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Development of attentional networks in childhood☆

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Abstract

Recent research in attention has involved three networks of anatomical areas that carry out the functions of orienting, alerting and executive control (including conflict monitoring). There have been extensive cognitive and neuroimaging studies of these networks in adults. We developed an integrated Attention Network Test (ANT) to measure the efficiency of the three networks with adults. We have now adapted this test to study the development of these networks during childhood. The test is a child-friendly version of the flanker task with alerting and orienting cues. We studied the development of the attentional networks in a cross-sectional experiment with four age groups ranging from 6 through 9 (Experiment 1). In a second experiment, we compared children (age 10 years) and adult performance in both child and adults versions of the ANT. Reaction time and accuracy improved at each age interval and positive values were found for the average efficiency of each of the networks. Alertness showed evidence of change up to and beyond age 10, while conflict scores appear stable after age seven and orienting scores do not change in the age range studied. A final experiment with forty 7-year-old children suggested that children like adults showed independence between the three networks under some conditions.

Keywords: Orienting; Alerting; Conflict; Executive processes development; Child ANT

1. Introduction

In our work, we have divided attention into three networks that carry out the functions of alerting, orienting and executive control (Fan, McCandliss, Sommer, Raz, & Posner, 2002; Posner & Fan, in press; Posner & Petersen, 1990). We (Fan et al., 2002) developed an Attention Network Test (ANT) for adults that could be used to provide a measure of the efficiency of these three different functions of attention. The test was built around the flanker task (Eriksen & Eriksen, 1974), but used cues to vary alertness and orienting. The ANT was built upon many neuroimaging studies that suggest different anatomies of the three networks (Corbetta & Shulman, 2002; Fan, McCandliss, Flombaum, & Posner, 2001; Fan, McCandliss, Flombaum, Thomas, & Posner, 2003; Marrocco & Davidson, 1998; Pardo, Fox, & Raichle, 1991; Posner & Petersen, 1990).

In a study of 40 adults we found relatively high immediate test–retest reliability for the scores of each attentional network provided by the ANT test (Fan et al., 2002). Furthermore, these scores were not correlated across individuals, suggesting that the efficiency of each network can be measured somewhat independently with the ANT.

The adult ANT requires only about 20 min to complete and since it provides scores for all three networks it has been used to obtain information on the state of attention for genetic studies (Fossella et al., 2002), in cases of psychopathology (Posner et al., 2002; Swanson et al., 1991) and to examine the outcome of therapies (Sohlberg, McLaughlin, Pavese, Heidrich, & Posner, 2000).

For the current study, we have adapted the ANT for use with children. In previous work we found that children work best when there is a story and when there is clear feedback on their performance (Berger, Jones, Rothbart, & Posner, 2000). In the child version of the ANT one or five colorful fish replaced the arrows that typically appear in the flanker task. We invite the children to help us feed the central fish by pressing a button corresponding to the direction in which the middle fish is swimming. Much of what is known about

☆ Experiment 1 was conducted in Almería, Spain, Experiment 2 in Eugene Oregon and Experiment 3 was conducted in New York City.

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the behavioral development of attention during childhood has been thoroughly reviewed recently (Brodeur & Enns, 1997; Richards, 1998; Ridderinkhof, van der Molen, Band, & Bashore, 1997; Ridderinkhof & van der Stelt, 2000; Ruff & Rothbart, 1996; van der Molen, 2000). These reviews show that some mechanisms of attention are present from early infancy and provide evidence of quantitative development occurring at different rates for various attentional functions. Below, we discuss some of this evidence with respect to networks involved in alerting, orienting and executive control.

Alertness induced by warning signals has been a topic in which children and adults have been compared (Kraut, 1976; Smothergill & Kraut, 1989). In these studies, a cue is given prior to a target event. The cue serves both as a warning signal and to provide specific information about the target. The authors found that children and adults encode the target relevant information at equivalent rates, but children make less use of the warning aspect of the cue. Ridderinkhof et al. (1997) manipulated information about when a target would occur by comparing fixed and variable warning intervals for 5- to 10-year-old children. Fixed fore periods led to faster RTs than variable and often allowed for specific preparation for more difficult conditions, but there was no difference in these effects as a function of age.

Orienting both to explicit cues and during visual search has been studied extensively (Akhtar & Enns, 1989; Brodeur & Enns, 1997; Canfield, Smith, Brezsnyak, & Snow, 1997; Enns, 1990; Haith, Hazan, & Goodman, 1988; Richards, 1998; Ruff & Rothbart, 1996; Trick & Enns, 1998). In general, the ability to shift attention to exogenous cues differs little between children and adults, while the speed of moving attention voluntarily, the accuracy of its termination, and the ability to disengage seem to improve with age. A serial reaction time task has been used to trace the development of the ability of infants, children and adults to learn to orient to visual events that occur in sequence (Canfield et al., 1997; Clohessy, Posner, & Rothbart, 2001; Haith, Hazan, & Goodman, 1988; Thomas & Nelson, 2001). These studies suggest that implicit learning of unambiguous locations begins in early infancy (at least by 4 months) and, although the number of associations that can be learned, speed of executing responses, use of explicit knowledge (Thomas & Nelson, 2001) and tolerance for ambiguity all increase with age, the rate of learning single unambiguous associations changes little (Clohessy, Posner, & Rothbart, 2001; Posner, 2001).

There have been a number of studies examining higher-level forms of attention such as the resolution of conflict among stimulus elements, often as one feature of executive function. Imaging studies have suggested a network of brain areas including the anterior cingulate and lateral prefrontal cortex that may be involved in resolving conflict in tasks like color-word Stroop effect (Bush, Luu, & Posner, 2000; Fan et al., 2003).

