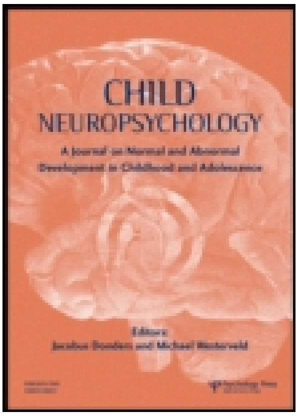

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Charting the developmental trajectories of attention and executive function in Chinese school-aged children

Jian-Ying Zhan[1], John Wilding[2], Kim Cornish[3], Jie Shao[1], Chun-Hong Xie[1], Yan-Xia Wang[1], Kang Lee[4], Annette Karmiloff-Smith[5], and Zheng-Yan Zhao[1]

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Attention is a complex domain that has reawakened research interest in recent years. There are relatively few studies that have examined age-related changes across different attention subcomponents, such as selection, maintenance, and control, using large samples covering a wide age range. The present study assessed performance in 466 participants in order to identify the ages at which mature performance was reached across differing attention subcomponents. Furthermore, we investigated whether the nature of the attentional demands or task difficulty predicted the age at which stable levels of performance were reached. The results supported the former rather than the latter alternative.

Keywords: Attention; Executive function; Developmental trajectory; Visual search; Vigilance.

INTRODUCTION

Attention is a complex cognitive skill that can no longer be viewed as a single, unitary entity. Instead, researchers have begun to tease apart an array of specific subprocesses that interact across many different cognitive domains. One widely accepted taxonomy distinguishes selective attention, maintenance of attention, and control of attention (e.g., Parasuraman, Warm, & See, 1998; Shapiro, Morris, Morris, Flowers, & Jones, 1998; Manly et al., 2001), but these distinctions have not been strongly supported empirically. Moreover, many tasks confound several of the subprocesses so that their individual effects cannot be separated.

Posner and colleagues (e.g., Posner & Petersen, 1990; Posner & Rothbart, 2007) have provided the most explicit model of attention to date, outlining three neural networks: First, the posterior system responsible for disengaging attention from one stimulus, moving its focus to another spatial position and reengaging attention on the new input; second, a right frontal hemisphere system underpinning alerting, arousal, and maintenance of attention.

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Finally, they identified a prefrontal control system (Posner & Petersen, 1990). Such a system is often referred to as "executive function" and includes a variety of coordinating mechanisms required for organizing complex behavior, such as inhibition of irrelevant inputs or responses, attention switching, and planning. Posner's Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002; Fan & Posner, 2004) and its modified version for children (Rueda et al., 2004) are designed to measure these mechanisms separately. Other researchers have proposed alternative but complementary models such as Mirsky (1996) who has identified four attention factors that show some similarity to those proposed by Posner: Focus, Encode (both related to selective attention), Sustain, and Shift (the latter being one aspect of attentional control). However, Cornish and Wilding (2010) question the reliability of these factors since they were based on the analysis of only six tasks and each consisted of measures from only a single task. Robertson and colleagues also proposed the same threefold distinction in their Test of Everyday Attention (TEA; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1994), and its modified version for children (TEA-Ch; Manly et al., 2001). One of the major concerns with this battery, however, is that the different demands of the tasks themselves are confounded with the measures used (e.g., speed measures for selective tasks but accuracy measures predominantly for maintenance and control). Recent research by Wilding and colleagues using visual search (selection) and vigilance (maintenance) tasks (e.g., Wilding & Cornish, 2007; Cornish, Wilding, & Hollis, 2008) has clearly demonstrated that different measures within these tasks can reflect different component processes (such as speed of neural conduction and precision of neural connections) that combine to achieve selection and other attentional processes. Hence the focus of research should be on identifying the component processes in different tasks (such as the disengage, move, and engage components involved in shifting attention from one location to another that Posner and his colleagues have identified) rather than on attempting to prove that a given task is a pure test of a single aspect of attention. Wilding also argued that all but the very simplest attention tasks involve control processes to organize strategies of selection and maintenance, so independent identification of these latter processes is far from easy.

A frequently posed question that relates to the above issues concerns the development of attentional ability. If selection, maintenance, and control can be investigated independently, do they show parallel development in infancy and childhood or do they have different developmental trajectories? The huge increase in recent years in the use of brain-imaging technology has confirmed that there are differential rates of development across the cortex, with visual systems maturing by about 6 years and frontal lobes continuing to mature into late puberty (Toga, Thompson, & Sowell, 2006). These findings tally with the general pattern of performance that demonstrates that control (or executive) functions, as tested by a variety of different tasks, mature relatively late compared with less complex functions, which reach (near) adult levels at an earlier age (e.g., Welsh, Pennington, & Groisser, 1991; Huizinga, Dolan, & van der Molen, 2006).

