Training, maturation, and genetic influences on the development of executive attention

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A neural network underlying attentional control involves the anterior cingulate in addition to lateral prefrontal areas. An important development of this network occurs between 3 and 7 years of age. We have examined the efficiency of attentional networks across age and after 5 days of attention training (experimental group) compared with different types of no training (control groups) in 4-year-old and 6-year-old children. Strong improvement in executive attention and intelligence was found from ages 4 to 6 years. Both 4- and 6-year-olds showed more mature performance after the training than did the control groups. This finding applies to behavioral scores of the executive attention network as measured by the attention network test, event-related potentials recorded from the scalp during attention network test performance, and intelligence test scores. We also documented the role of the temperamental factor of effortful control and the *DAT1* gene in individual differences in attention. Overall, our data suggest that the executive attention network appears to develop under strong genetic control, but that it is subject to educational interventions during development.

attentional intervention | child development | dopamine genes | effortful control | network efficiency

Attention involves separable networks that compute different functions. One of these, the executive attention network, involves the anterior cingulate and lateral prefrontal areas and is activated strongly in situations that entail attentional control, such as when there is conflict between responses suggested by stimulus dimensions (1–3). An imaging study showed that three different tasks involving conflict activated a common network that included the anterior cingulate and lateral prefrontal brain areas (3). Although conflict is a good way to activate this network, it has been shown to be active in a wide variety of tasks that involve thinking about the required response. In previous work we have related executive attention to the mechanisms for self-regulation of cognition and emotion (4).

All human beings have an executive attention network with a similar enough anatomy to average over subjects in imaging studies (2, 3). However, there are also clear individual differences in the efficiency of network performance. A twin study showed that the efficiency of the executive network was highly heritable (5). To date, alleles of four dopamine-related genes have been found to relate to the efficiency of performance in this network (6–9).

Our studies of the executive network in children have adopted a child version of the Attention Network Test (Child ANT) (10). This test uses a version of the flanker task (11) to assess the ability to resolve conflict and uses different cue conditions to examine alerting and orienting (10). We have found a substantial development of executive attention between 3 and 7 years of age (4, 10). Although much of this development is under genetic control, it is also likely that the home and school environment can exert an influence, as has been shown for other cognitive networks (12–14).

In this study, we explore how a specific educational intervention targeted at the executive attention network might influence its development. We explore training at ages 4 and 6 years so that we might compare influence of specific training at these two ages with general improvement due to development. The intervention we developed was designed to train attention in general, with a special focus on executive control in children of 4 years of age and older. We adopted a method used to prepare macaque monkeys for space travel (15) and modified the various training modules to make them accessible and pleasant for young children. Before and after training, we assayed attention skills of the children by giving them the Child ANT while monitoring brain activity from 128 scalp electrodes. We also measured their intelligence (16). Their parents filled out a temperament questionnaire about the children as well (17).

The executive attention network has been related to individual differences in effortful control as assessed by caregiver questionnaires (18, 19). Studies have also shown that alleles in several dopamine genes (e.g., *DAT1*) are related to performance among adults in the ANT and related conflict tests (6–9). Therefore, we explored differences in temperament and genotype as a possible way of understanding which children might benefit from attention training.

Methods

Participants. A total of 49 4-year-old children (25 males; mean age: 52 months; SD: 2.2 months) and 24 6-year-old children (12 males; mean age: 77 months; SD: 3.2 months) participated in the study. All participants were recruited from a database of births in the Eugene–Springfield, OR, area. Children's caregivers gave written consent to participate in the study. Each family received $135 in compensation for their participation.

Experimental Design. Three experiments were conducted. Twenty-four 4-year-olds participated in Exp. 1, 25 4-year-olds in Exp. 2, and 24 6-year-olds in Exp. 3. For each experiment, children were randomly divided into experimental (to-be-trained, $n = 12$) and control ($n = 12$, $n = 13$ in Exp. 2 only) groups.

The experimental group was treated the same in all three experiments. On the first day they received assays on attention (Child ANT), intelligence (Kaufman Brief Intelligence Test, K-BIT) (16), and parent-reported temperament (Children's Behavior Questionnaire, CBQ) (17), and then were given 5 days of training over a 2- to 3-week period. The Child ANT presents five fish in a horizontal row. The task was to respond to the center fish by pressing a key in the direction in which the fish pointed. On congruent trials, the flanking fish pointed in the same direction as the center fish, and on incongruent trials, the flanking fish pointed in the opposite direction. The conflict score was obtained by subtracting congruent from incongruent reaction times (RTs) (10). On the final day they received the same assays as on day 1, except that the temperament questionnaire was given to the caretaker to

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Abbreviations: ANT, Attention Network Test; K-BIT, Kaufman Brief Intelligence Test; CBQ, Children's Behavior Questionnaire; RT, reaction time; EEG, electroencephalogram; ERP, event-related potential.

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take home and return, filling it out based on the 2 weeks after the final session.

