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Developmental Trajectories of Attention in Typically Developing Chinese Children: A Four-Wave Longitudinal Study

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ABSTRACT
We conducted a 4-year longitudinal study to investigate trajectories of attention in a sample of 145 Chinese children. The Test of Everyday Attention was administered and latent growth modeling was used to capture developmental trajectories. We found that children's selective attention showed a linear increase, whereas attentional control and sustained attention increased rapidly then slowed down over 4 years. There was no significant correlation between the slopes of growth model for any subsystems. Girls showed higher initial levels of selective attention than boys, but no difference in growth rate. These findings support different developmental patterns in the attention network systems.

Introduction

Attention, which has been viewed as a multidimensional system (Posner & Petersen, 1990), plays an important role in children's knowledge acquisition and integration (LeFevre et al., 2013; Steele, Karmiloff-Smith, Cornish, & Scerif, 2012; Stevens & Bavelier, 2012). Empirical findings suggest that deficits in attention may potentially affect children's academic and social outcomes (Baweja, Mattison, & Waxmonsky, 2015; Daley & Birchwood, 2010; Federico, Marotta, Martella, & Casagrande, 2016). Therefore, understanding the developmental trajectories of attention systems in children would help guide optimal educational strategies for parents and teachers. In the present study, we aimed to investigate the developmental trajectories of selective attention, attentional control/switching, and sustained attention, which have been identified as three major dimensions of the attention system (Chan, Wang, Ye, Leung, & Mok, 2008; Manly et al., 2001; Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991; Posner & Petersen, 1990), among Chinese primary school children.

Developments of selective, attentional control/switching, and sustained attention systems

Cross-sectional studies have provided extensive evidence suggesting potentially differential developmental trajectories of these three attentional subsystems (Klenberg, Korkman, & Lahti-Nuuttila, 2001; Steele et al., 2012). Furthermore, these attentional subsystems are associated with differential

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age-related changes in the gray matter morphological shape and the white matter anisotropy in the frontal and the parietal lobe, as well as in the basal ganglia and the thalamic pathways during childhood and adolescence (Barnea-Goraly et al., 2005; Konrad et al., 2005; Lenroot & Giedd, 2006; Schmithorst, Wilke, Dardzinski, & Holland, 2002). For instance, the parietal lobe cortical gray matter has been observed to peak at 10–12 years, while the frontal lobe gray matter reaches its maximal volume at 11–12 years. White matter volume and fractional anisotropy in this region, on the other hand, was reported to continuously increase (Barnea-Goraly et al., 2005; Silk, Vance, Rinehart, Bradshaw, & Cunnington, 2009). This reflects progressive myelination and density enhancement, which are very important for attention development (Barnea-Goraly et al., 2005; Silk et al., 2009).

Selective attention refers to the ability to detect a target from competing or unrelated stimuli, objects, and locations. It involves two distinct processes: top-down and bottom-up processes (Desimone & Duncan, 1995; Muller et al., 2017). Top-down attention (i.e., endogenous attention) can be voluntarily deployed toward dedicated items in a goal-driven manner (i.e., searching for bright yellow lemon in the fruit market). This process is supported by the dorsal attention network (DAN) that is mainly located in the frontal eye fields and the intraparietal sulcus (Corbetta & Shulman, 2002; Posner & Petersen, 1990; Squire, Noudoost, Schafer, & Moore, 2013). Bottom-up attention (i.e., exogenous attention), on the other hand, is more involuntarily and often automatically oriented to physically salient stimuli (i.e., a sudden falling of a yellow stuff). This process is more a function of the ventral attention network (VAN) centered in the temporoparietal junction and the ventral frontal cortex (Corbetta & Shulman, 2002; Posner & Petersen, 1990; Squire et al., 2013). It is generally agreed that these two processes interact with one another in the tasks of selective attention (Barnea-Goraly et al., 2005).

Findings of cross-sectional studies have shown that the abilities of bottom-up and top-down selective attention show continuous improvements from infancy to early adolescence (Klenberg et al., 2001; Määttä, Pääkkönen, Saavalainen, & Partanen, 2005; Tummeltshammer, Mareschal, & Kirkham, 2014). Specifically, infants from 3 to 6 months old begin to show the phenomenon of "pop out" when searching for visual stimuli with unique perceptual features from dissimilar distractors (Adler & Orprecio, 2006; Tummeltshammer et al., 2014). Findings from another study using a colored shape searching task suggest that 6-month-old infants are able to orient their attention using rapidly learned top-down knowledge about features of the visual environment (Tummeltshammer & Amso, 2017). This ability continues to develop until late childhood (Abundis-Gutierrez, Checa, Castellanos, & Rosario, 2014; Klenberg et al., 2001; Määttä et al., 2005). Neuroimaging studies have also reported that functional connectivity within the DAN for top-down attention and the VAN for bottom-up strengthens with age (Farrant & Uddin, 2015; Rohr et al., 2016).