Developmental studies have stressed the relative lack of executive control in infants (Ruff & Rothbart, 1996). In one study, toddlers were asked to respond to a stimulus by pressing a key with the identical figure while suppressing information on whether the key was on the same side of the display as the target (Gerardi-Caulton, 2000). Between 2 and 4 years of age, children progressed from an almost complete inability to carry out the task to relatively good performance. However, like adults, they were slower on incompatible trials. In a related study using a child version of the Stroop task, strong evidence for development was shown in later childhood (Gerstadt, Hong, & Diamond, 1994). Studies using go-no-go tasks that involve the ability to inhibit a response while making one to related stimuli show evidence of both behavioral and brain development in the period from 6 to 13 years (Casey, Trainor, Giedd et al., 1997; Casey, Trainor, Orendi et al., 1997).

One study (Ridderinkhof et al., 1997) examined the interactions between conflict, temporal uncertainly (alertness) and stimulus size (orienting) for children of different ages. All three aspects of attention showed somewhat larger effects in younger children. Conflict, as introduced by incongruent flankers, produced significant interference for all groups, which declined with age, reaching adult levels by age 10 years. The size effect was also significant with larger targets being responded to most easily. Foreperiod variability also had a significant effect, but this did not change with age. While the flanker effect provides clear evidence for improved handling of conflict from early to later childhood, it is more difficult to interpret the other effects reported in this study. While foreperiod variability is likely to influence alertness, it does so only if participants learn to use it to anticipate the signal and it also influences other factors that are based on the predictability of the signal. Stimulus size no doubt influences the ability to orient to the target, but other factors like visual eccentricity of the target and masking by the flankers are also changing in this paradigm, making isolation of one cognitive process difficult.

It is likely that all the functions of attention undergo some development. When many functions are combined this could appear to be a continuous development from birth to adulthood, but it is impossible to tell the form of development because there has been little effort to provide a measure of different attentional functions that could be used to make these comparisons. An example where differential effects are clear is a study of inhibitory control (Band, van der Molen, Overtoom, & Verbaten, 2000). By using the same stop task the authors were able to show different developmental functions for beginning and stopping the movement.

Our eventual hope is to have means for tracing development from early infancy through adulthood. We have studied the development of control of eye movements in infancy (Clohessy, Posner, & Rothbart, 2001; Posner, 2001). We have also compared eye movements to ambiguous sequences of visual stimuli with a key press task that produces a conflict between location and identity and have been able to show the two forms of conflict are correlated at 30 months (Rothbart, Ellis, Rueda, & Posner, 2003). A major goal of this paper is to study the rate of development of various attentional networks in childhood and to compare it with the performance of adults. To do this, we report the results of three studies with the child ANT. The first experiment is a cross-sectional developmental study aimed to trace changes in the attentional networks from 6 to 10 years of age. The second study allows more direct comparison between adults and children by comparing results of the adult and child versions of the ANT task with a group of 10-year-olds and adults. Finally, we conducted a third experiment with a group of 44 children between 6 and 8 years of age in order to assess the degree of independence between the attentional networks.

2. Experiment 1

The literature on attentional development discussed in the introduction led us to hypothesize that alerting and executive function will develop during childhood, but that orienting may be stable after infancy. The child ANT allows us to test these hypotheses using the same task. Accordingly, we studied children of age six through nine to examine development of each of the networks.

2.1. Method

2.1.1. Participants

Four groups of 12 children (6 boys and 6 girls) of the ages of 6, 7, 8 and 9 years participated in the experiment. The 6-year-olds group had an average age of 82 months (S.D. = 1.68). The 7-year-olds group had an average age of 93 months (S.D. = 1.86). The average age of children in the 8-year-olds group was 105 months (S.D. = 1.36). The 9-year-olds group had an average age 117 months (S.D. = 1.38). Participants were recruited from a public school in Almería (Spain) and completed the experiment at the school.

2.2. The child ANT

2.2.1. Stimuli

All stimuli were displayed on a computer screen. Each trial began with a central fixation cross. The target array was a yellow colored line drawing of either a single yellow fish or a horizontal row of five yellow fish, presented above or below fixation, over a blue–green background. The participant was to respond based on whether the central fish was pointing to the left or right by pressing the corresponding left or right key on the mouse (see Fig. 1). On congruent trials the flanking fish were pointing in the same direction, on incongruent trials the flankers point in the opposite direction from the central fish, and on neutral trials the central fish appeared alone (Fan et al., 2002).

Participants viewed the screen from a distance of about 53 cm. Each fish subtended 1.6° of visual angle and the contours of adjacent fish were separated by 0.21°. The five fish subtended a total of 8.84°. The target was presented either about 1° above or below fixation. Each target was preceded by one of four warning cue conditions: a center cue, a double