Exps. 1 and 2 differed only in the control group. In Exp. 1, the 12 control children came to the laboratory only twice: on day 1 for one assessment session and 2–3 weeks later for the second assessment session. In Exp. 2, the control group was brought in for five sessions over a 2- to 3-week period in which they watched popular children's videos. The videos were used to control for the number of sessions involving child–adult interactions on the effect of training. Every 30 s to 1 min, the video paused and a sea horse appeared on the screen. The child was instructed to press a key to continue the video. Exp. 3 involved 6-year-olds. The experimental and control groups were treated exactly the same as in Exp. 2. Because 6-year-old children were somewhat faster than 4-year-olds in completing the training program, in Exp. 3 we included one more exercise to complete the five training sessions. Exp. 3 allowed us to examine differences in attentional efficiency between 4- and 6-year-olds and to compare this developmental change with the effects of training. We also collected cheek swabs from most of the 6-year-olds involved in the study to genotype the children for alleles of the dopamine transporter type 1 (*DAT1*) gene, which had previously been shown to be related to executive attention (6).

Electroencephalogram (EEG) Recording and Data Processing. Assessment sessions involved EEG recording during performance of the Child ANT. Forty of the 49 4-year-old participants and 23 of the 24 6-year-old participants agreed to wear the sensor net that allows acquiring EEG data.

EEG was recorded by using the Electrical Geodesic system, with 128-channel Geodesic Sensor Nets (20) and NETSTATION software. The EEG signal was digitized at 250 Hz. Impedances were below 80 kΩ for each channel before recording. Recording was vertex-referenced with a time constant of 0.01 Hz. Continuous EEG data were filtered by using a finite impulse response (FIR) bandpass filter with 12-Hz low-pass and 1-Hz high-pass cutoffs and segmented into 200-ms pretarget and 1400-ms posttarget epochs. Segmented files were scanned for eye and/or movement artifacts. Twenty 4-year-old children (9 in the trained group and 11 in the control group), and 16 6-year-old children (8 in each group) had usable¶ data after artifact rejection. Segments were averaged across conditions and re-referenced to the averaged (across channels) activation.

Genotyping Procedure. Cheek swabs were collected from most of the 6-year-olds involved in Exp. 3, and genotyping of the *DAT1* gene was performed. DNA was isolated from cheek swabs by using the BucalAmp DNA extraction kit (Epicentre Technologies, Madison, WI). Standard PCR testing was performed in a total volume of 50 μl containing 25 ng of genomic DNA, 1.5 mM $MgCl_2$, 0.2 mM of each deoxyribonucleotide, 10 pmol of each primer (5′-tgtggtgtagggaacggcctgag-3′ and 5′-cttcctggaggtcacggctcaagg-3′) and 2.5 units of *Taq* DNA polymerase. The PCR conditions were 1 cycle of denaturation at 94°C for 5 min and 35 cycles of denaturation at 94°C for 30 s, annealing at 63°C for 1 min and extension at 72°C for 1 min before a final extension step at 72°C for 5 min. The PCR products were separated on a 3% high-resolution agarose gel (Sigma–Aldrich) with ethidium bromide staining and visualized under UV illumination.

Training Program. The 5 days of training were divided into 9 (Exps. 1 and 2) or 10 (Exp. 3) exercises. Each was structured to achieve a particular type of training that we thought would be related to executive attention. Each exercise was divided into a number of levels, with children progressing to the next level by making a number (usually three) of correct responses in a row. After each exercise described below, we provide information on the number of levels (*a*), the minimum trials needed to complete (*b*), and the trials-to-advancement criteria (*c*).

The first three exercises taught the children to track a cartoon cat on the computer screen by using the joystick. In the side exercise ($a = 7$; $b = 21$; $c = 3$), children were asked to move a cat to a grassy area and avoid the muddy ones. At first, the grass was on all four sides of the screen, but the grassy area became smaller as the muddy area expanded, increasing the difficulty of control. In the chase exercise ($a = 7$; $b = 21$, $c = 3$), children had to catch a moving umbrella to keep the cat dry. In the maze exercise ($a = 6$; $b = 6$; $c = 1$), children moved the cat through a maze to obtain food.

The *anticipation exercises* involved teaching the children to anticipate the movement of a duck across a pond by moving the cat to where they thought the duck would emerge. In the easier form of the game the duck was visible, whereas in the more difficult version the duck swam under the water so that its trajectory remained invisible ($a = 7$; $b = 21$; $c = 3$, for both visible and invisible versions).

The *stimulus discrimination* exercises consisted of a series of trials in which the child was required to remember a multiattribute item (different cartoon portraits) to pick out of an array. In the first version of the game, the sample portrait remained on the screen while the child selected the matched item. In the more difficult version, however, the sample portrait disappeared before the array was presented, forcing the child to memorize the attributes of the sample ($a = 7$; $b = 21$; $c = 3$, for both portrait and portrait delay).

For the *conflict resolution* set, the children first refreshed their knowledge of the Arabic digits in a series of trials in which they had to match a digit presented on the screen by selecting the correct digit from between two sets of items (number exercise, $a = 5$; $b = 45$; $c = 9$). Then, in a *Stroop-like exercise* (number Stroop exercise, $a = 6$; $b = 18$; $c = 3$ incongruent trials), children had to move their joystick to pick out the larger of two arrays. In the early levels, the arrays consisted of apples, and the number of items in each group differed by a distinct amount (e.g., two compared with seven). Later, the items became digits, and conflict was induced by presenting larger sets made up of smaller digits (e.g., a group of seven number 2s vs. a group of two number 9s).