In a forthcoming review, Cornish and Wilding (2010) examined the evidence over a wide range of tasks for the first appearance of the efficient operation of specific abilities such as target selection, inhibition of interference, or switching attention and for the age at which adult levels of competence were achieved and found a very varied pattern. Not only did ages differ between tasks (especially for adult competence) but different measures within a single task might show wide differences in their developmental trajectory. The authors concluded that different component processes mature at different rates and that the age at which overall adult competence is achieved will depend on the combination of processes involved in any given task.

However, assigning precise ages to the final maturing of specific functions is no simple matter. If performance on Task A reaches ceiling before performance on Task B, this could arise because the tasks are not matched in difficulty, rather than because they engage fundamentally different processes. For example, ceiling for Task A may conceal the possibility of further improvement than would be revealed if the task were made more difficult without fundamentally changing its nature. Such a version might produce later attainment of ceiling in Task A than in Task B. Furthermore, as already indicated, different measures within a task may produce different conclusions. Accordingly, detailed analysis is necessary, preferably using several versions of a task that vary in difficulty as well as several tasks that are assumed to make different demands on attentional processes. Also, conclusions about a specific function (e.g., selection) should not be based on a single task, but only on consistent findings over a number of tasks that enable isolation of that function. Only then will it be possible to decide whether any simple conclusions can be drawn concerning the developmental trajectory of performance for different varieties of attention.

Cornish, Wilding, and colleagues have employed a number of tasks devised by Wilding (collectively known as the Wilding Attention Tasks) to measure selective attention, maintenance of attention, and control of attention in a series of studies on groups of typically developing children aged 6 to 11 years (Cornish, Wilding, & Hollis, 2008; Wilding, 2003; Wilding, Munir, & Cornish, 2001; Wilding, Pankhania, & Williams, 2007). These tasks have consistently distinguished between groups of children rated by teachers as having either good or poor attention, with the most consistent index of attentional differences being the number of false alarms made to nontargets in a visual search, particularly in more difficult versions of the task. However, these studies have only tested groups within a relatively restricted age range and, hence, have thrown little light on the rate at which different components of attention develop.

The present study employed the same tasks with a large school-age population of Chinese children to examine the developmental trajectory of different attentional functions over a much wider age range than hitherto. After examination of the data for evidence of consistent gender differences (none emerged), the main questions addressed were:

1. What is the relation between age and each performance measure? Is it linear, indicating continuous improvement over the whole age range studied, or nonlinear, indicating either a decelerating improvement over the age range or improvement up to some point followed by no further improvement?
2. If the latter, can the age be estimated at which stable[1] levels of competence are attained on the different functions?

Clearly there may be cultural differences between the Chinese population of the present study and British children tested in earlier studies using the same tasks. Sabbagh, Xu, Carlson, Moses, and Lee (2006) have noted that impulse control is important in Chinese culture and children are encouraged to develop this executive skill from an early age. Also, they cite some evidence for genetic differences that may favor executive functioning

[1]In some cases attainment of a stable level of performance may indicate that an adult level has been reached, but to establish such a conclusion unambiguously would require extension of the age range above the 17 years employed here. Therefore, we will use the neutral term “stable” level of performance.

in populations from East and South Asia and their own study demonstrated superior executive functioning in Chinese preschool children compared with U.S. children of the same age. Wilding (2005) argues that poor performance on the tasks used in the present study is more apparent in the more difficult tasks that demand executive functions such as attention switching and maintaining attention. Consequently, where comparative data were available for British children, it was of interest to see whether any superiority was apparent in the Chinese children in the present study.

METHOD AND PROCEDURE

Participants

Participants were recruited from a primary and a middle school in the province of Zheijiang, P. R. China. These were state schools servicing the local community and included a range of socioeconomic classes. Though no formal measures were taken, a relatively normal distribution of ability is assumed. Prior to testing, informed consent was obtained from all participants and their parents. No parent refused consent. A total of 466 children (228 females and 238 males) were tested, aged between 6 and 17 years. None had a diagnosis of attention deficit/hyperactivity disorder (ADHD) and none had a history of a learning disability or sensory deficits of hearing or visual acuity.

Procedure

The study employed four tasks devised by Wilding, employed in a number of earlier studies (see above). Children were tested in one session lasting about 1 hour. Each task began with a demonstration and practice run, which ceased once it was clear that the child understood the task requirements. Though instructions were presented on the screen in English in each case, once these had been translated orally for the benefit of those administering the tasks, it was simple to explain the task requirements to the children by demonstration, as is indeed the normal practice when giving the tasks to English-speaking children.