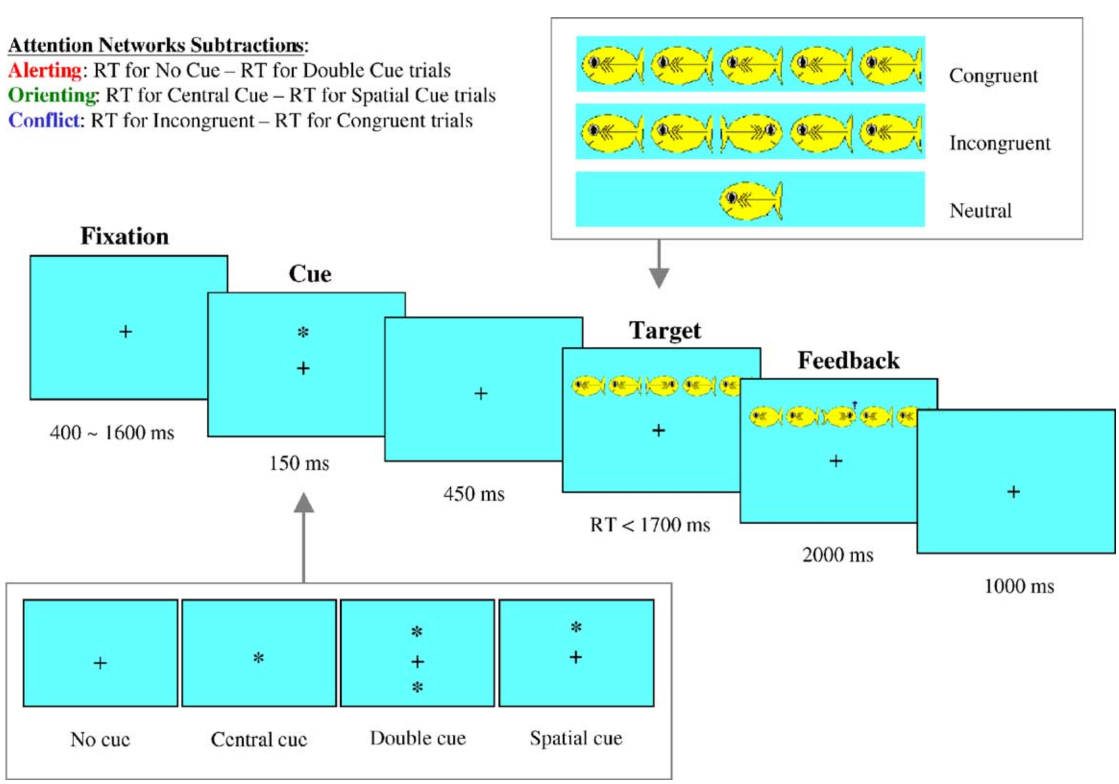

Fig. 1. Schematic of the child version of the ANT. In the actual task, the background color for every display is magenta while the fish appear in yellow.

cue, a spatial cue, or no cue. In the center cue condition, an asterisk is presented at the location of the fixation cross. In the double cue condition, an asterisk appears at the locations of the target above and below the fixation cross. Spatial cues involve a single asterisk presented in the position of the upcoming target.

2.2.2. Procedure

Each child completed the child version of the Attention Networks Test on an IBM compatible laptop computer. Two children completed the experimental session at a time, facing away from one another at individual desks, with the experimenter present throughout the test. Children held the mouse in one hand, or placed a finger on each button, whichever was more comfortable, and received the feedback through headphones. Each child was tested in one session lasting about 30 min.

A session of the ANT consisted of a total of 24 practice trials and three experimental blocks of 48 trials in each. Each trial represented one of 12 conditions in equal proportions: three target types (congruent, incongruent and neutral) × four cues (no cue, central cue, double cue and spatial cue). Participants indicate their responses via a right or left button-press on a mouse. Accuracy and reaction time are recorded.

Each trial began with a fixation period of a random variable duration of between 400 and 1600 ms. Subsequently, on some trials a warning cue was presented for 150 ms. A brief fixation period of 450 ms appeared after the disappearance of the cue, followed by either the simultaneous appearance of the target and flanker, or by the appearance of the target alone. This display remained on the screen until a response was detected, to a maximum of 1700 ms. After responding, the participant received auditory and visual feedback from the computer. For correct responses a simple animation sequence showed the target fish blowing bubbles and the participant was presented with a recording of child exclaiming "*Woohoo*!". Incorrect responses were followed by a single tone and no animation of the fish.

Participants were told that a hungry fish would appear on the screen and they were instructed to feed the fish by pressing the button on the mouse that matched the way the fish was pointing. They were first shown index cards of the single rightward and leftward fish stimuli (corresponding to the neutral condition) and were asked to demonstrate which button on the mouse would successfully feed the fish. They were then told that sometimes the hungry fish would be alone, the way they had just seen, and sometimes the fish would be swimming with some other fish as well. They were instructed that in this case they should pay attention to the fish in the middle and feed that fish using the mouse. The experimenters then showed the participants cue cards showing the stimuli in a congruent configuration and an incongruent configuration and asked them to demonstrate which button they should press to feed the fish in the middle. Finally, participants were instructed to maintain fixation on the cross in the center of the screen throughout the task and to respond as quickly and accurately as possible.

Participants began the practice block when it was clear that they understood the instructions. Each child was individually supervised during the practice trials and was given feedback and encouragement from the experimenter. Participants then completed the three test blocks with the experimenter in the room but they no longer received trial-by-trial encouragement. The practice block took approximately 3 min and each test block took approximately 5 min as well. The entire session usually lasted no more than 25 min in total. The children could take breaks at the end of the practice block and between test blocks. A small prize such as a sticker was given at the completion of each block.

