Modeling the Performance of Children on the Attentional Network Test

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Abstract

Recent research in attention indicates it involves three anatomical networks concerned with alerting, orienting and executive control (cf. Posner & Fan, 2007). The Attentional Network Test (ANT) provides a behavioral measure of the efficiencies of these three networks within a single task (Fan, MaCandliss, Sommer, Raz & Posner, 2002). This work adapts an ACT-R 6.0 model of adult performance on ANT (Hussain & Wood, 2009) to model the performance of children (aged 6, 7, 8, 9 and 10) on a child-friendly version of the task (Rueda, Fan, McCandliss, Halparin, Gruber, Lercari, Posner, 2004). Modifications are carried out within the framework of the ACT-R cognitive architecture (Anderson, Bothell, Byrne, Douglass, Lebiere, & Qin, 2004; Anderson & Lebiere, 1998). Models simulating the child study results indicate that improvements in latency and error rate can be attributed to incremental improvements in processing time and reduction in errors of commission respectively. In contrast the models indicate a qualitative difference between children under 9 and older age groups in both alerting efficiency attributed to specific reductions in processing surprise stimuli in the younger age groups, and executive control efficiency between 6 year olds and older age groups attributed to a slower ability in 6 year olds to focus the target in incongruent stimuli. An inhibiting effect of the alerting network on congruency, not found in the child study, was found in the model data consistent with adult studies (Callejas, Lupianez & Tudela, 2004; Fan, Xiaosi, Kevin, Xun, Fossella, Wang, Posner, 2009). Investigation of model performance under invalid spatial cueing conditions compared to adult model performance (Hussain & Wood, 2009) finds the models are differentiated by a slower ability to disengage from invalidly cued locations in the child models but are similar in benefiting from the facilitating effects of cueing on processing congruent stimuli.

Keywords: Attentional Networks; Attentional Network Test; ANT; ANT-C; Alerting; Orienting; Executive Control; Computational Modeling; ACT-R; Cognitive Development.

Introduction: Attentional Networks

Posner and Peterson (1990) propose that attention comprises a system of anatomical regions which can be divided into the networks of alerting, orienting and executive control. Alerting performs the function of achieving and maintaining a vigilant state; orienting refers to selective visual-spatial attention; and executive control involves monitoring and resolving conflict in the presence of conflicting information. Neuroscience studies have shown that different brain regions are associated with each network (Raz & Buhle, 2006). Orienting consists of three operations, namely disengagement, movement and engagement each associated with separate brain areas (Posner & Peterson, 1990).

Various behavioral tasks have been used to study the behavior of these networks, such as vigilance tasks, cueing tasks, Stroop task and so forth. Fan and colleagues (Fan, et al., 2002) designed the Attentional Network Test (ANT) that measures the efficiencies of all three networks in a single behavioral task. ANT is a 30 minute reaction-time based task combining cueing experiments (Posner, 1980) and flanker effects (Eriksen & Eriksen, 1974).

Attentional Network Test Adapted for Children

ANT-C is a child-friendly version of the combination of flanker and cueing paradigms used with adults modified to study the development of the networks in children (Rueda, et al, 2004). A series of experiments studied age groups ranging from 6 to 10 years in terms of the latency, accuracy and efficiencies of the networks. Figure 1 shows the design of ANT-C adapted to be more child-friendly by replacing the target stimuli with five colorful fish. There are four cue conditions: no-cue, center-cue, double-cue and spatial-cue and three congruency conditions: neutral, congruent and incongruent. Other than the replacement of the arrows with fish and the colorful display, the experimental setup remains the same.

Each trial begins with a central fixation cross followed by a cue (or a blank interval, in the no-cue condition) informing participants that a target will occur soon, and possibly where (spatial cue). The target always appears above or below the centre screen fixation point. An invalid cue (not part of the child study but explored in this paper to assess the effect of invalid cueing on disengaging) appears as a spatial cue but in the location opposite to where the target subsequently appears. The target array is either a fish on its own (neutral), or a central fish surrounded by flanking fish that point in either the same direction (congruent) or opposite direction (incongruent). Based on the direction of the centre fish, the children press the corresponding left or right button on the mouse. Reaction time (RT) spans stimulus presentation to button press.

