Gender effects during attentional development

Index	Girl coefficient (b0)	Boy coefficient (b1)	Coefficient difference (b0-b1)
EO	0.21**	0.18**	0.03
E→A	0.25*	0.20**	0.05
E→O	0.18**	0.22**	-0.04

Index	Girl coefficient (b0)	Boy coefficient (b1)	Coefficient difference (b0-b1)
EO→A	0.19**	0.25**	-0.06

- $p < 0.05$, ** $p < 0.01$

4 Discussion

We conducted a highly reliable assessment of developmental trajectories for basic attentional functions and their collaborations in primary school children. We found that development of E, EO, E→O, E→A, and EO→A continued throughout primary school, yet their growth rates slowed after ages 10, 11.6, 11.91, 12.25, and 12.38, respectively. However, we found no gender differences in developmental trajectories for any attentional scores.

This study provides trustworthy evidence that during primary school, attentional functions are marked by development of executive control, its collaboration with orienting, and its impact on orienting and alerting functions. Notably, this represents the initial attempt to evaluate developmental characteristics of attentional collaborations. Overall, we propose a mechanism of attentional development that revolves around executive control in primary school.

4.1 Development of Basic Attentional Functions in Primary School

For many years, debate has surrounded developmental trajectories of attentional functions. Some researchers concur that basic attentional functions develop gradually with age during childhood (Kronenberger et al., 2020; Morandini et al., 2021; Pan et al., 2019). However, other studies suggest basic attentional functions reach a plateau around age seven or nine, with continued enhancement in some literature potentially reflecting increased reaction speed rather than true developmental change (Abundis-Gutierrez et al., 2014; Lewis et al., 2018; Posner et al., 2020; Suades-Gonzalez et al., 2017). Consistent with the latter view, our research revealed that alerting and orienting did not show notable growth between ages 6 and 13. Beyond behavioral maturity, contingent negative variation (CNV), a typical electroencephalographic indicator of alertness, has been found to reach adult levels by ages 9–10 (Jonkman, 2006). Furthermore, activation of the putamen, a core brain region for orienting, achieves adult levels by ages 8–12 (Konrad et al., 2005). Indeed, alerting and orienting represent initial attention functions in infants (Graven & Browne, 2008; Hitzert et al., 2015), and their early development is essential for infants to explore the world.

By contrast, we observed that executive control continues developing throughout primary school, though its developmental rate slows. This may signify that executive control development has distinct stages, with late childhood signaling termination of the prior stage and the subsequent stage not initiating until adolescence. This assumption aligns with the “readiness for change” model, which suggests two-stage development of cognitive control during childhood and adolescence (Crone & Steinbeis, 2017). It can also reconcile inconsistent results showing executive control achieving stability during primary school in some studies while continuing to develop until young adulthood in others (Aubry & Bourdin, 2021; Boen et al., 2021; Lewis et al., 2018; Posner et al., 2020; Suades-González et al., 2017). An alternative interpretation is that executive control includes two components: conflict resolution and inhibitory control. Research suggests that after age 7, conflict resolution ability enters a plateau (Posner et al., 2020), but children exhibit gains in inhibitory control with age (Zhou et al., 2022). The Flanker task is more indicative of conflict resolution, possibly contributing to the slowdown in executive control development during later childhood. If so, other tasks such as the stop-signal task, which better reflect inhibitory control, may reveal different trends. Both assumptions require further verification.

4.2 Development of Attentional Collaborations in Primary School

Theoretically, successful operation of each attention network relies on cooperation from other networks. For instance, alerting depends on both bottom-up stimulus induction (i.e., phasic alerting) and top-down autonomic maintenance (e.g., tonic alerting), thus requiring cooperative participation of orienting and executive control (Sarter et al., 2001). Orienting depends on maintaining a certain level of alerting, stimulus selection, and eye movement control, making alerting and executive control integral to this process (Hendry et al., 2019). Executive control necessitates orienting to and maintenance of target stimuli, thus requiring orienting and alerting (Bast et al., 2018). Esterman and Rothlein (2019) proposed that sustained attention results from combined efforts of maintaining long-duration alertness, exercising autonomous control to suppress distractions, and maintaining constant orientation. Therefore, collaboration between different attention networks is necessary for successful attentional functioning and represents a significant theoretical issue. Moore (2016) advanced the idea that development of complex systems results from interactions among multiple factors or processes. Within this framework, complex attentional functions become apparent only when basic attentional functions reach certain levels and can collaborate effectively.

During primary school, alerting and orienting gradually stabilize while executive control continuously evolves at a high level (Lewis et al., 2017). Therefore, development of attentional collaboration may constitute the main objective at this stage. Consistent with this, we observed significant enhancement in executive control-orienting collaboration. Posner and Rothbart (2000) also stressed parallel development of orienting and executive attention networks, suggesting orienting may represent a rudimentary form of inhibition. Some researchers have pointed out that coordination of top-down executive attention and bottom-up attention orienting constitutes the neural mechanism underlying these cognitive processes (Tian et al., 2014). Exogenous orienting is a bottom-up, stimulus-driven process that occurs when salient stimuli or environmental changes automatically draw and direct attention. However, orienting toward distracting events may impair ongoing processes. To avoid permanent distraction in an ever-changing environment, attention based on expectancies or internal goals—referred to as endogenous or top-down orientation—is essential for ensuring goal-directed behavior (Moyano et al., 2022; Wetzel & Schröger, 2007). These mechanisms depend primarily on executive attention (Rothbart et al., 2011), which shares common neural substrates with endogenous orienting (Rueda et al., 2015). Therefore, development of endogenous orientation inevitably depends on executive control development. Wainwright and Bryson (2005) examined endogenous orienting development in 6-, 10-, and 14-year-old children and adults using Posner's visual orienting task, suggesting that older children's better performance could be understood as better executive control helping modulate the breadth and density of attentional focus. Sørensen et al. (2019) further suggested that cardiac vagal activity (CVA), a specific psychophysiological indicator of executive control, is associated with early-stage attentional orienting, showing that high CVA levels were modulated by interactions between intrinsic orienting and executive control.