2.3. Results

Table 1 shows the mean of the median RTs for correct responses and percentage of errors for each condition and age group. The analysis of variance showed significant main effects of age ($F(3, 44) = 6.24$; $P < 0.01$), cue type ($F(3, 132) = 68.0$; $P < 0.001$) and flanker type ($F(2, 88) =$

Table 1
Mean of Median RT in ms and (percentage of errors) for each age group in Experiment 1

Flanker type	Age (years)	Warning type			
		No cue	Center cue	Double cue	Spatial cue
Congruent	6	968 (11.8)	905 (5.6)	847 (7.6)	859 (6.9)
	7	905 (4.2)	833 (4.9)	794 (4.9)	762 (7.6)
	8	854 (3.5)	807 (6.3)	758 (4.9)	767 (4.9)
	9	783 (2.8)	752 (2.1)	677 (0.7)	702 (2.1)
Incongruent	6	1041 (25.0)	1006 (24.3)	954 (21.5)	959 (23.6)
	7	959 (6.9)	887 (4.2)	899 (2.1)	827 (10.4)
	8	922 (4.2)	864 (4.9)	825 (4.2)	854 (5.6)
	9	857 (4.9)	781 (3.5)	791 (4.2)	755 (1.4)
Neutral	6	991 (5.6)	890 (9.7)	906 (8.3)	835 (6.3)
	7	846 (7.6)	819 (6.3)	741 (2.1)	748 (6.3)
	8	834 (6.9)	790 (5.6)	765 (3.5)	691 (3.5)
	9	765 (2.1)	675 (2.1)	678 (2.1)	669 (0.7)

61.92; $P < 0.001$). There were no significant interactions between cue and flanker type ($F < 1$). Nor were there any significant interactions with age.

In our previous study of adults using the ANT (Fan et al., 2002), we found that a valid cue at the target location reduced the flanker effect in comparison with a central cue. This fit with general findings that attention at the cued location reduces the influences of the flanker (van der Molen, 2000). The lack of a significant interaction in any of our groups may be due to the relatively small number of subjects or to differences between the size of the target and flankers in the adult and child ANT.

The pattern was very similar for the accuracy data. An ANOVA of the accuracy data showed main effects of age ($F(3, 44) = 5.57$; $P < 0.01$) and flanker type ($F(2, 88) = 4.8$; $P < 0.05$). However, there was a significant age by flanker type interaction ($F(6, 88) = 3.7$; $P < 0.01$) revealing differences in the flanker effect (incongruent versus congruent) between age groups.

Three subtractions where computed to obtain the alerting, orienting and conflict scores for each participant. To find out the orienting and alerting scores per subject we computed the median RT per cue condition (across the flanker conditions). The alerting score was obtained by subtracting the median RT for double cue from median RT for the no cue condition, and the orienting score by subtracting the median RT for spatial cue from the RT for central cue. To obtain the conflict score we computed the participant's median RT for each flanker condition (across cue conditions) and subtracted the congruent from the incongruent RTs. The mean score, across subjects, was then computed for each network. The network scores are shown for each age group in the upper part of Table 2 which deals with the data from Experiment 1.

We carried out a set of one-way ANOVAs with age group as the factor in order to assay the developmental trend of the overall performance and the scores of each attentional networks. We obtained no significant effect of age group for alerting, orienting ($F < 1$ for both) and conflict ($F(3, 44) = 1.35$; $P = 0.27$) as measured by RT. The effect of age was significant for conflict when percentage of errors was used to get the conflict score ($F(3, 44) = 3.70$; $P < 0.05$). We also conducted a MANOVA with RT and accuracy conflict scores as dependent measures and obtained a marginal effect of age group (Wilks' $\lambda = 0.77$, $R(6, 86) = 2.02$; $P = 0.07$). The effect of age group was also significant for the overall increase in RT ($F(3, 44) = 5.44$; $P < 0.01$) and the overall increase in accuracy ($F(3, 44) = 5.85$; $P < 0.01$). Post-hoc tests were conducted using Bonferroni method for multiple comparisons in those effects that were found significant. For conflict accuracy differences were found to be significant between the youngest group and the age 8 years ($P < 0.05$), and marginal between the youngest group and age 7 years ($P = 0.06$) and 9 years ($P = 0.09$) groups. Difference in the overall RT was significant between the oldest group and age 6 years ($P < 0.01$), and there was also a marginal difference between age 9 and 7 years ($P = 0.06$) groups. Finally, for overall accuracy, differences were significant between the youngest group and age 7 years ($P < 0.05$), 8 years ($P < 0.05$) and 9 years ($P < 0.01$).

2.4. Discussion

Between 6 and 10 years of age reaction times and error rates improve steadily. We chose to compute the network scores by using the absolute differences between conditions rather than taking them as a percentage of the overall RT. This strategy is discussed more fully in Section 5.

The network scores show different rates of development. The alerting network shows no important change between age six and 10. The orienting network shows a small tendency to be reduced at the oldest of our ages, but this does not reach significance. We did not monitor eye fixation in this study because it is known that there is very substantial overlap in the anatomy of covert and overt orienting (Corbetta & Shulman, 2002). Moreover, RTs are normally increased on trials when adults move their eyes toward the cue (see

Table 2
Attention network subtractions, overall RT (ms) and overall accuracy (percentage of errors) by age

Experiment	Age (years)	Attentional networks subtractions				Overall RT	Overall error rates
		Alerting	Orienting	Conflict	Conflict for errors[a]		
Child ANT							
1	6	79 (75)	58 (76)	115 (80)	15.6	931 (42)	15.8
	7	100 (75)	62 (67)	63 (83)	0.7	833 (125)	5.7
	8	73 (67)	63 (66)	71 (77)	−0.3	806 (102)	4.9
	9	79 (47)	42 (48)	67 (38)	1.6	734 (68)	2.7
2	10	41 (47)	46 (44)	69 (44)	2.1	640 (71)	2.2
	Adults	30 (32)	32 (30)	61 (26)	1.6	483 (36)	1.2
Adult ANT							
2	10	78 (61)	60 (56)	156 (76)	3.9	710 (90)	2.8
	Adults	40 (34)	52 (35)	131 (62)	4.7	532 (54)	2

Standard deviations are presented between parenthesis for the RT data. This table summarizes data from Experiments 1 and 2.
[a] Percentage of error for incongruent trials − percentage of errors for congruent trials.