Attentional control/switching refers to the ability to intentionally deploy attention to a contextually appropriate target rather than a predominant one. These processes are closely associated with the middle cingulate-insular-inferior frontal network (Brocki, Clerkin, Guise, Fan, & Fossella, 2009; Cieslik, Mueller, Eickhoff, Langner, & Eickhoff, 2015), as well as the parietal regions (Yantis & Serences, 2003). A large number of cross-sectional studies have suggested a potential nonlinear developmental trajectory in attentional control/switching (Daza & Phillips-Silver, 2013; Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004; Lewis, Reeve, & Johnson, 2016; Rueda et al., 2004). For example, Rueda and colleagues (2004) employed Attention Network Test (ANT) and found that prominent maturation of attentional control typically occurred between 6 and 7 years of age and largely stabilized by 7 years. Klimkeit et al. (2004) employed a novel selective reach task and found that maturation of set-shifting and response inhibition occurred between 8 and 10 years, with a plateau in performance between 10 and 12 years of age. These findings suggest a nonlinear growth trend in the set-shifting and response inhibition abilities. Meanwhile, other studies have argued that attentional control/switching develops over childhood and does not completely mature until 12 years old (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Davidson, Amso, Anderson, & Diamond, 2006; Daza & Phillips-Silver, 2013). Neuroimaging study found that children aged 8–12 years showed reduced frontoparietal activity during anti-saccade preparation, along with longer reaction times and more errors compared to adolescents 13–17 years and adults 18–25 years old, indicating that these nonlinear brain maturation trends are also associated with behavioral performance (Alahyane, Brien, Coe, Stroman, & Munoz, 2014).

Sustained attention refers to the ability to maintain attentional focus over time, which is facilitated by the anterior cingulate, the dorsolateral prefrontal, the parietal cortical regions, and the cholinergic inputs originating in the basal forebrain (Sarter, Givens, & Bruno, 2001). Extensive cross-sectional studies have suggested that the ability of sustained attention follows a nonlinear developmental trajectory. For instance, studies using visual and auditory continuous performance tasks (CPTs) have reported a rapid improvement in sustained attention in early childhood (around 3–6 years; Guy, Rogers, & Cornish, 2013) and middle childhood (around 6–9 years; Betts, McKay, Maruff, & Anderson, 2006; Lin, Hsiao, & Chen, 1999). Similarly, studies using CogState and "Score!" (one subtest of children version of Test of Everyday Attention) have also revealed continuous developmental change of sustained attention during early childhood (Betts et al., 2006; Guy et al., 2013; Klimkeit et al., 2004; Lin et al., 1999). Further, Lin et al. (1999) found that the ability of sustained attention followed a quadratic growth from ages 6 to 15 years. Specifically, they found a rapid improvement during early childhood (6–9 years), but a slow growth during adolescence (around 10–15 years; Lin et al., 1999). Imaging studies have also found that multiple neural networks related to sustained attention exhibit significant maturation from childhood to young adulthood, including the networks within the default mode network (DMN), and between the DMN, the frontoparietal network (FPN), the DAN, and the VAN (Bunge et al., 2002; Fair et al., 2008; Kessler, Angstadt, & Sripada, 2016; Sripada, Kessler, & Angstadt, 2014). A resting-state imaging study of 519 youths aged 8–17 years found that the intra-connectivity within the DMN, the interconnectivity between the FPN and the DAN were modulated by age (i.e., increased connectivity with age; Kessler et al., 2016).

Taken together, evidence from cross-sectional studies suggests that there are different maturation trajectories in different subsystems of attention. However, a common limitation of previous studies is that they adopted a cross-sectional design, which does not necessarily determine developmental change patterns comparing to a longitudinal design. For example, a cross-sectional design is unable to disentangle time-variant unobserved individual differences (such as sex differences) and is therefore unable to make causal inferences. To the best of our knowledge, there is a lack of studies investigating developmental changes in these attention subsystems among typically developing children using a longitudinal design. We only found one longitudinal study in this area, which measured different structure of attention subsystems (Lewis et al., 2016). This study found that the alerting subsystem continued to develop after 11 years old, whereas the orienting subsystem and attentional control subsystem stabilized by 6 and 7 years old, respectively. However, repeated measures analysis of variance adopted in this study only assessed the mean differences of attention system over time. Thus, the specific characteristics within the developmental trajectory of attention remain unclear. Therefore, we employed latent growth modeling (LGM) to examine attention systems in children longitudinally across 4 years, as it allows precise and flexible evaluation of developmental trajectories (Voelkle, 2007).

In the present study, we employed the Test of Everyday Attention for Children (TEA-Ch; Manly et al., 2001) to examine selective attention, attentional control/switching, and sustained attention of interest. The adult version of the ANT in Lewis' (2018) study comprises of several laboratory-based tasks, which might not accurately reflect children's attention functioning in their everyday life (Bruyneel et al., 2013; Chan et al., 2008), and thus might affect children's motivation to complete the tasks. Therefore, TEA-Ch is a more ecologically valid and child-friendly task. It has several advantages over conventional laboratory-based assessments. The primary advantage is that the tasks incorporated are more relevant to everyday life activities. For example, in the Map Mission task, children are asked to search the map of a real region and to find out the target symbol ("fork and knife," representing restaurant) from distractor symbols (i.e., petrol machine, representing Petrol Station, etc.). Second, TEA-Ch is a game-like test that may better motivate children to complete the test. In the Sky Search task, for instance, cartoon spaceships are used as the stimuli. Finally, a validated Chinese version of TEA-Ch is available, with a stable three-factor model of attention with acceptable psychometric statistics (Chan et al., 2008).

Another gap in the literature is that the effect of sex on attention development in children is poorly understood. Previous studies have reported disorders of attention such as attention deficit hyperactivity disorder (ADHD), symptoms of which occur more in males than in females, with a 3:1 male-to-female ratio in community samples and even higher ratio in clinical samples (Silk et al., 2009). Further, sex differences have been observed in selective attention (Merritt et al., 2007), sustained attention (Riley et al., 2016), and attentional switching (Riley et al., 2016) measured by various experimental paradigms such as Posner Cueing task and the gradual onset CPT. For example, males performed faster and less variably than females but made more commission errors in the gradual onset CPT (Riley et al., 2016). Neuroimaging studies have also found that gray matter volume in the frontal lobe and the parietal lobe, which relates to attention processing (Cieslik et al., 2015; Posner & Petersen, 1990; Squire et al., 2013), peaked at earlier age for females (Frontal: age 9.5; Parietal: age 7.5) than males (Frontal: age 10.5; Parietal: age 9; Lenroot & Giedd, 2006). Nevertheless, other studies showed no sex differences in the performances of selective (Solianik, Brazaitis, & Skurvydas, 2016), sustained attention (Chan, 2001), or attentional switching (Bellaj, Salhi, Le Gall, & Roy, 2016). Thus, the present longitudinal study aimed to explore whether the developmental trajectories of attention systems vary by child sex.