To complete the 5 days of training, 6-year-olds performed an inhibitory control exercise (farmer exercise, $a = 7$; $b = 66$; $c = 6$ with at least 1 no go trial). In this exercise, children were told to help the farmer bring sheep inside a fence. Children were to first click on a bale of hay presented in the middle of the screen to display the animal behind it, which could be either a sheep or a wolf in sheep's clothes. Children were instructed to click as fast as possible when there was a sheep but to withhold the response if the cartoon was a wolf. In the more difficult levels, the sheep would become a wolf after a short interval.

Results

Most, but not all, children were able to move through the various tasks and levels within the five training sessions. Table 1 shows children's average performance on the training phase for each experiment.

Assessment Scores. We calculated a number of scores related to each of the tasks used in the assessment sessions for each participant. For the child ANT, we computed conflict RT (median RTs for incongruent trials minus median RT for congruent trials), as well as the overall RT and overall % errors. The K-BIT test provides two scale scores, one related to abstract reasoning skills (matrices) and one related to language and experience-related knowledge (vocabulary), as well as an IQ composite score. From the parent-reported temperament questionnaire, we obtained individual scores on three factors typically observed in the CBQ: surgency/extraversion, effortful control, and negative affect.

¶The criterion for usable data was having a minimum of 12 (4-year-olds) or 18 (6-year-olds) clean segments per condition among the correctly responded trials.

Table 1. Average performance of children on training phase for each experiment

Exp.	No. of completed exercises	No. of trials	Trial-to-advance rate	% incorrect trials	% missed trials
1 (4-yr-olds)	6.8	247.5	5.2	8.0	4.2
2 (4-yr-olds)	6.8	250.8	5.5	9.3	3.1
3 (6-yr-olds)	9.3	283.1	4.1	5.0	0.8

Four-Year-Old Children. To test possible differences in the pattern of results for the two experiments involving 4-year-old children, we conducted a set of ANOVAs including experiment (1 and 2), group (trained and control), and assessment session (pre and post) as factors, using each of the assessment scores previously described as dependent variables. The factor experiment was not significant and did not interact with any other factor for any of the scores. In addition, training performance data from the experimental groups involved in Exps. 1 and 2 did not differ significantly (see Table 1). Therefore, Exps. 1 and 2 were combined for all subsequent analyses.

Child ANT. Data from children with >40% errors in any or both sessions were excluded from the analysis. A total of 36 children were included in the analysis, 18 in the experimental group (mean age: 52.4 months, SD: 1.62 months) and 18 in the control group (mean age: 52.9 months, SD: 1.94 months).

The upper part of Table 2 shows the pre- and posttraining overall RT and conflict scores for trained and control groups. Using these scores as dependent variables, we conducted a set of mixed ANOVAs with group (trained and control) and session (pre and post) as between- and within-subjects factors, respectively. The main effect of session was significant for overall RT scores [$F(1, 34) = 36.07$; $P < 0.001$] and overall errors [$F(1, 34) = 4.25$; $P < 0.05$]. Both trained and control groups showed a significant reduction in the overall RT in the postsession [$F(1, 34) = 8.29$; $P < 0.01$, and $F(1, 34) = 31.52$; $P < 0.001$, respectively].

K-BIT. Data from four children with scores 2 SD below the mean in any or both sessions were excluded from the analysis. In addition, one child refused to complete the K-BIT in the presession and, therefore, was also excluded from the analysis.

The middle section of Table 2 shows the results of the intelligence test (K-BIT) scores. Scores for each of the K-BIT subtests and the IQ composite were submitted to a mixed factorial ANOVA with group and session as independent variables. The main effect of session was significant for IQ [$F(1, 42) = 10.19$; $P < 0.01$] and vocabulary [$F(1, 42) = 9.47$; $P < 0.01$] and marginally significant for matrices [$F(1, 42) = 2.96$; $P = 0.09$]. More importantly, the group × session interaction was found significant for IQ [$F(1, 42) = 4.3$; $P < 0.05$] and matrices [$F(1, 42) = 7.31$; $P < 0.01$], indicating that the pre vs. post difference in these scores was significant only for the trained group [$F(1, 42) = 13.87$; $P < 0.001$ for IQ and $F(1, 42) = 9.79$; $P < 0.01$ for matrices; $F < 1$ for both comparisons for the control group].

Six-Year-Old Children. ***Child ANT.*** Data from one child in the control group showed a percentage of overall errors 2 SD above the mean for the group in both pre and post sessions. Data from this child were omitted from further analysis. The pre and post ANT data are shown in the upper section of Table 2. We conducted 2(group) × 2(session) ANOVAs for each of the scores. The ANOVAs revealed a significant main effect of session for overall RT [$F(1, 21) = 51.91$; $P < 0.001$]. The group × session interaction was not significant for any of the scores. However, the greater reduction in conflict RT scores shown by the trained group (see Table 3) was predicted. We tested this control vs. trained difference in the postconflict score by using a t test, but the effect did not reach significance [$t(21) = 1.41$; $P = 0.17$].

K-BIT. Data from all participants (see middle section of Table 3) were included in a set of 2(group) × 2(session) ANOVAs with vocabulary, matrices, and IQ as dependent variables. We found significant main effects of session for IQ and vocabulary [$F(1, 22) = 5.83$; $P < 0.05$ and $F(1, 22) = 6.01$; $P < 0.05$, respectively] and a marginal effect for matrices [$F(1, 22) = 3.38$; $P = 0.08$]. Although the group × session interaction was not significant for any of the scores, we assessed predicted pre vs. post differences for each group by using planned comparisons. The pre vs. post difference was not significant for the control group in any of the scores, although for the trained group this difference was significant for vocabulary [$F(1, 22) = 4.59$; $P < 0.05$] and marginally significant for IQ [$F(1, 22) = 3.51$; $P = 0.07$] and matrices [$F(1, 22) = 2.77$; $P = 0.11$].