Selective Attention Task. The Visearch task is a computerized visual search task that presents on a computer screen a picture with trees, a river, and a variety of other objects. Each child is required to search for a certain type of target (e.g., a vertical black ellipse) according to the instructions and to click on it to reveal a monster hidden behind this shape. If the child clicks on the distracter items, the monster does not appear on the screen. There are 20 monsters to be found in each trial. Once all the monsters are found or the frequency of clicking reaches 50, the trial terminates automatically. There are three versions of this task requiring search for a single type of target, each administered once. Two versions require search for single targets that are relatively easy to identify (a black vertical ellipse in the first case and a brown horizontal ellipse in the second case); 25 targets are present plus 75 distracters of different shapes in one or other of these two colors. The third single-target search task is a difficult single-target search, with 40 additional distracters very similar in shape to the target. The total number of correct targets found (maximum value 20), the mean time for correct responses, the number of false positives, the mean distance traveled between detected targets, and the number of mouse movements made are all recorded by the computer program for each trial. Since all the targets are normally found by all children, this measure was not analyzed further. Mean distance travelled proved highly unreliable and was therefore not analyzed further.

Divided Attention/Attentional Control Task. In the Visearch dual-target task the child has to search alternately for the black vertical ellipse and the brown horizontal ellipse to reveal a hidden monster by clicking on the appropriate target. Fifteen targets of each of the two types are present, plus 70 distracters. There is one trial only, with a maximum of 20 targets to be found (10 for the first shape and 10 for the second). The game terminates when all the monsters have been found or a maximum of 50 clicks has been reached. The same scores as for the single-target search are all recorded by the computer program. This task is now regarded more appropriately as a test of the control function involved in switching attention between different stimuli.

Maintained Attention Task. The Vigilan task (WATT) is a computerized vigilance task. Using the same screen display as for the Visearch task (see above), each child has to watch for a yellow border that appears randomly surrounding a target shape on the screen. Sixteen targets show up one by one at irregular intervals. The dependent variables are number of correct targets detected (maximum 16), mean response time to a target, number of false positives and total distance wandered while awaiting a target.

Executive Function Task. The Wisconsin Card Sorting Task is a popular method of testing one aspect of executive function. Participants have to discover a rule for sorting a series of cards (e.g., by color), but once they have achieved 10 correct responses in succession, the rule is covertly changed (e.g., to shape). Thus the task requires switching attention to a new stimulus feature and inhibition of the previously successful sorting rule in favor of a new one.

The Wilding Monster Sorting Task (WMST) is identical in form to the Wisconsin Card Sorting Task (WCST). At the beginning of the task, there are four monster kings with different number, color, and shape characteristics displayed on the screen. Then participants are asked to sort 64 monsters one by one to the kings, basing this on one of the characteristics (e.g., color), without being told the sorting rule. If they make a correct sort, the king smiles. Otherwise, the king cries. After 10 consecutive correct responses, the sorting rule is changed but this is not mentioned to participants. The number of correct responses, number of sorting categories completed, conceptual-level responses, perseverative errors (i.e., persistence in using the same cue when it has been shown to be incorrect), and times for responses following an unambiguous correct response or following an error are recorded by the computer program, all defined as for the original WCST. The first three of these measures produced virtually identical patterns of response and therefore results will only be presented from the number of correct responses, plus the other measures listed.

RESULTS

The analyses were based on the questions posed earlier. Data with a non-normal distribution were converted into a normal or close-to-normal distribution using a logarithmic transformation (all false alarm measures, mouse movements, and distance wandered). The number of participants for each age group and gender are given in Table 1. Measures were subjected to an independent groups analysis of variance, testing for gender and age group differences; the linear and quadratic components of the age effect were computed in each

Table 1 Numbers of Children in Each Age Group.

Age Group	Age Range (Years)	Females	Males
6	5.5–6.5	6	11
7	6.5–7.5	13	15
8	7.5–8.5	34	14
9	8.5–9.5	18	19
10	9.5–10.5	13	24
11	10.5–11.5	15	27
12	11.5–12.5	16	17
13	12.5–13.5	20	27
14	13.5–14.5	28	24
15	14.5–15.5	20	20
16	15.5–16.5	29	26
17	16.5–17.5	16	14

case. As 20 different scores were analyzed, the criterion for significance was set at $p < .002$, but effects significant at $p < .01$ are also indicated. Table 2 gives means and standard deviations for each measure for each age group and Figures 1–3 plot the measures against age group. Table 3 shows the results of the analyses of variance for the two independent variables and their interaction.

A preliminary examination of the data for gender differences indicated that there were five such cases where $p < .01$ but only one of these achieved the stricter criterion level of significance indicated above (errors in the alternating search task). However, there was some general tendency for boys to respond more rapidly than girls (in one of the single-target visual Search tasks and the dual-target Visual Search task, the Vigilance task, and WMST; although this was only true in the older age groups in the case of the dual-target Visual Search task and Vigilance, yielding an interaction of Sex × Age Group). In the absence of unequivocal gender differences, this issue is not considered further.

What is the relation between age and each performance measure? Is it linear, indicating continuous improvement over the whole age range studied, or nonlinear, indicating either a decelerating improvement over the age range or improvement up to some point followed by no further improvement?

Every 1 of the 20 measures showed a highly significant linear improvement with age.