Fig. 1 in Posner & Cohen, 1980).There is no evidence of this happening in the peripheral cue condition of our study which has among the lowest RT of any of the cue conditions at all ages. However, in future studies, it would clearly be of interest to monitor eye movements and determine their influence in more detail. In some ways the conflict network is the most remarkable. It shows a clear improvement from 6 to 7 years of age in both errors and RT, but is surprisingly stable after that.

3. Experiment 2

Because the fish ANT has such a different display than the arrows used for adults it is not possible to compare directly child and adult scores. This seemed particularly important for the alerting network, which remained at very high values throughout the ages studied. Experiment 2 deals with a comparison of the adult and child versions of the ANT with 10-year-olds and adults. In order to make a more direct comparison between the scores of children and adults we decided to run both groups on the child and adult version of the ANT. This allows us to separate the effects of age from those due to stimulus type.

3.1. Method

3.1.1. Participants

Twelve adult volunteers (five females) between 19 and 41 years of age (27-year-old on average) were paid US$ 10 for their participation. They were recruited from sign up sheets in the Psychology Department at the University of Oregon. Twelve 10-year-old children (10 years and 4 months old on average), 7 of them females, were recruited from a database of child births in the Eugene area that has been updated over the last 12 years. They were given a choice between US$ 10 and US$ 10 gift certificate for their participation.

3.1.2. Stimuli

Each participant completed two different versions of the ANT that differed only in the types of stimuli that appeared. All adult and child participants completed a version that presented colored fish as target and flanker stimuli, just as described in Experiment 1, with the exception that visual and auditory feedback were omitted. All adult and child participants also completed a version of the task that presented simple arrows instead of fish. The arrow version of the task was identical to the task described in Experiment 1 except that the stimuli are the arrows used in the adult ANT described by Fan et al. (2002). The time course of the trials, the cues, and the background color on the screen were identical to Experiment 1 described above. The only difference between the fish and arrow versions was the stimulus type.

3.1.3. Procedure

Each participant went through an experimental session that took place individually in a testing room at the University of Oregon. The experimental session consisted of two tasks: the fish version and the arrow version (child or adult, accordingly). Both versions of the task were completed on an IBM compatible laptop computer. The order of each task was counterbalanced across participants within each group. Each of the tasks consisted of a practice block with 24 trials and two experimental blocks of 48 trials each.

The instructions were the same for both versions of the task. Participants were told that an arrow (or fish) would appear on the screen and that the purpose of the task was to press the button on the mouse that matched the way the arrow (or fish) was pointing. They were then told that sometimes several arrows (or fish) would appear at once. They were instructed that in this case they should pay attention to the arrow (or fish) in the middle and press whichever button matched the way that arrow (or fish) was pointing. Finally, participants were instructed to maintain fixation on the cross in the center of the screen throughout the task and to respond as quickly and accurately as possible.

In both versions of the task children and adults were given feedback during the practice trials (the word "Correct" or "Incorrect" appears after their response to the target) and there was no feedback following experimental trials. The experimenter remained in the room with the participants only for the practice block. Participants then completed the test blocks. The practice block took approximately 3 min and each test block took approximately 5 min. Each task usually lasted approximately 20 min. Participants could take breaks at the end of the practice block and between test blocks. After completing the first version of the task the second was explained and performed in the same fashion. The entire session lasted no more than 45 min in total.

3.2. Results

The means of the median RTs (ms) for correct responses and percentage error per experimental condition are presented in Table 3. The data were entered into an analysis of variance with stimulus type (arrow versus fish) cue condition (no cue, double cue, central cue or center cue) and flanker condition (congruent, neutral and incongruent) as within subject factors, and group (adults versus child) as between subject factor. All of the main effects were highly significant: age group, ($F(1, 22) = 49.55$; $P < 001$; stimulus type, $F(1, 22) = 43.57$; $P < 0.001$; cue type, $F(3, 66) = 38.65$; $P < 0.001$; and flanker type $F(2, 44) = 146.82$; $P < 0.0019$. In addition the stimulus type interacted with cue ($F(3, 66) = 5.57$; $P < 0.01$) and flanker condition ($F(2, 44) = 54.6$; $P < 0.001$), both showing smaller effects with the simpler fish stimuli than with the arrow stimuli. No other interactions were significant and there were no significant differences between the effects of task variables between the two groups. The lack of interaction between cue type and flanker type for both the children and adult ANT shows that the presence of an

Table 3
Comparison of 10-year-old children and adults on the child and adult ANT

Group	Flanker type	Warning type			
		No cue	Central cue	Double cue	Spatial cue
Adult ANT					
Children (10-year-old)	Congruent	758 (4.2)	695 (0.0)	654 (0.0)	621 (1.0)
	Incongruent	877 (4.2)	860 (7.3)	858 (6.3)	802 (3.1)
	Neutral	683 (1.0)	634 (1.0)	629 (1.0)	586 (4.2)
Adults	Congruent	548 (0.0)	523 (0.0)	523 (1.0)	485 (0.0)
	Incongruent	668 (7.3)	668 (3.1)	650 (8.3)	603 (2.1)
	Neutral	524 (2.1)	477 (0.0)	458 (1.0)	446 (0.0)
Child ANT					
Children (10-year-old)	Congruent	655 (2.1)	656 (1.0)	618 (1.0)	591 (1.0)
	Incongruent	719 (4.2)	723 (3.1)	677 (5.2)	674 (1.0)
	Neutral	673 (2.1)	619 (2.1)	577 (2.1)	584 (1.0)
Adults	Congruent	505 (0.0)	477 (0.0)	469 (0.0)	453 (2.1)
	Incongruent	546 (4.2)	548 (0.0)	525 (3.1)	527 (1.0)
	Neutral	476 (0.0)	467 (0.0)	438 (4.2)	429 (0.0)

Table shows the mean of median RT (in ms) and (percentage error) per experimental condition obtained in Experiment 2.

interaction may not depend on the type of display used, but may depend on having sufficient subjects.