Age vs. Training Effects. Because we ran quite similar experimental procedures in the two studies involving children of different ages, we can explore the relative influences of age and experience in the set of scores obtained for evaluating attention, intelligence, and temperament. To do this, we conducted separate ANOVAs for each of the assessment scores, including age and group as between-subjects factors and session as within-subjects factor.

For the child ANT scores, we observed significant main effect of age for all of the child ANT scores: overall RT [$F(1, 55) = 63.86$; $P < 0.001$]; overall errors [$F(1, 55) = 44.02$; $P < 0.001$]; and conflict RT [$F(1, 55) = 4.17$; $P < 0.05$]. The main effect of session was

Table 2. Pre- and postassessment scores for 4-year-old children (Exps. 1 and 2 combined) in control and trained groups

		Experimental			Control		
Task	Score	Pre	Post	Post − Pre	Pre	Post	Post − Pre
Child ANT	Overall RT	1,733	1,525	−208	1,873	1,466	−407
	Overall errors	17.9	17.8	−0.1	17.9	12.0	−5.9
	Conflict	150	134	−16	257	179	−78
K-BIT	Vocabulary	115.3	119.3	+4.0	113.4	117.9	+4.5
	Matrices	105.4	111.9	+6.5	108.4	107.0	−1.4
	IQ	111.5	117.5	+6.0	112.8	114.1	+1.3
CBQ	Surgency	4.71	4.46	−0.25	4.76	4.68	−0.08
	Effortful control	5.00	4.92	−0.08	4.91	4.88	−0.03
	Negative affect	3.94	4.01	+0.07	4.07	4.13	+0.06

Table 3. Pre- and postassessment scores for 6-year-old children (Exp. 3) in control and trained groups

		Experimental			Control		
Task	Score	Pre	Post	Post − Pre	Pre	Post	Post − Pre
Child	Overall RT	1,102	956	−146	1,006	870	−136
ANT	Overall errors	2.8	1.8	−1.0	2.4	1.7	−0.7
	Conflict	73	34	−39	86	72	−14
K-BIT	Vocabulary	109.3	112.8	+3.5	105.7	107.8	+2.1
	Matrices	107.5	110.9	+3.4	108.7	110.6	+1.9
	IQ	108.8	111.7	+2.9	107.9	110.2	+2.3
CBQ	Surgency	4.33	4.60	+0.27	4.59	4.65	+0.06
	Effortful control	5.22	5.15	−0.07	5.14	5.14	0
	Negative affect	3.80	3.67	−0.13	3.74	3.88	+0.14

significant for overall RT [$F(1, 55) = 45.73$; $P < 0.001$] and overall errors [$F(1, 55) = 4.09$; $P < 0.05$]. We also found an age × session interaction for overall RT [$F(1, 55) = 6.29$: $P < 0.05$]. This interaction indicated that, although the overall RT reduction was significant for both groups, it was greater for 4-year-olds [$F(1, 55) = 55.17$; $P < 0.001$; mean: -307] than for 6-year-olds [$F(1, 55) = 7.41$; $P < 0.01$; mean: -141].

To examine age effects on the K-BIT scores, we used the raw scores to run the ANOVAs. The main effect of age was significant for all of the scores: vocabulary [$F(1, 64) = 35.93$; $P < 0.001$], matrices [$F(1, 64) = 77.6$; $P < 0.001$] and composite [$F(1, 64) = 67{,}97$; $P < 0.001$]. The main effect of session was also significant for all of the scores: vocabulary [$F(1, 64) = 17.08$; $P < 0.001$], matrices [$F(1, 64) = 9.95$; $P < 0.01$] and IQ composite [$F(1, 64) = 27.82$; $P < 0.001$]. We also observed a significant group × session interaction for matrices scores [$F(1, 64) = 4.32$; $P < 0.05$], indicating that only the trained group increased the matrices scores in the postsession.

In Table 4 we compare the percentage change due to age from 4 to 6 years with the percentage of change found in the trained group in all of our studies. For the Child ANT and intelligence, the percentage of change in the trained group is always in the same direction as the percentage change due to age, but it is always much smaller.

Underlying Brain Network. Electrophysiological data served to investigate changes in the pattern of brain activations due to training. According to previous studies with the same and similar flanker tasks, conflict-related effects were most expected around the N2 component for channels located at frontoparietal and prefrontal areas (21, 22). In addition, results from adult studies have shown that the fronto-parietal N2 reflects conflict-related activity in the anterior cingulate (22). Target-locked event-related potentials (ERPs) for trained and nontrained children of each age group at prefrontal (Fz) and frontoparietal (Fcz and Cz) positions are presented in Fig. 1. The leftmost set of ERPs represents adults run with the same task in a previous study (21).

Table 4. Training and age effects

		Change due to:	
Task	Score	Training	Age
Child ANT	Overall RT	−12.6	−43.8
	Overall errors	−18.1	−86.3
	Conflict	−32.0	−63.8
K-BIT	Vocabulary	+6.1	+28.0
	Matrices	+9.6	+51.1
	IQ	+7.3	+36.4
CBQ	Surgency	+0.5	−2.1
	Effortful control	−1.5	+5.0
	Negative affect	−0.8	−7.1

Data are the percentage of change due to training {[(post-training score − pre-training score)/pre-training score]·100} or due to age {[(4-yr score −6 yr score)/4-yr score]·100} for each of the assessment scores.