The present study

The present study examined the three attention subsystems in 7-year-old children over 4 years using TEA-Ch. In order to ascertain the stability of attention system over 4 years, we first assessed factorial invariance of the three-dimensional attention models. Then, we aimed to assess developmental trajectory of each attention subsystem by using LGM. Given sex differences found in previous studies (Feng et al., 2011; Merritt et al., 2007), we also examined sex differences in the developmental trajectories of the attention systems. We hypothesized that the construct of the attention systems would be stable over 4 years. We also hypothesized that the selective attention subsystem might follow a linear increase, whereas switching/controlling attention and sustained attention subsystems might show nonlinear developmental trajectories. Finally, we hypothesized that there would be sex differences in the developmental trajectories of attention. Specifically, regarding faster rate of brain maturation (i.e., prefrontal structure) in female (Lenroot et al., 2007), girls may show better initial ability or higher growth rate in the attention system than boys.

Method

Participants

A total of 152 Chinese children were recruited from one "general" primary school in the city of Shanghai (located in Eastern China), which enrolls approximate 155 students each year. A "general" primary school in China usually enrolls around 800–1,200 students across five grades coming from working-class families. There are 4–8 classes in each grade and 30–50 teachers teaching different subjects including literature, mathematic, and natural science. Seven children were excluded from the present study due to the following reasons: (1) 12 months older or younger than the average enrollment age (7 years old) of the primary school (n = 1); (2) missing data due to school transfer (n = 1); (3) low scores on Raven's Test (<70; Gonzalez et al., 2016; Zhang, Liu, Zhang, & Yu, 2011; n = 1); and (4) incomplete data (data were unavailable for more than one wave, n = 4). Finally, 145 children at the first wave were included in further analyses. The average standardized score of Raven's assessment was 118 (range: 90–135, SD = 10.77; Skewness = −.02, Kurtosis = −.62 for the current sample; 100 is the mean score for the standardization sample).

Written consent was obtained from parents before the tests. According to each child's Personal Health and Development Record that was completed at the first year of their enrollment by physicians, no child was diagnosed with conduct disorder, ADHD, autistic spectrum disorder, schizophrenia spectrum disorder, or mood disorders. All of them had normal or correct-to-normal vision and were naturally or forced right-handed (i.e., someone, who is born left-handed, was routinely made to use right hand to do some of tasks like writing, drawing, and eating). The present study was approved by the Ethics Committee of East China Normal University.

Design and materials

We employed the TEA-Ch to measure the ability of selective attention, attentional control/switching, and sustained attention (Manly et al., 2001). Using the Chinese version, Chan et al. (2008) showed that the assessments yielded a similar factor structure as that of the original version, Goodness of fit: χ^2 (24) = 34.56; *Root mean square error of approximation* (RMSEA) = .04, p = .08. Furthermore, the official guideline reported high test–retest reliability correlations for all the subtests (.71–.85; Manly et al., 2001).

Five subtests of TEA-Ch including Score, Score DT, Code Transmission, Walk Don't Walk, and Sky Search DT were employed to measure sustained attention. Creature Counting and Opposite Worlds tasks were used to assess attentional control/switching. Finally, Map Mission and Sky Search tasks were employed to measure selective attention.

TEA-Ch's version

Selective attention

Sky Search. Sky Search is a 3-min subtest, containing two blocks: Searching Block and Motor Control Block. In Searching Block, children were provided with an A3-sized paper sheet filled with 108 pairs of identical and similar distractor spaceships, then were asked to find out as many identical pairs as possible. In the Motor Control Block, children were subsequently presented with 20 pairs of identical spaceship and asked to circle all the 20 pairs to measure the baseline motor speed of each child. The correct items and time spent were recorded in the Searching and Motor Control Blocks. To measure the ability of selective attention free from the influence of motor speed, the score of Sky Search was calculated by subtracting the time spent in Motor Control Block from the time spent on correctly identifying the identical pairs in the Searching Block.

Map Mission. In the Map Mission subtest, children were given a city map containing varied symbols representing different facilities. Children were instructed to search the map to find as many target symbols (i.e., Knife-and-Fork) as they could in 1 min. The number of targets correctly marked was recorded as the score of Map Mission.

Attentional control/switching

Creature Counting. In this subtest, children were asked to count a variable number of aliens in their burrow, with occasional arrows (up or down) indicating a change of the direction in which they were counting. The Up arrow indicates counting upward, whereas the down arrow indicates counting downward. Children were asked to complete seven test items after two practice items, which took approximately 5 min. Time taken and accuracy were recorded in this subtest.

Opposite Worlds. Opposite subtest is a 1-min subtest including two blocks: the Same World and the Opposite World. In the Same World block, children were asked to follow a path naming digits 1 and 2 that are randomly arranged. In the Opposite World block, children were presented with the same type of task except that children must say "one" when they saw the digit "2" and say "two" when they saw digit "1." The time taken to complete the task was recorded as the score of this subtest.