Pozuelos et al. (2014) also observed significant interactions between orienting and executive control in the ANT for children aged 6–12 years, with this trend continuing to develop throughout this period. Accordingly, enhanced collaboration between executive control and orienting may indicate a more complex system that can coordinate top-down and bottom-up information more effectively.

Furthermore, research suggests that the attentional disengagement component of orienting is influenced by the inhibitory control component of executive control, with stronger inhibitory control capability enabling faster attentional detachment (Hitzert et al., 2014). Thus, rapid inhibitory control development promotes attentional disengagement and reorientation. Sørensen et al. (2019) argued that higher CVA may facilitate flexible uptake of valid information during goal-oriented behavior while concurrently preserving attention on task-specific stimuli in the presence of distracting cues. In sum, higher executive control levels can beneficially affect orienting.

The effects of executive control, in conjunction with orienting, on alerting also increased with age. Our findings are highly replicable, yet these phenomena represent initial discoveries lacking theoretical explanation. Theoretical interdependence among attention networks may contribute to the effect of executive control-orienting collaboration on alerting. Furthermore, sustained attention studies have provided limited but valuable evidence regarding executive control effects on alerting. For instance, Luna et al. (2022) found that decreases in the executive component of vigilance were moderated by changes in executive control across time-on-task. This may explain why executive control effects on alertness have not been found in traditional ANT with event-related design. Additionally, in traditional ANT, executive control is always conducted after alertness, making it impossible to identify effects of later events on earlier ones. In the current study, participants persistently performed the same task over time, allowing us to detect the influence of executive control on alertness similar to that in sustained attention tasks.

Beyond these findings, regression analysis showed that when controlling for E influence, the linear developmental trajectory of attentional collaborations remained, indicating that developmental patterns between basic attentional functions and their collaborations are somewhat different.

4.3 Gender Differences

Gender differences in cognitive development have attracted considerable interest (Bethlehem et al., 2022). The absence of gender influence on attentional development trends aligns with some scholars' views but not others (Grissom & Reyes, 2019; Panwar, 2021; Slot & von Suchodoletz, 2018). For instance, a longitudinal study using the ANT explored attentional development differences between children with ADHD and typically developing children, revealing that gender and ADHD symptoms interacted with age on executive attention performance. Notably, girls with ADHD demonstrated superior performance and greater advancements over time (Suades-Gonzalez et al., 2017). Another ANT study with normal participants found no significant gender differences in alertness and executive control but revealed significant gender differences in orienting (Liu et al., 2013). However, earlier research indicated no orienting disparities between males and females (Koshino et al., 2000). Orientation involves multiple operations such as disengage, switch, and engage (Posner & Petersen, 1990; Posner & Raichle, 1994), yet we and other researchers did not decompose orienting for measurement as in the ANT-R (Fan et al., 2009). Additionally, varying stimulus onset asynchronies (SOAs) between cues and targets influence orienting (Mullane et al., 2016). Discrepant results among studies may stem from measuring different orienting types. However, combined with these findings, sex differences are often triggered by other factors such as motivation level (Dye & Bavelier, 2010) and cultural differences (Sobeh & Spijkers, 2012). Exploration of gender differences during attentional development remains necessary.

4.4 Paradigm and Reliability

We used steady-state block design, non-orthogonal computation, and directional interaction techniques to improve the validity and reliability of the classic ANT. Based on the HR-CAT, we determined that split-half reliability for primary school children reached approximately 0.8, representing a substantial increase compared to previous child research achieving reliability of only about 0.2 (Ishigami & Klein, 2014). This suggests the HR-CAT has potential to advance attention research in children as well as individuals with abnormal attention patterns.

5 Limitations

Future research would benefit from addressing several limitations of the present study. First, we did not control intra-individual differences across time. A longitudinal design is needed to overcome this limitation, wherein a cohort of children undergoes the HR-CAT at multiple time points. Second, we did not include older children, adolescents, or adults. This must be kept in mind because our results offer no information regarding attention network development trajectories beyond age 13. Additionally, although the study included both urban and rural subjects, we did not collect data on household economics. While split-half reliability in this work reached approximately 0.8, it remains limited by sample sources and other potential factors. Current findings warrant further studies with broader sampling environments and larger sample sizes.

6 Conclusion

This study provided a highly reliable paradigm for measuring developmental trajectories of attention in primary school children. It broadened the scope of attentional development by examining collaboration and directional influence between attentional functions. The development of basic attention and its collaborations, despite revolving around executive control, is driven by relatively independent mechanisms.

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