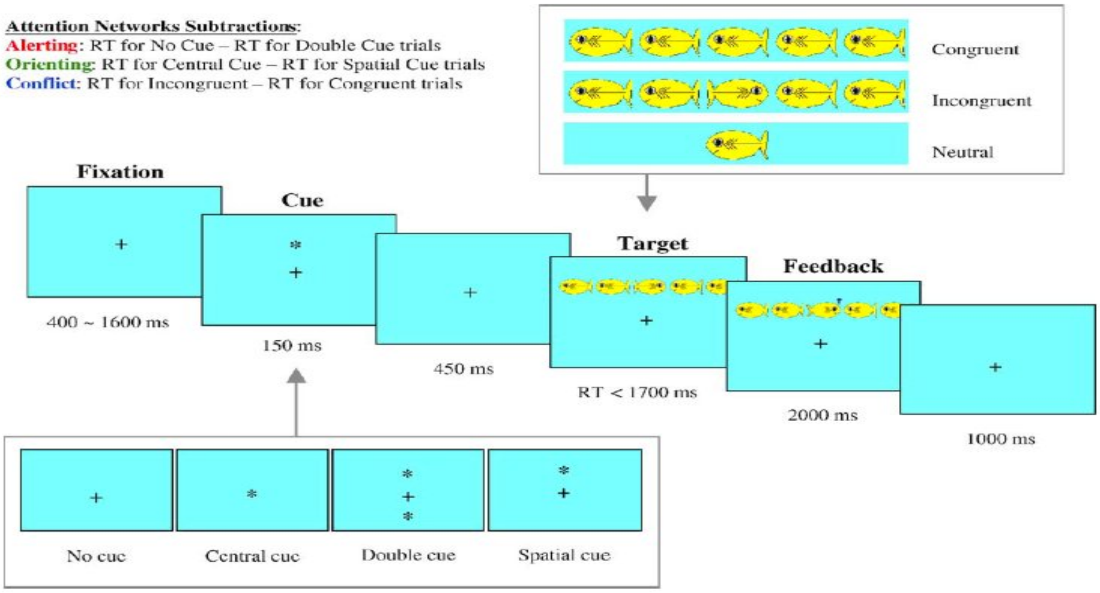

Figure 1: Child version of the Attentional Network Test (ANT-C), in which yellow fish on a blue background replace flanker arrows in the adult version of ANT (Rueda et al, 2004).

The duration of each trial is 25-30 minutes and children are given sufficient practice on the task before the data is formally collected. The formulae used to calculate the efficiencies remain the same as in the adult study, given in equations 1-3 (Fan et al, 2002). An invalid cue condition to study the effect of disengagement of attention is calculated as given in equation 4 (Callejas, et al, 2004; Fan et al, 2009).

$$Alerting = RT\ (no\text{-}cue) - RT\ (double\text{-}cue) \tag{1}$$
$$Orienting = RT\ (center\text{-}cue) - RT\ (spatial\text{-}cue) \tag{2}$$
$$Executive\ control = RT\ (incongruent) - RT\ (congruent) \tag{3}$$
$$Validity = RT\ (invalid\text{-}cue) - RT\ (valid\text{-}cue) \tag{4}$$

The child study (Rueda et al, 2004) reported that latency and accuracy improve over age, up to adulthood. The efficiency of the alerting network is much higher in children up to 9 years with no significant change across age. By age 10 and for adults alerting efficiency significantly reduces. The orienting network seems to be relatively stable up to 10 years with no change. Rate of development of executive control seems to reduce significantly from ages 6 to 7, but after that seems to stabilise up to adulthood with no significant change. Results are similar for 10 year olds and adults on both ANT and ANT-C. This paper compares the results from experiment 1 of the Rueda et al (2004) study that reports performance of age groups 6-9, and the partial results from experiment 2 for performance of 10 year olds on ANT-C, with model performance.

Simulating the Performance of Children on ANT-C Using ACT-R

A symbolic model of adult behavior on ANT (Wang and Fan, 2004) re-implemented in ACT-R 6.0 and extended to model invalid cueing and inter-network modulation effects (Hussain & Wood, 2009) is modified and adapted to simulate children's performance on ANT-C (Rueda et al, 2004). The ACT-R model display was not modified to show colorful fish instead of arrows as from the point of view of the functionality and behavior of the ACT-R model, it would not make a difference (ibid.) The important element to be captured here is the behavior in terms of the cuing and congruity information content of the display, and not color, shape and other visual aspects of the stimuli. The child models were also run on a variation of the task incorporating invalid cuing to assess validity efficiency (eq. 4) and the disengaging effect. Performance is compared with recent findings from adult human studies (Fan et al, 2009) and adult model performance (Hussain & Wood, 2009) based on the adult human studies of Fernadez-Duque & Black (2006) and inter-network modulation effects (Callejas et al, 2004).

Design and Functionality of the Model

The major functionality of the model remains the same as the Hussain & Wood (2009) model of ANT simulating healthy young adults. It consists of four blocks of code: (1) fixation and cue expectation, (2) cue processing, (3) stimulus processing and (4) responding to stimulus.

Associated with each functional step are a number of condition-action (if-then) production rules and parameter settings that combine to produce latency and accuracy data. Through a combination of certain rules firing based on the values in its buffers and underlying parameter settings, the model implements the effects of the alerting, orienting and control networks on attention performance, calculated by equations (1-4) and summarized below (for details refer to Hussain & Wood, 2009; 2009a).