Sustained attention

Score. This subtest is a 10-item sounds-counting task, which takes around 6 min for children to complete. In each trial, children were asked to silently count the number of "scoring" sounds they hear on a tape and report the total number at the end of the trail. The number of "scoring" sounds was presented for around 345 ms, separated by varied silent intervals (ranging from 500 to 5,000 ms). We recorded the number of trials, in which the child gave the correct response.

Score DT. Children were asked to combine the task of "Score" with another task involving reporting animal names while listening to a spoken news bulletin. Specifically, children were asked to keep counting the scoring sounds while listening to and orally reporting animal names from the spoken news bulletin simultaneously. We recorded the number of correct response to "score" sounds and animal names, respectively.

Code Transmission. In this subtest, children were asked to monitor a stream of monotonous digits and immediately announce the digit presented just before two "5." There were 40 digit targets in total, lasting approximately 12 min. Their performance was indicated by the total number of digits which were correctly announced.

Walk Don't Walk. In this subtest, children were asked to take one step along a paper path by marking the path using a pen, after each tone they heard on a tape. When children heard a tone that ended differently from the rest, they needed to stop marking. The intervals between each tone were continuously decreasing from 1,500 ms at the beginning trial to around 500 ms at the ending trial. The entire subtest took over 6 min. We recorded the number of correct responses as the score of this subtest.

Sky Search DT. This is 1-min subtest, combining the tasks of finding spaceships (Sky Search) and counting "score" sounds (Score!). We recorded the time taken to complete the trial, the number of correct counting, and the correct number of identical pairs of spaceships as the scores of this subtest.

All children, sitting individually in a quiet room at the primary school, were administrated with the TEA-Ch by well-trained research assistants between April and May each year. In addition, to measure intelligence, Raven's Progressive Matrices test (Raven, Raven, & Court, 1998) was administered to all the children.

Data analyses

Factorial invariance analysis

Data analyses were performed using Mplus Version 7 (Muthen & Asparouhov, 2006). To test the stability of latent structure of TEA-Ch, we established and tested longitudinal factorial invariance of the model which contained three attention subsystem factors (Chan et al., 2008). We had four nested models which involved a hierarchy of increasingly stringent constraints (Hofer, Horn, & Eber, 1997; Meredith, 1993) including (1) baseline model, where configural invariance was evaluated; (2) weak factorial invariance, where factor loadings were constrained across four waves; (3) strong factorial invariance, where additional equality constraints were placed on the intercept terms; and (4) strict factorial invariance, in which residual variances were additionally constrained. Goodness of fit for the factorial invariance models was tested by examining the Chi-square to the degrees of freedom (χ^2/df). Bonferroni correction was used for multiple comparisons. The p value for the χ^2 above .05 was regarded as acceptable. Relative fit indexes did not decrease more than 0.02 for any of the models (Conroy & Metzler, 2003).

Latent growth modeling (LGM)

LGM was performed to evaluate the developmental trajectory of the three attention subsystems. The intercept represents the initial level of each latent construct. The slope represents the rate of average change over time. In order to determine the trajectories of the three attention subsystems, we tested both linear and quadratic growth models separately and evaluated which model fit the observed data better for each attention subsystem across four waves. The Intercept loadings of growth models were constrained to be equal, and the loadings of the slope were set to be 0, 1, 2, and 3 for four waves. Quadratic loadings were additionally set as 0, 1, 4, and 9 in quadratic models (Hess, 2000). Further, in order to determine the relationship of developmental trajectories of different attention subsystems, we established a model comprised of three attention subsystems across four waves. In view of different scaling used in these subtests of TEA-Ch (i.e., correct number in Map Mission; time taken in Opposite Worlds), we calculated the transformed scores for each attention subsystem. Before forming unit-weighted transformed scores, we standardized scores with respect to the means and the standard deviations of wave 1 scores (Wagner, Torgesen, & Rashotte, 1994). Thus, we created scores that were referenced to the amount of naturally occurring variance found in wave 1.

In order to test sex differences in the developmental trajectory of attention, we conducted multiple group analyses by comparing the model of no constraint with those of increasing stringent invariance constraints including intercept mean, slope mean, intercept variance, slope variance, covariance of intercept and slope, and residual errors.

Chi-square to the degree of freedom (χ^2/df) served as the absolute goodness of fit. Value of p above .05 indicates no significant difference between theoretical model and observed data and that the model is acceptable. In the present study, we performed Satorra–Bentler scaled Chi-square testing for the nested models with robust maximum likelihood estimators. In addition, RMSEA (with acceptable value below .06), comparative fit index (CFI, with acceptable value above .95), and standardized root mean square residual (SRMR, with acceptable value below .05) were also employed to reflect the model fitness, which are sensitive to model misspecification and insensitive to distribution and sample size (Bentler, 2010). In addition, before running the LGM, missing data for some children was estimated by using Full information Maximum Likelihood Estimation imputation in Mplus.

Results

Demographic characteristics

In the present study, a total of 152 children were assessed; however, 7 were excluded from further analysis as they did not meet the inclusion criteria. Finally, 145 children (male = 73, female = 72) aged 86.53 months (SD = 3.79) were included in the analysis. There were no significant differences in age means between children eliminated from sample (M = 88.17 months, SD = 3.79) and children included (M = 86.53 months, SD = 6.97) at wave 1, $t = -.016$, $p = .99$. As to sex, we did not find significant differences in sex ratio between children eliminated from sample (male = 73, female = 72) and children included (male = 4, female = 3), χ^2 (1) = .12, $p = .73$.