For the accuracy data we found significant the main effect of cue type ($F(3, 66) = 2.9$; $P < 0.05$) and flanker condition ($F(2, 44) = 13.45$; $P < 0.001$), but no effect of group or stimulus type. The only significant interaction was the cue type × flanker condition ($F(6, 132) = 21.78$; $P < 0.05$).

The results for children and adults are summarized for each of three attentional networks for both versions of the task. The data for the child ANT is in the bottom two lines of the top part of Table 2, while the data from the adult ANT is at the bottom of the table. We conducted a set of ANOVAs to examine the effects of age group and stimulus type on overall RT, accuracy and each of the network scores. The main effect of group was only significant for the overall reaction time, with the adults being faster than the children ($F(1, 22) = 47.64$; $P < 0.001$). Although the 10-year-old children were about 170 ms slower than the adults they were almost as accurate. The difference between children and adults in alerting approached significance overall ($F(1, 22) = 3.42$; $P = 0.08$). Planned comparisons revealed a significant difference in the alerting score between children and adults in the arrow ANT ($F(1, 22) = 4.38$; $P < 0.05$), but no differences between groups for the fish ANT ($F < 1$). There were no significant differences between 10-year-olds and adults in either the orienting or conflict networks with either of the two stimulus types.

3.3. Discussion

When 10-year-olds and adults were compared directly on the two forms of the test there were significant differences between the two in overall reaction time and for the adult ANT in the alerting network.

Surprisingly adults were not significantly more efficient than 10-year-olds in the conflict network for either of the versions of the test. Although the arrow ANT provided conflict scores nearly twice as high as the fish ANT, neither version showed a significant difference between children and adults. This result is consistent with what had been reported previously for the flanker task (Ridderinkhof et al., 1997; Ridderinkhof & van der Stelt, 2000). The effects of flanker interference in the two tests were highly similar for children and adults even though the adult version was considerably more difficult.

4. Experiment 3

In our adult study, we found that the three networks were independent. Consistent with this we found no interactions between cue and flanker types in Experiments 1 and 2. In Experiment 3, by running a larger number of children we attempt to replicate the finding of no interaction between conditions and also test the degree of correlation across subjects between the network scores.

4.1. Method

4.1.1. Participants

Forty-four children between the ages of 6 years, 10 months and 8 years, 5 months (mean age 7 years, 6 months) participated in Experiment 1. Participants were recruited from a public school in Queens, NY, and completed the experiment at the school. Informed consent was obtained from parents prior to the experimental session.

4.1.2. Procedure

Each child was run individually on a IBM compatible laptop computer, but between 2 and 4 children completed the experimental session at a time, facing away from one another at individual desks, with two experimenters present throughout the test.

Table 4
Mean of Median RT (ms) and (percentage error) for Experiment 3

Flanker type	Warning type			
	No cue	Center cue	Double cue	Spatial cue
Congruent	875 (6.8)	822 (4.4)	808 (5.5)	789 (6.1)
Incongruent	966 (12.9)	929 (12.5)	926 (12.5)	925 (13.5)
Neutral	868 (7.2)	828 (6.3)	795 (5.1)	785 (5.7)

The version of the ANT was exactly the same as the one used in Experiment 1 as well as the instructions given to the participants. Each participant performed 24 practice trials that were followed by three experimental blocks of 48 trials in each. The session took no longer than 25 min.

4.2. Results

Table 4 shows the mean of the median reaction times for correct responses and percentage of error for each cue condition and target type. Preliminary analysis showed that there are no differences between left and right pointing targets or between targets that appeared above and below fixation. Therefore, these conditions were combined in all subsequent analyses. An analysis of variance (three flanker type × four cue type) showed large main effects of cue type ($F(3, 129) = 20.65$, $P < 0.01$) and flanker type $F(2, 86) = 65.3$, $P < 0.01$) but no interactions ($F(6, 258) = 1.03$, $P > 0.05$) between the two. The lack of interaction with the child ANT, in agreement with the results of Experiments 1 and 2, shows that the lack of significant interaction was probably not due to the low N. It seems likely that the reduction of flanker effects with valid cueing may depend upon complex factors such as display size, visual angle or stimulus intensity not completely controlled in these studies.

The results of an ANOVA on accuracy scores were quite similar, because long RTs were systematically related to higher error rates.

The network scores that resulted from substracting cue and flanker conditions were the following: alerting had a value of 67 ms, orienting a value of 24 ms, and conflict had a value of 108 ms.

Table 5 shows the correlations between each of these network scores and overall reaction time. As can be seen, there are no significant correlations between the network scores or between any of them and overall RT and accuracy. Overall reaction time and accuracy are correlated so that long reaction times tend to go with high error rates.

Table 5
Correlations between the attentional networks and between each network and overall RT

	Alerting	Orienting	Conflict	Overall RT
Orienting	−0.07			
Conflict	−0.24	0.00		
Overall RT	−0.03	−0.16	0.07	
Overall accuracy	0.04	0.28	−0.04	−0.52[a]

Experiment 3.
[a] Correlation is at the 0.01 level (two-tailed).