In most cases, there was also a significant quadratic component, indicating curvature in the function. The exceptions were log false alarms in visual search and correct responses and log perseverative errors in WMST. Thus inhibition of responses to nontargets in the visual search task continued to decrease right through the age range, as did errors in the WMST task.

In a few cases, the quadratic trend was marginally rather than decisively significant (log false alarms for Visual Search Task 1, mean time per hit, and log distance wandered in Vigilance and mean time for correct responses following an error in WMST). This finding was ignored in the first of these exceptions, as the corresponding quadratic trends in the other visual search tasks were all nonsignificant, but in the other cases the measures were subjected to further analysis along with all the other significant quadratic trends; these analyses are described below.

Thus in all cases performance improved with age, with improvement slowing or plateauing in the older groups in many cases. To determine whether a stable level of performance had been achieved in such cases, further analysis was undertaken.

Table 2 Means (*SD*s) for Each Measure for Each Group.

Measure	Age Group 6	Age Group 7	Age Group 8	Age Group 9	Age Group 10	Age Group 11	Age Group 12	Age Group 13	Age Group 14	Age Group 15	Age Group 16	Age Group 17
Visearch1 (single target easy)												
Mean time per hit	6.15 (2.33)	5.84 (2.20)	3.88 (1.91)	3.61 (1.64)	2.59 (1.07)	2.07 (.71)	1.97 (.94)	1.75 (.56)	1.56 (.77)	1.50 (.61)	1.40 (.46)	1.41 (.55)
Log false alarms	0.69 (.43)	0.61 (.42)	0.53 (.42)	0.56 (.42)	0.38 (.28)	0.42 (.38)	0.33 (.30)	0.34 (.27)	0.38 (.31)	0.35 (.31)	0.37 (.34)	0.42 (.36)
Log mouse moves	3.45 (.21)	3.46 (.24)	3.22 (.24)	3.21 (.17)	3.10 (.16)	3.09 (.16)	3.05 (.19)	3.07 (.19)	3.17 (.14)	3.07 (.19)	3.13 (.18)	3.07 (.21)
Visearch2 (single target easy)												
Mean time per hit	5.22 (1.73)	4.52 (1.71)	3.42 (1.89)	2.96 (1.07)	2.26 (.68)	1.98 (.65)	1.88 (.56)	1.69 (.62)	1.41 (.56)	1.31 (.35)	1.32 (.40)	1.38 (.48)
Log false alarms	0.67 (.40)	0.50 (.42)	0.48 (.34)	0.63 (.34)	0.38 (.33)	0.35 (.34)	0.32 (.36)	0.36 (.30)	0.32 (.32)	0.35 (.35)	0.36(.35)	0.34 (.35)
Log mouse moves	3.36 (.16)	3.35 (.21)	3.14 (.22)	3.17 (.16)	3.07 (.15)	3.08 (.18)	3.06 (.18)	3.06 (.21)	3.14 (.17)	3.04 (.19)	3.11 (.18)	3.09 (.22)
Visearch5 (single target difficult)												
Mean time per hit	6.33 (1.85)	4.86 (1.57)	4.21 (2.17)	3.28 (.97)	2.88 (1.25)	2.46 (1.12)	2.41 (.96)	2.12 (.79)	1.75 (.64)	1.67 (.75)	1.59 (.56)	1.76 (.83)
Log false alarms	0.93 (.46)	0.65 (.43)	0.64 (.45)	0.81 (.42)	0.55 (.43)	0.50 (.41)	0.52 (.38)	0.55 (.37)	0.43 (.37)	0.40 (.37)	0.40 (.36)	0.44 (.40)
Log mouse moves	3.55 (.12)	3.43 (.13)	3.30 (.20)	3.28 (.12)	3.22 (.13)	3.20 (.19)	3.22 (.15)	3.22 (.20)	3.27 (.14)	3.17 (.18)	3.22 (.15)	3.19 (.18)
Visearch6 (dual target alternating)												
Mean time per hit	6.43 (2.15)	5.62 (1.55)	4.20 (1.42)	4.16 (.125)	3.15 (.91)	2.75 (.73)	2.64 (.57)	2.37 (.67)	1.96 (.61)	1.87 (.51)	1.80 (.46)	1.95 (.65)
Log false alarms	0.99 (.37)	0.68 (.52)	0.60 (.45)	0.66 (.43)	0.53 (.43)	0.55 (.48)	0.59 (.52)	0.48 (.45)	0.34 (.30)	0.44 (.37)	0.37 (.43)	0.44 (.46)
Log mouse moves	3.56 (.16)	3.53 (.17)	3.33 (.26)	3.35 (.18)	3.29 (.16)	3.29 (.17)	3.29 (.19)	3.27 (.19)	3.35 (.16)	3.23 (.19)	3.30 (.17)	3.26 (.19)
Vigilance												
Number of hits	10.18 (2.81)	11.86 (3.01)	13.73 (2.39)	13.54 (1.73)	14.59 (1.19)	15.05 (1.27)	15.15 (1.09)	15.49 (.83)	15.75 (.59)	15.85 (.58)	15.87 (.51)	15.77 (1.10)
Mean time per hit	4.23 (.63)	4.09 (.86)	3.62 (.76)	3.47 (.67)	2.91 (.71)	2.80 (.80)	2.49 (.73)	2.15 (.67)	1.85 (.70)	1.69 (.53)	1.45 (.43)	1.68 (.41)
Log false alarms	0.76 (.41)	0.42 (.33)	0.41 (.35)	0.42 (.36)	0.33 (.42)	0.20 (.28)	0.27 (.38)	0.23 (.27)	0.21 (.31)	0.35 (.42)	0.19 (.25)	0.25 (.45)
Log distance wandered	5.56 (.27)	5.48 (.30)	5.54 (.36)	5.43 (.28)	5.36 (.29)	5.35 (.23)	5.39 (.27)	5.38 (.28)	5.38 (.25)	5.38 (.30)	5.35 (.26)	5.42 (.27)
WMST												
Correct responses	22.71 (8.01)	21.29 (8.34)	23.40 (7.90)	23.43 (7.85)	30.89 (11.04)	33.43 (11.12)	34.21 (10.40)	37.94 (12.11)	40.75 (10.93)	40.70 (11.40)	45.56 (9.89)	46.33 (9.93)
Mean time (correct following unambiguous correct response)	10.16 (6.62)	8.80 (4.47)	6.48 (4.57)	5.77 (2.72)	5.06 (4.06)	3.83 (1.91)	3.82 (1.74)	3.14 (1.71)	2.95 (1.32)	2.64 (1.01)	2.96 (1.64)	2.56 (.83)
Mean time (correct following error)	6.61 (1.69)	7.84 (5.25)	5.53 (2.38)	5.70 (3.74)	4.76 (2.19)	5.06 (2.42)	5.08 (3.17)	3.63 (1.95)	3.60 (1.47)	3.41 (1.53)	3.68 (1.54)	4.19 (2.07)
Log perseverative errors	1.0 (.46)	1.0 (.44)	1.14 (.36)	0.87 (.50)	0.96 (.44)	1.09 (.39)	1.01 (.38)	0.95 (.45)	0.90 (.50)	0.96 (.44)	0.72 (.46)	0.67 (.47)