Establishing factorial invariance of attention system

Factorial invariance over the four waves was analyzed for the model containing selective attention, attentional control/switching, and sustained attention factors. Goodness of fit statistics for the different level of invariance are presented in Table 1. The model with strict factorial invariance exhibited acceptable goodness of fit, suggesting that the latent structure of attention system over 4 years is reliable, $\Delta\chi^2$: .60–11.51, Δdf: 18–9, p-values > .05; ΔCFI: .11–.23; ΔRMSEA: .01–.02.

Table 1. Testing of measurement invariance.

Model	χ^2	*df*	*CFI*	*SRMR*	*RMSEA*	$\Delta\chi^2$	Δdf	Δp	ΔCFI	$\Delta RMSEA$
Configural	125.48	96	0.95	0.05	0.05					
Weak	136.99	114	0.96	0.07	0.04	11.51	18	.87	.01	.01
Strong	141.10	132	0.99	0.07	0.02	4.11	18	.99	.02	.02
Strict	141.70	141	0.99	0.07	0.01	0.60	9	.99	.01	.02

Note: df = degree of freedom; CFI = comparative fit index; SRMR = standardized root mean square residual; RMSEA = root mean square error of approximation.

Developmental trajectories of attention system in children

Figure 1 presents trajectories of selective attention, attentional control/switching, and sustained attention in children over four waves. We found that both the linear LGM (χ^2 (5) = 4.70, p = .45, CFI >1.00, RMSEA <.01, 90% confidence intervals (CIs) [0.00–0.11], SRMR = .04) and the quadratic model (χ^2 (1) = 1.19, p = .28, CFI = .99, RMSEA = .04, 90% CI [0.00–0.23], SRMR = .02) provided good fit for the data of selective attention. We further evaluated Akaike Information Criteria (AIC; Fair et al., 2008) and Bayesian Information Criteria (BIC) for these two models and found LGM seemed to have a more acceptable value than quadratic model, Linear: AIC/BIC = 1,326.60/1,353.39; Quadratic: AIC/BIC = 1,331.21/1,369.91. But the relative likelihood ratio between linear model and quadratic model was relatively higher than .05 (Relative likelihood ratio = .08), indicating linear model only had a tendency to fit the data of selective attention over quadratic model. Selective attention tended to develop at a constant and rapid growth rate in children from 7 to 10 years, Slope = .68; Intercepts = .02 (see Supplementary Figure 1 for the path diagram).

Regarding attentional control/switching, the quadratic growth model rather than the linear growth model fit the observed data well (Quadratic model: χ^2 (1) = .05, p = .83, CFI >1.00,

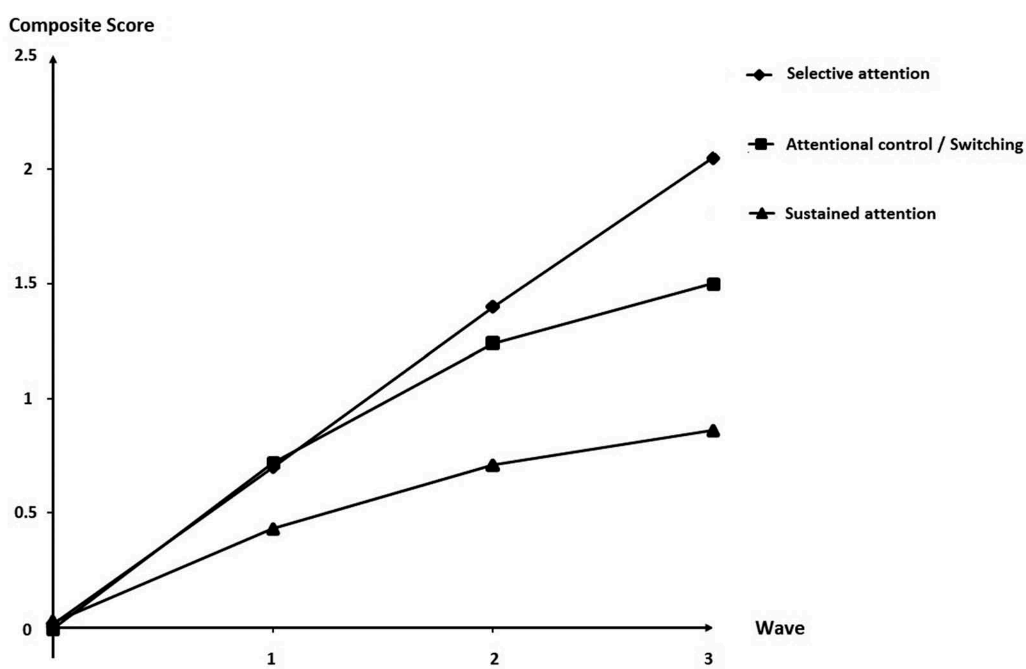

Figure 1. Developmental trajectories of attention subsystems in children.

The figure showed developmental trajectories of selective attention, switching/control attention, and sustained attention subsystems. The horizontal axis refers to waves, and the vertical axis refers to transformed scores of TEA-Ch.

RMSEA <.01, 90% CI [0.00–0.13], SRMR = .003, AIC/BIC = 711.04/749.73; Linear model, χ^2 (5) = 60.52, p < .01, CFI = .75, RMSEA = .28, 90% CI [0.00–0.13], SRMR = .14, AIC/BIC = 767.10/793.89). It indicates a curvilinear change in attentional control/switching with sharply rapid improvements from relatively low initial level at early period of childhood followed by stable improvements at later period, Linear coefficient: 0.86; Intercept: −.01; Quadratic coefficient: −.12 (see the path diagram of Supplementary Figure 1).