4.3. Discussion

Results of the current study fit rather well with the previous data. The children in Experiment 3 (Table 4) had an average age of 7 years, 6 months, thus they were between the youngest (6 years, 9 months olds) and the second group (7 years, 9 months old) in Experiment 1. The overall RT for the children in Experiment 3 was 851 (9.3% error) and for the 6- and 7-year groups in Experiment 1 it was 931 (15.8% error) and 833 (5.7% error), respectively. Experiment 1 showed a somewhat larger effect of alerting and orienting but was very similar in scores for the conflict network. It is also important that in both studies there were no interactions between the type of cue and flanker type suggesting relatively independence between the networks in childhood.

5. General discussion

In this paper, we have explored the use of a version of the ANT appropriate for children between 6 and 10 years of age and examined changes in attentional networks over this period and from this period to adulthood.

There are clear significant improvements in speed and accuracy with age using both the child and adult versions of the ANT. This is clearest in Experiment 2, which provided direct comparisons between 10-year-old children and adults on the same versions of the task. Experiment 1 also provides confirmation of this developmental trend in speed and accuracy improvement within the range of ages 6 and 9 years.

To obtain scores for each network we used appropriate subtractions of the RTs. We did not use ratios of these scores to overall RT for several reasons. First, in our adult studies we found no correlation among the networks scores suggesting that they did not depend heavily upon the common overall RT. Second, one would expect the efficiency of resolving conflict, for example, to produce lower overall scores and lower ratios. Indeed, brain damage and mental illness tend to increase conflict scores in the flanker and stroop tests. If we had used ratios, young children would have higher efficiency in conflict than adults since RT declines with age and the conflict scores are stable after age 7 years. Thus, the conflict scores and not their ratios appear to be more appropriate as a measure of network efficiency. However, the overall RT for each condition is present in the tables and readers may easily calculate the ratios if they wish to do so.

Independence between the network scores for the child version of the ANT is suggested by the lack of correlation between the scores shown in Experiment 3 (see Table 5). However, the lack of correlation may reflect unreliability rather than independence. In our studies, we found no interactions between cue conditions and target flanker condition in any of the experiments. In adults, we did find two small interactions in which the degree of conflict was less when either no cue or a correct spatial cue was given. Neither of these were significant in the current study. These findings are in the direction of some degree of independence between the networks. This finding fits with evidence that they depend on generally different brain areas (Fan et al., 2001). Even if the findings are correct under the conditions of our experiment it would not be reasonable to consider the networks as totally independent since the brain areas involved clearly communicate with each other and orienting can result from instructions that activate the executive network.

5.1. Orienting network

The data summarized in Table 2 suggest, despite some considerable variability, that there is no change in orienting effects from 6 years to adulthood in this task. Orienting to the correct location produces a similar improvement in RT at all ages. This improvement comes from the need to move attention from the central fixation to the expected location. In the ANT, we did not use any invalid trials thus the load on disengaging attention is rather low. The central (neutral) cue occurs at a location where no target is ever presented and thus represents less of a disengagement difficulty than would be true for an invalid cue at a location where there is often a target. The ANT involves a very simple sense of orienting to visual locations that uses the ability of a peripheral cue to redirect attention to one of two places above and below fixation. In a closely related study (Akhtar & Enns, 1989) it was found that children showed a strong tendency for an interaction between orienting and conflict that was reduced between 5-year-olds and adults. These findings were under conditions where orienting involved an invalid cue and thus required a voluntary shift of attention. Apparently, the time to disengage from a cued location is reduced with age, but the movement of attention toward a peripheral cue shows no change between 6-year-olds and adults.

In our previous work with eye movements in infants we have found great stability in learning basic associations between locations and objects from about age 4 months (Clohessy, Posner, & Rothbart, 2001; Posner, 2001). Previous studies of orienting (Ruff & Rothbart, 1996; Trick & Enns, 1998) have suggested that only voluntary movement speed and the accuracy of termination continue to improve in late childhood. Since we used a peripheral cue that tends to pull attention to the central portion of the target, our task would appear to be one whose requirements would suggest an early developmental course. Most of the work in this area, including developmental studies summarized by Trick & Enns (1998) compares valid and invalid cue conditions (cost plus benefit) and thus provide stronger evidence of the time to disengage and reorient from an attended location. Nevertheless, this evidence supports the early development of the orienting network in conformity with our results.

5.2. Alerting network

The alerting network behaves in a quite different way. For alerting we see great stability during middle childhood but the numbers are much higher than in adults. There is a significant decline from 10-year-olds to adults in the alerting scores using the adult ANT and there may also be some improvement in late childhood because the 10-year-olds tend to have lower alerting scores than the younger children. In general, large alerting scores appear to arise because children do poorly when there is no cue. There could be a number of reasons for this result. It may be difficult for children to maintain the alert state thus when there is no cue they lose their attention to the task. This loss of set for the task may involve more than a change of state, it may also reflect a need to retrieve the rules by which they are operating. When a cue is present one can carry out this retrieval function during the delay interval, but when no cue is present the retrieval may on some trials occur after the target is presented.

Clearly alerting also has to develop at an early age, since infants show an increased ability to maintain the alert state during the first year of life. Every stimulus operates both via midbrain systems to tune cortical activity and via sensory pathways to deliver information related to the identity of the stimulus (Hebb, 1949). In recent years, the neural systems related to alerting have been shown to involve the norepinepherine systems arising from the locus coeruleus (Marrocco & Davidson, 1998). Previously, it was found that children had difficulty with the warning aspect of stimuli in comparison to encoding of the identity of a stimulus (van der Molen, 2000; Smothergill & Kraut, 1989). The difficulty in alerting in normal children is supported by our finding of the relatively poor ability of even 10-year-old children to maintain the alert state in the absence of a warning signal.