Table 3 *Significant F* Ratios for the Effects of Sex and Age Group on the Performance Measures, and Age Beyond Which No Further Significant Change in Performance Occurred.

Measure	Gender (df = 1, 442)	Age Group (Linear) (df = 1, 442)	Age Group (Quadratic) (df = 1, 442)	Age Above Which No Further Change Occurred
Visearch1 (single target easy)				
Mean time per hit	6.1*	502.0**	94.0**	14
Log false alarms		20.2**	8.1*	[9]
Log mouse moves		94.0**	40.7**	9
Visearch2 (single target easy)				
Mean time per hit		461.2**	80.0**	14
Log false alarms		213.0**		[10]
Log mouse moves		51.0**	27.8**	8
Visearch5 (single target difficult)				
Mean time per hit		407.4**	72.0**	14
Log false alarms		37.6**		[11]
Log mouse moves		81.6**	31.6**	9
Visearch6 (dual target alternating)				
Mean time per hit	0.01[a]	663.2**	91.5**	14
Log false alarms	10.23**	32.8**		[12]
Log mouse moves		46.3**	18.2**	8
Vigilance				
Number of hits		3387.2**	70.3**	14
Mean time per hit	[b]	633.1**	7.35*	15
Log false alarms		43.8**	17.8**	10
Log distance wandered		11.9**	7.4*	10
WMST				
Correct responses		237.1**		
Mean time (correct following unambiguous correct response)	7.59*	212.4**	37.1**	13
Mean time (correct following error)		68.6**	6.5*	12
Log perseverative errors		16.0**		

Numbers in square brackets in the final column are estimates from the graphs, not figures derived from statistical analysis. [a]Group x Sex $F(11, 442) = 2.64$*. [b]Group × Sex $F(11, 442) = 2.37$*. WMST = Wilding Monster Sorting Task. *$p < .05$; **$p < .01$.

Where a significant quadratic trend was detected, did this indicate that a stable level of competence was attained?

Where a significant quadratic trend indicated leveling off in performance as age increased, further analyses of variance were used to test the upper ranges of age groups in order to detect the age above which no further statistically significant change in performance was apparent. For example, scores from the three oldest groups were analyzed and, if these did not differ significantly, the next oldest group was added and the analysis rerun until a significant difference emerged at the lower end of the age range. The final column in Table 3 gives the age above which no further significant change was found for each measure. These results can be summarized as follows:

- In visual search, response times all achieved a minimum by age 14 but, as already indicated, False Alarms continued to decline throughout the age range tested. The number of Mouse Moves reached a minimum at age 8–9.