Finally, we found that the quadratic growth model (χ^2 (1) = .09, p = .08, CFI >1.00, RMSEA <.001, 90% CI [0.00–0.15], SRMR = .01, AIC/BIC = 658.66/697.36) provides a good fit for the data of sustained attention as compared with the linear model (χ^2 (5) = 17.40, p = .004, CFI = .90, RMSEA = .13, 90% CI [0.00–0.15], SRMR = .07, AIC/BIC = 668.98/695.77). The ability of sustained attention increased at moderate speed during early period but a slow rate during later years, Linear coefficient: 0.47, Intercept: 0.02, Quadratic coefficient: −0.06 (see the path diagram of Supplementary Figure 1).

Difference between developments in attention subsystems

In order to determine the relationship between developmental trajectories of different attention subsystems, we established a model comprised of three latent growth sub-models of attentional systems. In this model, correlations of intercepts and slopes of three LGM of attention subsystems were examined. This model fit data well (χ^2 (34) = 31.48, p = 0.59, CFI = 1.00, RMSEA <.001, 90% CI [0.00–0.05], SRMR = 0.05, AIC/BIC = 2,611.86/2,778.55).

We found that the intercept of attentional control/switching was positively related to intercepts of selective attention, r = .25, and sustained attention, r = .20, suggesting close relationships between the initial levels of attention subsystems at 7 years of age. We did not observe any significant correlation between slopes of selective, attentional control/switching, and sustained attention, suggesting an independent development pattern of these three subsystems in children (see Table 2).

Sex differences in the developmental trajectories of attention network

There was a significant sex difference in the intercept of selective attention, $\Delta\chi^2$ = 6.12, Δdf = 1, p < .05, but not in the slope comparing with that of the none-constrained model. In particular, the intercept value of girls was higher than that of boys. However, we did not observe any other significant differences in slopes or intercepts of other two attention subsystem models (all p-values > .05).

Discussion

The present study aimed to examine developmental trajectories of attention subsystems including selective attention, attentional control/switching, and sustained attention subsystem in children aged from 7 to 10 years. There was no significant variability in the three-factor model of attention system, indicating that the structure of the attention system assessed by TEA-Ch was stable in children aged 7–10 years. We found that children displayed a linear growth trend in selective attention, but showed curvilinear trends in attentional control/switching and sustained attention. Further, we did not observe any significant correlations between slopes of attention subsystems, indicating that there are independent growth rates for different attention subsystems. This sex difference was only observed in children’s initial ability of the selective attention but not in other two attention subsystems.

Table 2. Relationship between intercept, slope, and quadratic index of three-dimensional model of attention system.

			Intercept			Slope			Quadratic	
			CO	SE	SU	CO	SE	SU	CO	SU
Intercept	CO									
	SE	r	0.25**							
		95% CI	(.13, .37)							
	SU	r	0.20**	0.07						
		95% CI	(.10, .30)	(−.02, .15)						
Slope	CO	r	−0.26*	−0.10*	−0.06					
	95% CI	95% CI	(−.46, −.05)	(−.19, −.01)	(−.13, .003)					
	SE	r	0.03	−0.003	0.02	−0.01				
	95% CI	95% CI	(−.01, .06)	(−.07, .06)	(−.01, .05)	(−.03, .02)				
	SU	r	−0.01	0.05	−0.09	0.05	−0.01			
	95% CI	95% CI	(−.11, .08)	(−.03, .13)	(−.26, .08)	(−.03, .13)	(−.04, .02)			
Quadratic	CO	r	0.04	0.02	0.01	−0.03	0.002	−0.01		
	95% CI	95% CI	(−.004, .09)	(−.01, .04)	(−.01, .03)	(−.08, .02)	(−.01, .01)	(−.03, .01)		
	SU	r	−0.008	−0.02	0.02	−0.01	0.001	−0.02	0.003	
	95%CI	95% CI	(−.04, .02)	(−.04, .01)	(−.02, .06)	(−.03, .01)	(−.01, .01)	(−.07, .02)	(−.003, .01)	

Note: CO = control attention/switching; SE = selective attention; SU = sustained attention; CI = confidence interval. *<0.05, **<0.01.

Developmental trajectories of attention subsystems

In the present study, we found that selective attention followed a linear developmental trend, which indicates a constant rapid development in children from 7 to 10 years old. Our findings are consistent with previous cross-sectional studies that found age differences in children employing various laboratory-based paradigms (Klenberg et al., 2001; Määttä et al., 2005; Mulder, Pitchford, Hagger, & Marlow, 2009). For example, studies have found that selective attention improves from infancy (Bhatt, 1997; Klenberg et al., 2001; Plude, Enns, & Brodeur, 1994). One study that used eye-tracking techniques and the colored shapes searching task reported that infants as young as 6 months exhibited faster searching time, fewer looks at distracters, and more anticipation of targets when the same contexts are displayed again. This indicates that young infants are able to orient their attention to the targets with the help of their rapidly acquired knowledge (Tummeltshammer & Amso, 2017). Other studies that used the color attention task found age-related decreases in the latencies of frontal selection positivity (140–275 ms), N2b (200–450 ms), and P3b (300–700 ms), which paralleled decreases in their response time and error rates on the task among young adults (i.e., aged 19–24; Van Der Stelt, Kok, Smulders, Snel, & Gunning, 1998). These findings suggest that there is a constant growth in selective attention across a large age range. This linear growth trajectory may also be associated with the continuous development in children's prefrontal and parietal function.