To examine the effect of congruency of flankers on brain activity, we computed amplitude differences between congruent and incongruent conditions sample by sample along the entire ERP segment. Dependent-samples *t* tests were carried out to assess the significance of these differences in each group. The shadowed areas between congruent and incongruent ERPs in Fig. 1 show the sections of the segments in which the differences were significant. Remarkably, 6-year-old children in the trained group showed significant differences in the N2 time-window in the same channel (Cz) as observed for adults, whereas nontrained 6-year-olds showed a more anterior effect (channel Fz). For the 4-year-olds groups, only the trained children showed a hint of an effect in the expected direction (more negative amplitude for incongruent trials than for congruent ones) at Fz. Thus, for 4-year-olds, training seemed to produce an EEG pattern at Fz similar to the untrained 6-year-olds, whereas for 6-year-olds the effect of training was to produce a more adult-like pattern.

Attentional Performance, Temperament, and Genes. Fifteen families participating in Exp. 3 gave consent for taking DNA samples of the children. We genotyped the DNA samples for the *DAT1* gene. In previous work, we had found that particular polymorphisms of this gene were related to performance in the conflict task (6). Seven of the children in our study carried the pure long (10 repeat) form of the gene; eight had the long/short heterozygote form; and only one had the pure short form (9 repeat).

We compared the group of children carrying the pure long allele (*L* group) to the group of children carrying the long/short (*L*/*S* group) in the assessment scores obtained at the first session. Because of the small number of children involved, we combined the trained and untrained groups. The mean for each group in each of the assessment scores is presented in Table 5. We tested the mean differences between the two groups in each score by using one-way ANOVA. The *L* group had significantly lower conflict RT scores than the L/S group [$F(1, 13) = 5.65$; $P < 0.05$]. This finding may at first seem different from the result we previously reported (6), where adults containing at least one long allele were worse than the pure short allele group in conflict scores. However, a reanalysis of the data in ref. 6 showed that, consistent with the current data, the effects found there were mostly due to the large conflict scores for individuals with the mixed long/short alleles.

The data on temperamental variables of negative affect, surgency, and effortful control are reported in Tables 2, 3, and 4. An analysis of the temperament data showed that the *L* group had lower surgency scores [$F(1, 13) = 45.55$; $P < 0.001$] and higher effortful control scores [$F(1, 13) = 14.41$; $P < 0.01$] than the *L*/*S* group. The finding for effortful control was in line with the lower