We have documented an automatic effect of warning signals on performance at age 5 years (Berger et al., 2000), but shown the 5-year-olds have trouble managing the more strategic aspect of alertness that is involved when warning intervals are varied between trials. The presentation of a target without a warning signal in our test is relatively rare and this may reveal the problem children have in maintaining a level of alertness in the face of varying target arrival times. Further work on this aspect of the test may clarify why there is a late development of this system.

5.3. Executive network

Conflict scores also showed a decrease between ages 6 and 7 years. When RT and accuracy are combined this decrease is significant between 6- and 8-year-olds. In current work we have run 4-year-olds in the child ANT and have found much larger conflict scores in both RT and errors than in older children, thus confirming the development up to age 6 or 7 years. Following age 7 years there is remarkably little difference in conflict RT or errors up to and including adults. This result is surprising given the general expectation that the executive network would improve until adulthood as children are able to solve more difficult problems. However, our results fit rather well with the previous literature using the flanker task. A previous developmental study of the flanker task (Ridderinkhof et al., 1997) shows improvement in conflict from age 5 to 10 years and then little difference between this age and adults. This study also shows that size of the display was important. Since our fish display was much larger than the arrow, the previous result suggests it should reach adult levels at an earlier age, and Experiment 1 shows evidence for this. Ridderinkhof et al. (1997) concludes that the major problem for children in flanker tasks is in the translation of the input code into an appropriate response code, particularly when the response is incompatible. Ten-year-olds did show somewhat larger difference between incongruent and congruent RTs than do adults, but they actually had lower conflict related error rates in the adult version of the ANT. Similarly, Diamond and Taylor (1996) carried out a study in which they evaluated performance of children between 3- and 7-year-old in the tapping test. In this test, children are ask to tap once when the experimenter taps twice and tap twice when the experimenter taps once. Correct performance on this test is thought to require certain aspects of executive control like the ability to hold two rules in mind and the ability to inhibit the tendency to imitate the experimenter. Diamond and Taylor found an steady improvement in both accuracy and speed on the tapping test over the ages 3–7 years, however, consistently with our result, most of the improvement occurred by 6 years showing the 7-year-olds group an accuracy rate close to 100%.

Our findings of little or no development in the executive network for the resolution of conflict after age 7 years may not extend to more difficult executive tasks (e.g. those involving strategic decisions like the tower of Hanoi). A recent imaging study found a common network of brain areas involved in the arrow version of the flanker task (similar to the adult version of the ANT), the color Stroop and in a task involving a conflict between location and identity (Fan et al., 2003). Of these tasks the flanker had the largest conflict effect as measured by RT difference and the strongest activation within the anterior cingulate area. Moreover, the child and adult ANTs differ a great deal in difficulty and yet they show about the same developmental trend. These findings suggest an earlier than might have been expected development of neural areas related to aspects of conflict and this will need to be tested more directly in future work.

In informal pilot work, we have taken the fish version of the ANT down to 4 years of age without difficulty. Below this age some children have trouble in pressing keys that are remote from the stimulus and that require translation from the vertical plane of the stimulus to the horizontal plane of the keys. We have developed a touch screen version of the Child ANT and conducted a pilot study with children as young as 3 years and 6 months old. At still younger ages it is possible to study conflict by examining anticipatory eye movements to ambiguous stimuli (Clohessy, Posner, & Rothbart, 2001; Rothbart et al., 2003).

The ability to measure changes in control networks at varying points in the life span may be very helpful both in considering disorders of attention and in assaying the effectiveness of intervention designed to improve their operation. For example, the relatively late development of alerting and to a lesser extent the executive network may make them likely targets of disorders. It is notable that alerting depends heavily upon norepinepherine (Marrocco & Davidson, 1998) while the conflict network involves dopamine (Posner & Fan, in press). These are the two transmitters most often implicated in ADHD. Studies of ADHD children using tasks somewhat similar to the ANT have shown some evidence of abnormalities in alerting and/or executive control (Bush et al., 1999; Swanson et al., 1991). Practice in attention skills have shown some effects in brain injury patients (Sohlberg et al., 2000; Sturm, Willmes, Orgass, & Hartje, 1997) and may provide additional benefits in performance at times when attentional networks are developing. Our current data suggest that children below the age of 7 years may be good candidates for studies of training the executive attention network.

5.4. Individual differences

The discussion so far deals with group differences between ages. The adult ANT has been used as a measure of individual differences (Fan et al., 2002; Fan, Wu, Fossella, & Posner, 2001). The adult ANT proved to have reasonable test retest reliability for the network scores within the same session and showed relatively high correlations in the subsequent twin study (Fan et al., 2001) and thus has proven useful as a phenotype for genetic studies (Fossella et al., 2002).

We have only limited evidence on test–retest reliability in children. When we conducted the test twice among a set of 28 children who took part in Experiment 3 we found no significant correlations between the original network scores and their repetition 6.5 months later. To get some additional information on this question we divided our first session data into odd and even trials and calculated the split half reliability between them. Overall RT (0.94) and error rate (0.93) were highly correlated in this comparison. The conflict (0.59) and alerting (0.37) were significantly correlated but orienting (0.02) was not. One reason for the relatively low correlation was the smaller number of trials available for each half of the data. Nonetheless, we will need to do additional work to determine whether the differences between child and adult reliability are due to age, type of stimulus, or the delay between the first and second sessions.

The child ANT does seem to provide a rapid method to survey three attentional networks in children 4 years and above. Since these networks have been defined anatomically in many studies (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Corbetta & Shulman, 2002; Fan et al., 2001; Fan et al., 2003; Posner & Fan, in press) this feature can make it attractive for assaying normal development and for use in diagnostic and treatment studies of childhood psychopathology.

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