In addition, neuroimaging studies showed that children's age was positively correlated with functional connectivity between the nodes of the DAN (including the frontal eye field and the intraparietal sulcus) in 4–7-year-old children (Rohr et al., 2016). Meanwhile, the functional connectivity between these two brain areas decreased in children from 8 to 12 years old compared to adults (Farrant & Uddin, 2015), indicating a potential continuous brain network development during childhood. Note that the subtests of TEA-Ch which captures children's attentional ability in their everyday life might require more top-down cognitive processing as compared to those tests administered in the laboratory environment. Specifically, in the selective attention subtests of TEA-Ch, children need to consciously select the target they have previously learned amongst a number of very similar distractors. Thus, the subtests might tap into the ability of endogenous, voluntary shifts of attention rather than selective attention. This suggests that "endogenous" selective attention may require much more time to reach maturity during childhood.

Regarding the attentional control/switching system, we found that this ability showed a curvilinear trend across four waves, with rapid improvements during early years and a steady growth later. Our findings are in line with previous cross-sectional studies reporting significant improvements between ages 8 and 9–10 years, followed by slow improvements in performance from ages 9 to 10 years to early adulthood (Davidson et al., 2006; Klimkeit et al., 2004; Pozuelos, Paz-Alonso, Castillo, Fuentes, & Rueda, 2014; Satterthwaite et al., 2013).

This developmental trajectory may reflect protracted rates of morphological (i.e., gray matter loss) and functional (activity and connectivity) changes in the anterior cingulate cortex, insula, and inferior frontal gyrus which are associated with executive control (Amso & Scerif, 2015; Cieslik et al., 2015; Fair et al., 2007; Gogtay et al., 2004). However, other studies using ANT to measure executive attention have reported that the developmental improvement of this ability increases until approximately 7 years old, with no reliable improvements after 7 years old (Daza & Phillips-Silver, 2013; Lewis et al., 2016), which is partially consistent with our findings. The inconsistency for the age of maturity can be interpreted as the result of different types of task employed in different studies. It is possible that better performance of ANT in the laboratory environment reflect specific and basic processes associated with executive control, which might reach maturation at early stage of childhood. The TEA-Ch, however, may reflect more general and comprehensive construct of attentional control system, which we speculate may develop at a later childhood. Taken together, our findings suggest that there is a curvilinear trend in attentional control/switching subsystem with major development in early stages of primary school followed by a plateau in subsequent primary school years.

Similarly, the sustained attention also showed a curvilinear trend from ages 7 to 10 years old in the current study, which is consistent with the findings of cross-sectional studies (Betts et al., 2006; Lin et al., 1999; Pozuelos et al., 2014). For example, Betts et al. (2006) employed simple reaction time tasks, the score task from TEA-Ch, and tasks from the CogState Battery, and found that children showed a rapid improvement from ages 5–6 to 8–9 years. However, they also observed a subsequent developmental plateau from 8–9 to 11–12 years with only minor improvement (Betts et al., 2006). In another study with a larger sample (n = 341), Lin et al. (1999) reported that hit rate and sensitivity in the CPT in children aged 6–15 years old suggested a quadratic trend, improving rapidly in early childhood and leveling off during late childhood. Further, evidence from a functional neuroimaging study showed that there was an age-related increase in activation in the right inferior frontal, the superior temporoparietal, and the cerebellar cortices during processing of sustained attention in participants aged between 10 and 43 years. These findings may suggest that these areas are associated with underlying neurodevelopmental substrates of sustained attention in late childhood, adolescents, and adults (Smith, Halari, Giampetro, Brammer, & Rubia, 2011). However, the developmental trajectory of brain network for sustained attention during early childhood remains unclear. Further longitudinal neuroimaging studies are needed to verify these findings. Nevertheless, our findings suggest a nonlinear developmental trajectory in sustained attention with fast development changes in early primary school stage and slow changes in later stage.

Additionally, we did not observe any significant relationships between the change rates (slope) of selective, attentional control/switching, and sustained attention. This suggests that there may be separate developmental trajectories for each attention subsystem. In line with our findings, other studies using ANT have also found differential developmental trajectories for alerting, orienting, reorienting, and executive attention (Lewis et al., 2016; Pozuelos et al., 2014), which may be associated with different brain maturity rates of each attention subsystem (Posner, 2012). Studies examining loss of gray matter volume have shown that the visual and sensory cortex develops in early stage of childhood (orienting), followed by the temporoparietal regions (sustained attention), and then the prefrontal regions (attentional control/switching and selective attention; Amso & Scerif, 2015; Gogtay et al., 2004). Since the prefrontal cortex is one of the last brain regions to lose gray matter volume, this may be reflected in the later maturation of the selective attention subsystem in the present study.

Notably, substantial evidence has suggested a close relationship between different aspects of the attention subsystems and stages of working memory (Chun, 2011; Gazzaley & Nobre, 2012; Olivers, Peters, Houtkamp, & Roelfsema, 2011; Shipstead, Lindsey, Marshall, & Engle, 2014). Using a dual task paradigm, Olivers et al. (2006) found that the presence of distractors interfered more strongly with the performance of selective attention when participants were asked to simultaneously memorize visual stimuli. This suggests involvement of visual selective attention in the encoding and maintenance stage of working memory (Gazzaley & Nobre, 2012).

Further, these two stages of working memory may also involve sustained attention to a limited number of visual objects and locations. This is because success of working memory maintenance largely depends on the ability of internal vigilance and inhibiting both perceptual and cognitive distraction (Chun, 2011; Matsukura, Luck, & Vecera, 2007). Kim, Kim, and Chun (2005) examined attentional control by varying working memory load and found increased interference when both working memory load and Stroop task were in the same modality (i.e., both verbal). This may indicate that attention control and central executive system of working memory may share common mechanisms (Kim et al., 2005). We found that some subtests of TEA-Ch themselves are highly cognitive demanding. For example, in the Score Dual task, children were required to retain the updating number of "Score" sounds while identifying the animal name occasionally appeared in the spoken news. Thus, we acknowledge that the findings of attention development trajectory of selective attention, attentional control/switching, and sustained attention could be affected by children's development of working memory. Thus, future studies are warranted to address specifically how working memory interact with the development of attention during childhood.