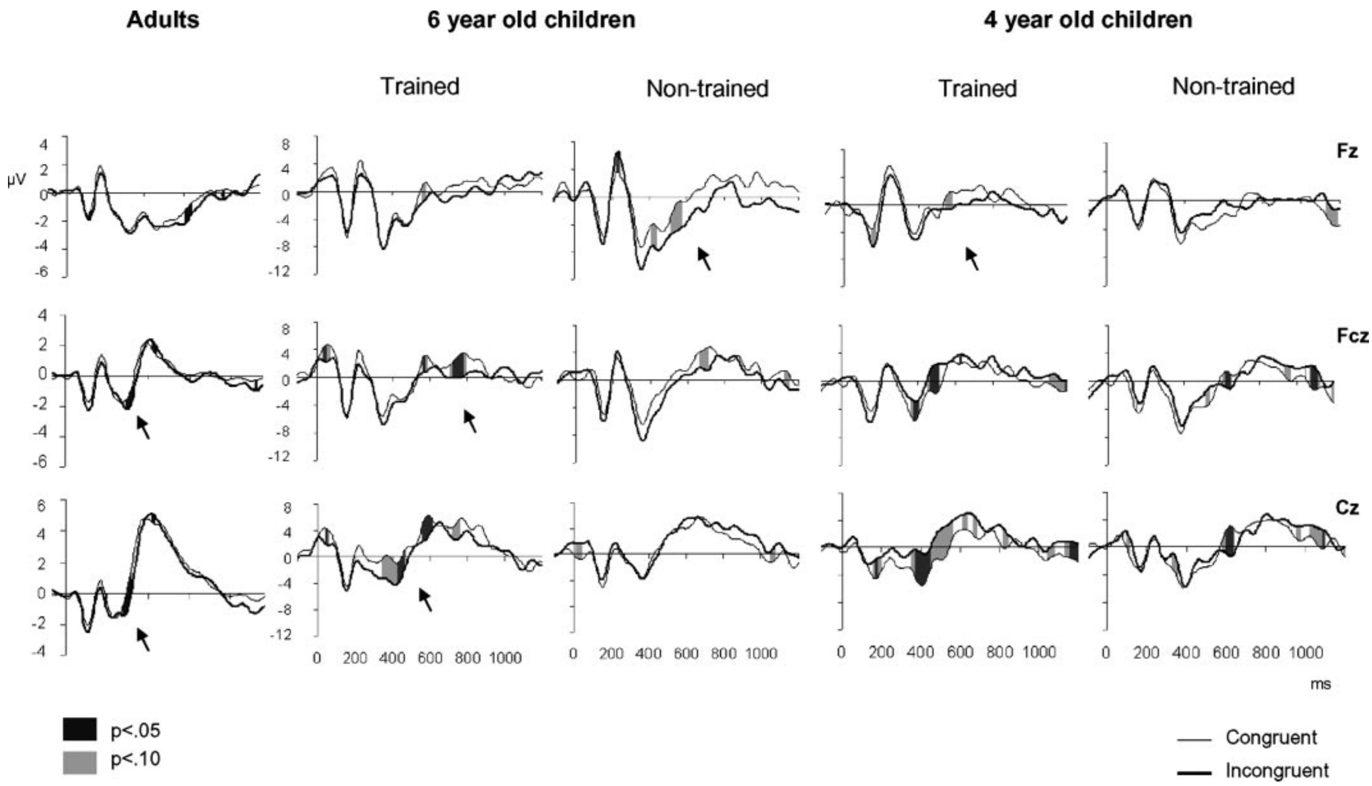

Fig. 1. ERPs over three frontal midline channels during incongruent (dark) and congruent (light) trials of the Child ANT. Data are from adults (21) and trained and nontrained 6- and 4-year-old children at postassessment session. Shadowed areas show significant differences between conditions as assessed by *t*-tests.

conflict score of the *L* group, and it extended the relationship with this polymorphism to children's behavior in the everyday settings observed by caregivers.

Eleven children (six with the long and five with the long/short forms of the gene) of the 15 we had genotyped had usable ERP data. To examine possible differences in the pattern of brain activations between *L* and *L/S* groups, we calculated the flanker effect on peak amplitude of the N2 component (time window 300 to 500 ms) and tested differences in the magnitude of the effect between the two groups. We found significant group differences in the N2 effect at channel Fz [$F(1, 9) = 5.82$; $P < 0.05$]. Hence, the group that showed reduced conflict and higher effortful control scores (*L* group) also showed the N2 effect in the expected direction (more negative amplitude for incongruent trials) at prefrontal leads, whereas the children having higher conflict and lower effortful control scores (L/S group) had the revered N2 effect.

Table 5. Data of each of *DAT1* polymorphism for several dependent variables

Domain	Score	*DAT1* gene polymorphism *L**	*DAT1* gene polymorphism *L/S*[†]	*P*
Attention	Conflict	8	217	<0.05
	Overall RT	996	1,110	
Temperament	Surgency	3.55	5.21	<0.001
	Effortful control	5.62	4.48	<0.01
	Negative affect	3.72	3.83	
Intelligence	IQ	113	106	
	Vocabulary	115	106	
	Matrices	108	107	
Brain	N2 effect at Fz	−3.57	5.02	<0.05
Activation	N2 effect at Cz	0.63	−1.31	

**L*, subjects are homozygous for the long allele.

[†] *L/S*, subjects are homozygous for the short allele or are heterozygous long/short alleles.

Discussion

Age Differences. Executive attention develops strongly in the period we have studied between 4 and 6 years of age (23). This development was found in significantly lower conflict scores in the ANT and a 5% increase in effortful control as measured by questionnaires. Improvement in executive attention is also indexed by changes in the scalp recorded EEG. When performing the ANT, untrained 4-year-olds showed no evidence of a larger frontal negativity for incongruent than for congruent trials, whereas 6-year-olds did show such evidence. In adults, the more negative amplitude for incongruent trials around the N2 component at frontoparietal leads has been related to activity in the anterior cingulate (22), an important node of the executive attention network (3).

Training. Our study used only a very brief 5-day training period with normally developing children. We hoped to find only the rather minimal changes that we might be able to observe with sensitive performance assays, suggesting the use of attention training for a wider range of children than just those diagnosed with deficits.

We found evidence of a change in the executive attention network in the direction of reduced difficulty in resolving conflict. Reaction time differences were highly variable as suggested by the difference at pretest, especially for 4-year-olds. However, the averaged conflict scores at posttest were smaller and more adult-like for the trained group at both ages than for their controls. The posttraining score for 6-year-olds (39 ms) is rather similar to adult scores (30 ms) for this task (21). The training effect overall was about half as large as the one due to the 2 years of development from 4 to 6 years of age (see Table 4). In all respects, training effects resembled those of development in making the conflict scores more adult-like. However, the lack of a significant interaction between attention training and conflict scores means that the ANT data itself do not provide sufficient evidence for a specific training effect.

Electrophysiological data suggested that training had a specific effect on the scalp distribution of the ERPs that was similar to the influence of development, confirming the direction of the behavioral data in showing more adult-like performance after training. Trained 4-year-olds (but not controls) showed a prefrontal effect where more negative amplitudes were observed for incongruent than congruent trials. By 6 years of age, the same prefrontal effect was present in the untrained children. However, the trained 6-year-old children showed the more dorsal frontal effect found in adult data. Anterior vs. posterior subdivisions of the anterior cingulate have been respectively associated with emotional and cognitive forms of attentional regulation (2). Our data suggest that the affective division of the system might be available first in the course of development, moving to the dorsal-cognitive division with maturation and/or training.

Our studies also showed clear evidence of generalization of the benefits of training to aspects of intelligence that were quite remote from our exercises. The improvement was small in overall intelligence and strongest in the matrices subscale. The matrices scale measures more culture-free aspects of intelligence as simultaneous processing, nonverbal reasoning, and fluid thinking. It is known that parts of the adult IQ loading on general intelligence (g) activate the cingulate and other nodes of the executive attention network (24). Moreover, the matrices scale of the K-BIT was also improved in a training study of working memory (25).