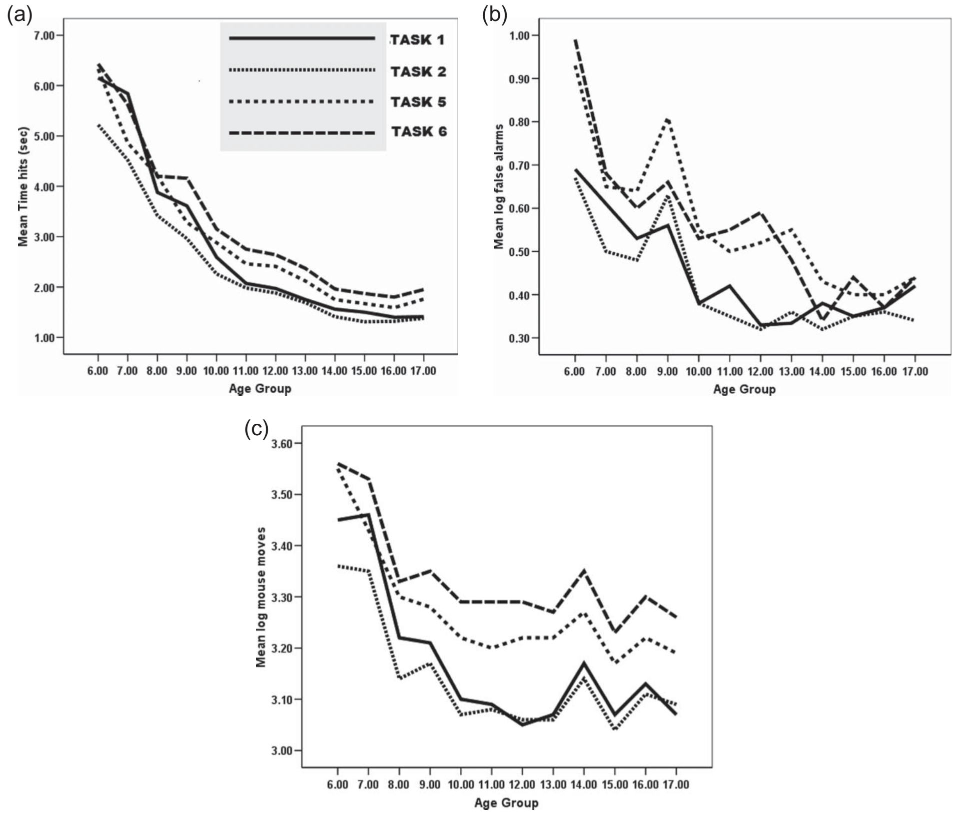

Figure 1 Visual search measures plotted against age groups: (a) Mean time per hit; (b) Mean log number of false alarms; and (c) Mean number of mouse moves.

- In vigilance, target detection reached close to ceiling at age 14, but response times continued declining beyond this point until at least age 15. False alarms and wandering declined to a minimum by age 10, a similar age to that at which the number of mouse moves leveled off in visual search.
- In WMST the number of correct responses was still increasing and the number of perseverative errors was still decreasing at age 17. Response times reached a minimum earlier than for the other tasks at age 12–13.

DISCUSSION

How do the relations with age and the age at which stable competence is achieved differ between tasks and between different measures within a task, and what conclusions can be drawn?

First we note that some measures demonstrated much greater consistency over the age groups than others (see Table 2). As a general rule, speed of performance produced the most consistent relations with age, whereas measures of accuracy and movement around the screen were less consistent, even after the logarithmic transformations of the data.