Altogether, our findings suggest that children aged 7–10 years old have differential developmental trajectories of attention subnetworks, which may again support Posner's framework on attention network (Posner & Petersen, 1990).

Sex differences in the development of attention network

We observed that girls performed better than boys in the selective attention tasks over four waves. This finding was consistent with Merritt et al. (2007)'s study employing the basic Posner cueing paradigm. They reported that adult females showed larger validity effects in the endogenously cued task than males (Merritt et al., 2007). This might be related to the top-down cognitive processing required in the tasks (i.e., Map Mission, Sky Search, and Posner cueing paradigm, which involves internal knowledge and voluntary shifts in attention). Therefore, when more voluntary and cognitive resources are required, girls may perform better in the selective attention tasks than boys do. Moreover, our findings are also in line with neuroimaging studies. Females' higher scores on the performance of selective attention tests might be associated with their earlier maturation of the prefrontal cortex compared to males (Lenroot et al., 2007). Further, the gray matter volume of the frontal lobe was proportionately larger in females than in males even after controlling for total brain volume, in which the neural functions are closely associated with the ability of selective attention (Corbetta & Shulman, 2002).

Of note, we could not exclude the possibility of systematic bias in selective attention between females and males. Given the facts that females possess more than three cone pigments in their retina, they are able to perceive more chromatic bands in the range of 380–780 nm than normal males (Jameson, Highnote, & Wasserman, 2001) and thus have an advantage to pay more attention on the green–red axis compared with males in the color vision task (Bimler, Kirkland, & Jameson, 2004). Therefore, females might be more sensitive to the target in the colorful Map Mission task than males. Further studies are encouraged to address this possibility of systematic bias of sex by using varied types of tests to measure selective attention.

Nevertheless, we did not observe sex differences in the development of the other two subsystems, (i.e., attentional control/switching and the sustained attention). In line with our findings, a number of cross-sectional and longitudinal studies have also found that sex differences are insignificant on the performance of these two subsystems (Daza & Phillips-Silver, 2013; Lewis et al., 2016; Stoddard, Beckett, & Simon, 2011). Furthermore, there is evidence from neuroimaging studies showing no sex differences in cortical thickness (O'Donnell, Noseworthy, Levine, & Dennis, 2005; Salat et al., 2004) and in gray matter volume of most brain regions such as the parietal lobe, corresponding to sustained attention and attentional control/switching (Lenroot et al., 2007).

Clinical implications

Previous studies have reported that the onset for impulse-control disorders (i.e., ADHD), oppositional-defiant disorder, conduct disorder) is quite early, starting from 11 years old (Kessler et al., 2005; Kieling, Kieling, & Rohde, 2010). Given the fact that children with these disorders (i.e., ADHD) exhibit impairments in selective attention, attentional control, and sustained attention (Heinrich et al., 2017; Wang et al., 2013), our findings of normative developmental trajectories of attention system in early childhood (7–10 years) might be beneficial to aid early detection and intervention of those impulse-control disorders. For instance, future studies can be conducted to examine whether deviations from normative developmental trajectories of attention could reliably predict the early emergence of attention impairments and status of ADHD, which could facilitate the early detection of ADHD symptoms. Further, our finding showing the rapid development period for different attentional system (i.e., 7–9 years for attentional control/switching) may also indicate that the brain is likely to be more "plastic" during that period and susceptible to lasting trainings or preventions (Halperin, Bedard, & Curchack-Lichtin, 2012).

Limitations

The present study has several limitations. First, we did not have data on adolescence or adulthood. The maturation period of selective attention remains unclear. Further longitudinal studies including adolescents and adults are needed to figure out the developmental trajectory of this ability. Second, we were not able to rule out practice effect in assessing sustained attention and attentional control/

switching, which limits our understandings of developmental trajectory of these two subsystems. Therefore, multiple versions of the same tasks are needed in future longitudinal studies. Third, the generalization of present study could be limited by the sample recruited and battery administrated. We only recruited typically developing children from one single site with a positively skewed IQ estimate. These results might be specific to this school and cannot be generalized to the other populations including children with developmental difficulties. Of note, given the fact that "forced" right handedness is a common phenomenon in China, some children in our sample might be "forced" right-handed although we did not have the exact number. Since "forced" right handed can affect the behavioral, cognitive and even brain development in children, future studies are needed to carefully eliminate the influence of "forced" right-handedness on attention development. In addition, we only employed one battery to measure the sub-constructs of attention system, of which the findings might also be task-specific. In the future, more studies are needed to address the reliability of our findings using multiple batteries or assessments. Fourth, we acknowledge that the "Score Dual Task," "Sky Search Dual Task," and "Walk Don't Walk" are cognitively demanding, which might make the task progress arousing. Given the fact that sustained attention is the ability to self-sustain attention on unarousing stimuli, these three tasks might not be optimal to measure sustained attention. Finally, we did not screen children precisely with a clinical interview (such as Diagnostic and Statistical Manual of Mental Disorders 5) for the possibility of psychosis, developmental disorders, or other cognitive disorders.

Conclusions

In conclusion, our findings suggest that different attention subsystems develop differentially in primary-school-aged children, which supports the theoretical framework of attention network proposed by Posner and may provide a guideline for teachers and parents to seek for optimal educational strategies which adapts children's growth characteristics of attention.

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