Genes. Our genetics data help to explain some of the variability in pretest behavior among 6-year-olds. Those with the homozygous long allele showed significantly less difficulty in resolving conflict than those with the heterozygous (L/S) alleles. The association between genetic background and attentional efficiency raises the question of which children would be more susceptible to training. In our studies, children with poorer initial performance in conflict were more likely to show training effects than those without.

We found that the long form of the *DAT1* gene was associated with stronger effortful control and less surgency (extraversion). This finding suggests that the less outgoing and more controlled children may be less in need of attention training. The effortful control measure is related to executive attention during childhood (18, 26), so this finding fits with the ANT result and with the tendency of children with the pure long form of the gene to show a more mature ERP pattern. Effortful control and ANT conflict scores have been shown to be highly heritable (5, 27) and our finding of an effect of the *DAT1* gene polymorphism fits with its strong heritability. The surgency difference may result from greater control of expressive action in children with the pure long allele.

Practical Implications. Attention training arose primarily as a rehabilitation method. For example, attention process therapy can improve the performance of adults with brain injury (28). One recent study also found improvement in visual attention in normal adults after training with video games (29). Attention process therapy has also been adapted for use with children who have attentional deficits and has been shown to be beneficial for school age and preschool children (30, 31).

In a study training working memory with attention-deficit/hyperactivity disorder children, improvement in working memory and IQ was found after 25 h of training (25). Imaging of adults with a functional MRI before and after training showed increased activation in a network of brain areas that had been related previously to spatial working memory (32). Activity in the cingulate was reduced by training, suggesting that the trained subjects required less effort on the task to achieve better performance.

It has been reported that attention training is used in Middle European schools to help reduce the home differences due to parental income and other factors that relate to exposure of children to teaching in the years before school (33). Questions that arise from our current research are whether such training would be effective in preparing preschool children for primary education and how might various methods of training be best combined in developing curricula for preschool education. Additional consideration also needs to be given to the role of attention training in pathologies that involve attentional networks. To assist in answering these questions we have made access to our training program freely available through a web site (www.teach-the-brain.org) sponsored by the Organization for Economic Cooperation and Development (OECD).

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Educating executive attention

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Researchers in the newly emerging field of developmental cognitive neuroscience seek to understand how postnatal brain development relates to changes in perceptual, cognitive, and social abilities in infants and children (1). One of the areas of cognitive development that has benefited most from a developmental cognitive neuroscience approach is attention. The ability to attend to individual objects, people, and spatial locations within our complex and varied sensory environment is fundamental to human cognition. One important aspect of attention, so-called executive attention, refers to our ability to regulate our responses, particularly in conflict situations where several responses are possible. This aspect of attention is thought to develop until early adulthood but seems to undergo a particularly rapid development between 2 and 7 years of age (2, 3), and problems with this function as well as other executive functions may underlie some of the difficulties observed in children with Attention-Deficit/Hyperactivity Disorder (ADHD) (4).

In this issue of PNAS, Rueda *et al.* (5) present a study that elucidates several aspects of executive attention in young children. In their work, they have gathered measures of brain activity, cognition, and behavior in children aged 4 and 6 years. These measures include behavioral assessments of executive attention and intelligence, genotyping of a dopamine-related gene (DAT1), recording electrical activity at the scalp generated by neuronal function (ERPs), and parental questionnaires relating to the child's temperament. For each age group, half of the participants received a specific educational intervention designed to enhance executive attention. This training program, adapted to be child-friendly from a method originally used to prepare macaque monkeys for space travel, was given for 5 days over a 2- to 3-week period.

Rueda *et al.* (5) build on previous work showing that executive attention has a specific developmental course and strong genetic associations. For example, it has been shown that the executive attention network (6, 7) has a relatively large genetic component compared to more basic aspects of attention such as alerting and orienting (8). In addition, several studies have demonstrated that younger children, especially children below 4 years of age, have great difficulty performing tasks that involve solving some form of stimulus conflict and thereby engaging the executive attention network (2, 3, 5, 9–11). However, in a recent study, Rueda *et al.* (3) found that performance on the executive component of the Attention Network Test (ANT, a test battery measuring three core attentional functions) does not improve significantly beyond age 7, indicating that children this age perform close to adult levels. On this basis, Rueda *et al.* (5) reason that because children between 4 and 6 years of age are still developing this ability, they constitute the ideal group for studying training effects on executive attention. Furthermore, because of the strong genetic influence on executive attention in adults, possible interaction effects between genotype and training can potentially be established in a combined developmental and training study.

Executive attention refers to our ability to regulate our responses, particularly in conflict situations.

The work of Rueda *et al.* (5) significantly advances our understanding of the development of executive attention in two ways. Firstly, for the first time in young children they show an association between a cognitive function (executive attention), a measure of brain function (event-related potentials recorded from the scalp), and genotype (DAT1). This breakthrough potentially opens a new vista for experiments in developmental cognitive neuroscience in which genetics, brain function, and behavior can be related through the study of individual differences. Secondly, the paper advances the field because it demonstrates that executive attention skills can be trained, or development accelerated, in young children. This finding could potentially lead to better intervention strategies for children with attentional and other behavioral problems.