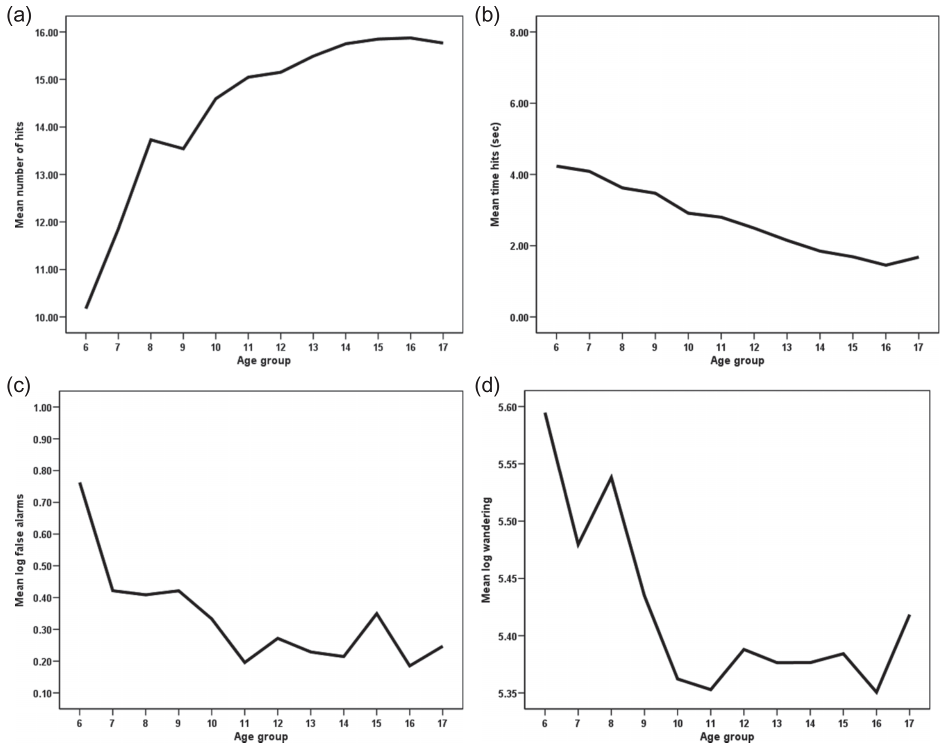

Figure 2 Vigilance measures plotted against age groups: (a) Mean number of hits; (b) Mean time per hit; (c) Mean log number of false alarms; and (d) Mean distance wandered while awaiting target.

In the vigilance task, however, it was the number of hits, rather than the time, that showed a steady decline in variability across age groups. Nevertheless, the accuracy and movement measures were all strongly related to age and the departures from smooth functions are more likely to reflect the lower reliability of these measures than the effects of unidentified independent variables. A further point of interest is that the speed measures showed a steady reduction in variability as age increased (see Table 2), indicating increasing similarity across individuals in the older groups that is not associated with group size. Accuracy and movement measures, on the other hand, demonstrated similar variability across age groups, indicating that factors other than age were responsible for individual differences on these measures.

The results indicate a wide variation between measures within tasks with respect to the age at which mature performance was achieved but little variation between different versions of the search task, despite differences in difficulty. This offers some support to the view that it is the nature of the attentional demands that determine the age at which stable levels of performance are reached, rather than the level of difficulty of a particular variant of the task. In all cases performance on visual search in terms of the number of mouse movements was maximally efficient as early as age 9, and response times were at stable levels by age 14. The statistical analysis did not yield an age at which false alarms had reached a minimum, but inspection of Figure 1 suggests that this may well be occurring also around the age of 14. It may be noted that previous studies employing these tasks have found strong relations between response times and age but none between false alarm

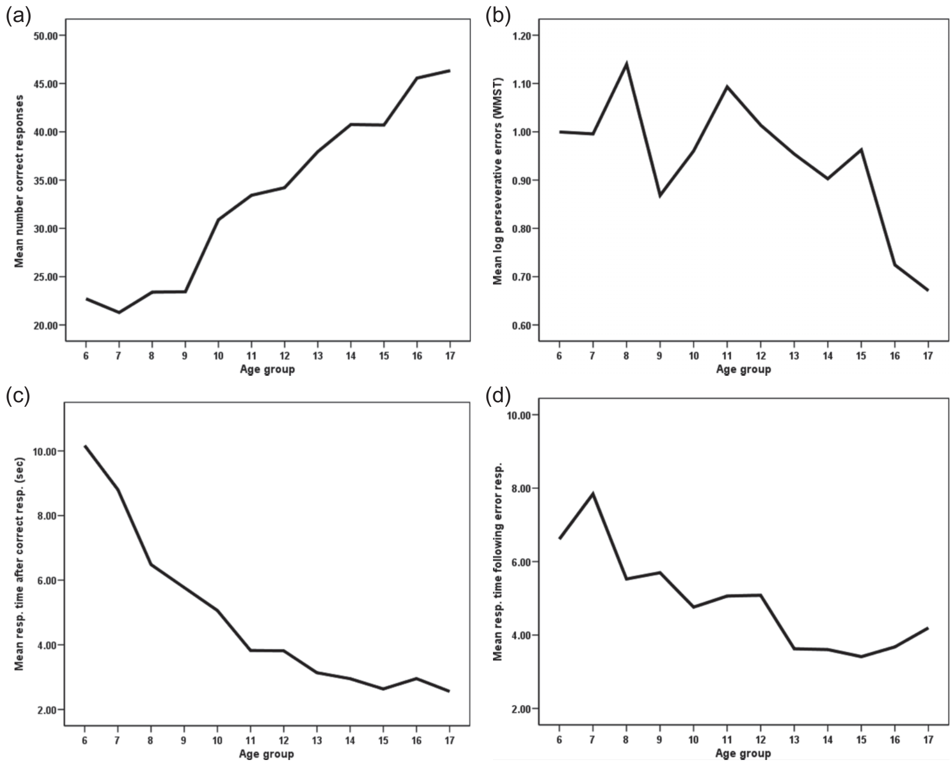

Figure 3 WMST measures plotted against age groups: (a) Mean number of correct responses; (b) Mean log number of perseverative errors; (c) Mean response time following correct response; and (d) Mean response time following error.

rates and age (Cornish, Wilding, & Hollis, 2008; Wilding & Cornish 2007). However, it is apparent from Figure 1 that, given a much larger sample and age range than previously studied, such a relation does indeed exist, but it is much less consistent than that between response times and age.

Target detection in vigilance reached a ceiling around 14 years, with virtually all targets detected, but clearly a more difficult task might show continued improvement in hit rate above this age, and indeed the response time measure did suggest continuing improvement throughout the age range studied here. While irrelevant responding (false alarms, which are probably different in origin in this task from visual search, since they occur in the absence of a target, and wandering around the screen with the mouse while awaiting a target) was reduced to a minimal level by an early age, the ability to detect a target and to respond quickly did not reach stable levels of performance until much later.

Finally, not surprisingly, the WMST task continued to challenge even 17-year-olds. Indeed, as Figure 3 indicates, it was not until the age of 10 that correct choices rose much above chance level (i.e., 16 correct responses). While speed of decision making reached a minimum level by the age of 13, clearly the ability to solve the puzzle efficiently challenges even near adults; the original WCST was of course designed for a stable population.

Inspection of the overall results reveals the interesting fact that leveling out of the various measures seems to occur around one of two main points in development, 8–10 years and 12–14 years. Up to 6 years of age, a great deal of pruning and organization occurs in the brain and by this age it has reached 95% of its final stable volume. Sensory and motor processes are the earliest to mature. Processes in the temporal and frontal lobes involved in higher order functions such as language and attention are the last to mature, together with attentional control, which engages the prefrontal and lateral temporal lobes. As widely pointed out (e.g., Hommel, Li, & Li, 2004), at age 7–8, there is a spurt in cognitive development and the earlier of these two points of development in components of attention appears to coincide with this period. The present evidence demonstrates elimination of unnecessary extra task activity at this stage (mouse movements in visual search and wandering and false alarms in the vigilance task), which might be either the consequence or cause of a better ability to focus on the essentials of the task.

The second key age apparent in the present data is around puberty and is marked by an achievement of stable levels of speed in responding (though some tasks may permit still further improvement as shown by the vigilance task here) and stable levels of accuracy on complex tasks that have strong EF demands such as the alternating visual search and WMST. This age represents a milestone in the final development of many such processes (see Toga, Thompson, & Sowell, 2006, for a detailed review and Casey, Getz, & Galvan, 2008, for a review of relations between brain maturation up to adolescence and performance on tasks requiring executive control). Mabbott, Noseworthy, Bouffet, Laughlin, and Rockel (2006) note the correlation between the development of white matter, particularly in frontal-parietal areas, and speed of visual search from 6 to 17 years, indicating maturing integration of the control and spatial attention systems.

The clear lesson of these findings is that different performance measures within a task reflect different aspects or demands of the task and that there is no simple answer to the question of when mature performance is achieved (presumably not until all measures yield adult-like performance). Nor is it possible to rank tasks or cognitive abilities in any simple way. We would not want to conclude on the basis simply of response times, for example, that the ability to maintain attention is more demanding and matures later than the ability to solve the WMST, simply because speed continues to improve up to a later age in the vigilance task than in the WMST. Presumably the problem-solving demands of the latter task set a relatively low limit to the maximum speed at which it can be performed, so this limit is reached relatively early in development, whereas detection of targets in the vigilance task is less demanding and leaves scope for increasing efficiency only in terms of faster speed of detection.

Comparative data from a British sample aged 8 to 10 years for the search and vigilance tasks were reported by Wilding and Cornish (2007, Study 2). (Other studies using these tasks compared groups high and low in attentional ability, distinguished by teacher ratings, so do not provide comparable samples from the whole population range of attentional ability.) In the Wilding and Cornish (2007) study, the mean hit times for visual search (for Tasks 1 and 2 combined, and for Task 6) were 2.94 (SD = 1.05) and 3.70 (SD = 0.94), while the mean log errors were 0.6 (SD = 0.32) and 0.8 (SD = 0.39). These values are close to the corresponding values for this age range from the present sample shown in Figure 1. For the vigilance task, Wilding and Cornish obtained a mean time per hit of 2.94 (SD = 0.94) and a mean log false alarm rate was 0.55 (SD = 0.36); Figure 2 suggests that the Chinese group was slower with fewer false alarms, though the differences are modest, lying within one standard deviation. Thus the two groups appear to perform at broadly similar levels on these tasks. No parallel British data are yet available for the WMST task.

The present study highlights the crucial importance of large-scale studies over a wide age range in gaining detailed understanding of the development of competence on these (and other) tasks. In particular, the data strengthen the argument already presented by Wilding and Cornish (2007) that different measures of performance can reflect very different underlying component processes that develop at different rates and mature at different ages. It is quite clear that, at least in the study of attention, we need careful analysis of these component processes and to avoid the temptation to regard a given task as simply measuring a distinct process or aspect of attention. Rather each task recruits a number of more elementary processes, each of which may have its distinct developmental trajectory and asymptote for performance.

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