In their interpretation of the results, the authors propose that improvements in performance induced by training are similar or identical to improvements caused by the passage of developmental time, i.e., maturation. Thus, they argue that the immature system can be trained to function in a more mature way (albeit that in their study the effects of training were smaller than the effects of maturation). They also argue that the effect of attention training extends to more general skills such as those measured by intelligence tests.

The behavioral data from the 6-year-old children strongly support their conclusions. In this experiment, the trained group did better than the untrained group on both the ANT and K-BIT (a test of general intelligence). The 6-year-olds improved more on the ANT measure than on the K-BIT. The behavioral data were supported by event-related potential (ERP) findings. These data showed a strong effect of "conflict" recorded over parietal channels for the trained group, whereas the untrained group tended to show an effect over frontal channels. These ERP findings fit well with the authors' claim that the trained 6-year-olds showed a more adult-like neural response than the untrained group did. The ERP result might also indicate that the trained 6-year-olds engage a more automatic posterior cortical system, whereas the untrained 6-year-olds have to recruit frontal cortical networks to exert executive control. This in itself is an interesting finding.

The data from 4-year-old children appear less clear-cut. Although the trained group did show significant improvement in their general intelligence measures, effects of training were not as strong on measures of executive attention. It is possible that other neural mechanisms are at play in the 4-year-old group, perhaps expressing the great difficulty with which this group performs executive attention tasks in the

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first place. A similar interpretation is discussed in another study by Rueda and colleagues (11) that compared adult and 4-year-old children's ERPs during ANT performance. Further studies will no doubt be required to establish the extent to which training affects executive attention measures in 4-year-old children.

An alternative interpretation of the data is that training effects lead to more mature or adult-like performance in various ways, but that such training depends on the age of the child. For example, the 6-year-old children may show a large training effect on the executive attention measure because they are approaching adult levels in the first place. The effect would thus constitute an acceleration at the end of the normal developmental course of this attentional function. Conversely, the 4-year-old children may not benefit so much in terms of executive attention performance because this function is still quite immature in children this age. However, as can be seen in tables 2 and 3 in Rueda *et al.* (5), the 4-year-olds actually showed a larger increase in intelligence measures than the 6-year-olds indicating that they may benefit from training in a more general way. We have illustrated these differential age and training effects in Fig. 1.

The genetic and temperament data presented in Rueda *et al.* (5) are interesting and consistent with the authors' hypothesis. As in previous studies (8, 12), the authors are able to show strong genetic contributions to individual differences in executive functioning even in a relatively small sample of children. As Diamond *et al.* (12) point out, gene association studies that are focused on well studied candidate genes do not require the usual large sample sizes used in genetic studies.

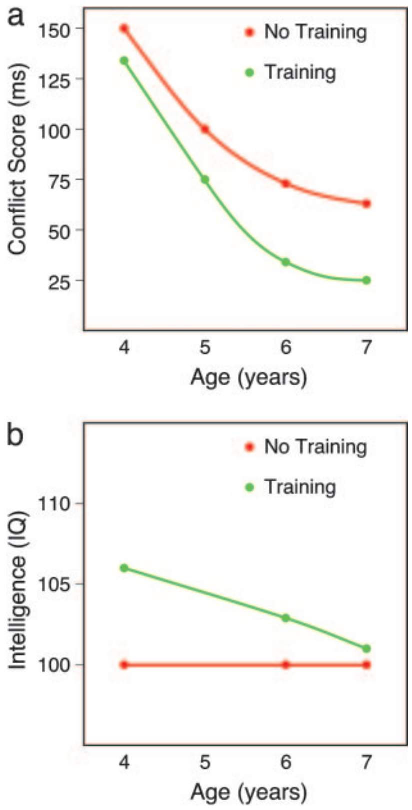

Fig. 1. Differential training effects across age. (*a*) The effect of training vs. no training (baseline) on executive attention performance. (*b*) The effect of training vs. no training on intelligence performance. Data points at ages 4 and 6 are based on data from Rueda *et al.* (5). The data point at age 7 for the average conflict score of the untrained group is based on data from Rueda *et al.* (3). All other data points are hypothesized because no data are available for these ages at present. Note that the IQ measure has been adjusted to a mean of 100 because this is likely to be the population mean of standardized test scores at all ages.

Nevertheless, a replication in a larger sample of children would allow an analysis of possible differential effects of training on children with different genotypes.

At a more general level, the study raises the question of the relationship between executive function and intelligence. As discussed above, the results seem to indicate that the training advanced children in different ways depending on their age. Whether this finding means that executive attention is a separate function that develops independently from intelligence, or whether executive attention is an integral part of intelligence that shows different training effects at different ages, cannot be addressed by the current study. In future studies, it will be interesting to investigate this question further. In addition, it would be relevant to follow up a group of children to establish whether the training effects persist over time or whether the effects of training are only short-term.

In conclusion, the study reported by Rueda *et al.* (5) shows that both genotype and training influence performance on specific attentional tasks and tests of general intelligence in 4- and 6-year-old children. However, more work will be required to unravel the complex interactions between age, genotype, and training efficacy. The training program devised in the study has considerable potential for practical application to both typical and atypical populations, especially children affected by ADHD. (The authors offer their program on the web at www.teach-the-brain.org/learn/attention.) However, it is clear from the results of the study that any training program should take into account factors such as the individual child's genotype and age. Such age and genotype targeted training programs offer great promise for the future.

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