Latency and Accuracy: The time between the appearance of a stimulus and the pressing of the key/mouse is the response time which accounts for latency in ms. Each processing step involved in performing the task involves a rule firing with a default timing of 40 ms. The model also reproduces errors seen in human studies. The number of errors made in each cue and flanker condition is recorded and the average percentage of incorrect responses is reported. The technique for modeling errorful performance corresponds to evidence that errors occur either due to confusion and distraction caused by incongruency, that is commission errors (Mezzacappa, 2004) or simply due to imperfect behavior, just randomly making a mistake.

Alerting: The efficiency of alerting is the difference in latency when there is no cue preceding the stimulus and when there is a double cue that prepares the subject but does not cue spatially. The element of surprise leads to the firing of an extra production, *notice-something-but-not-a-cue* [P1], to simulate the effect of alerting or preparing for the stimulus; this has a subsequent effect on the stimulus processing step by making it more costly (by 40 ms for the extra rule fired).

Orienting: The effect of orienting is achieved in two ways: (1) In the case of cueing, the model is made to focus on the target location using the buffer stuffing mechanism in ACT-R (URL 01) by varying the spread of visual attention determining which object is available for selective attention. For example, if the cue is spatial, then a narrower spread of attention will lead to a higher chance of focusing on the target and ignoring distracters as opposed to other cue conditions whereby both the target and distracters stand an equal chance of being selected for processing. (2) Also, when a spatial cue is encountered, the focus of attention is moved to that location in advance of the target appearing, so when the target stimulus is encountered attention is already engaged at the location, speeding up its selection as opposed to other cue conditions where attention had to be shifted to the target taking an extra processing step.

Executive Control: Executive control involves mental operations that are responsible for detecting and resolving conflicting situations. Here in the model, it is about simulating the flanker effect; showing that at times instead of the centre arrow (or fish) a flanker arrow located nearby may be selected due to distraction or even crowding of the scene (Pashler, 1998). The way the model handles this situation in the case where it encounters arrows in same direction (congruency condition), is by recognising the direction of the arrow and responding by pressing a key. There is no conflict or confusion and the model simply encodes the location and responds based on the direction of the arrow. The model responds through the rule *go-ahead-responding-if-congruent* [P2]. Incongruency is handled through competing productions whenever a flanker rather than the centre arrow is picked up (i) *harvest-direct-directly-if-incongruent* [P3] and (ii) *refocus-again-if-incongruent* [P4]. The first strategy using production P3 means that despite selecting a flanker instead of the target, the model encodes and responds to the direction of the centre arrow (taking a default 85 ms to move attention). In contrast, the second strategy, using production P4 requires the model to first shift attention to the centre arrow location and then recognize the direction of the centre arrow. Shifting attention involves firing an additional production (taking an extra 40 ms) at a total cost of 125ms making this strategy more costly. Choosing between competing rules is handled by the sub-symbolic component of ACT-R: [P3] and [P4] have utility values of 7 and 15 respectively corresponding to probabilities of 0.07 and 0.93. The probabilities are calculated on the basis of the default ACT-R equation (5). In this way, if there are a number of productions competing with expected utility value *Uj* then the probability of choosing production *i* is described below:

$$\text{Probability (i)} = \frac{e^{Ui\sqrt{2s}}}{\sum j \; e^{Uj\sqrt{2s}}} \tag{5}$$

Here the summation is over all productions that are currently able to fire, '*s*' is the expected gain noise.

Model Fitting and Justification

Generally there are two ways of modeling cognitive development: (1) either model adult behavior and then modify it to fit child behavior or (2) first model the child behavior (lower performance level) and progressively change to fit the adult behavior (higher performance level) (Jones, Ritter & Wood 2000). Using the former approach, the modeling work reported in this paper is implemented within the constraints of the ACT-R architecture. A cognitive architecture poses constraints on the implementation of a model and therefore influences design choices (ibid).

Researchers have shown that model behavior can be altered by making changes either to the knowledge retrieval capability of the model, the procedural rule based system or by making plausible changes to the sub-symbolic components (Jones & Ritter & Wood, 2000; Serna, Pigot, & Rialle, 2007; Rijn, Someren, Maas 2000). In this paper, the adult model was incrementally modified to simulate children's developmental trajectory. Theoretical interpretation of the human study findings suggested the basis for developmental differences in the various networks and their implementation, described further below. By modifying the adult model of ANT, five new models were created and run for 12 subjects each, to simulate the performance of each age group. In addition, an invalid cueing condition was introduced into the task and performance modeled to assess validity efficiency and the effect of disengaging from an incorrectly cued location. Various approaches with a sound theoretical basis were tried and the one giving the best statistical fit is presented here.

Latency: Response times improved progressively with age up to adulthood which was simulated by starting with an overall higher rule firing time for the model of 6 year olds then reducing this for each later age group to approach the adult rule firing time. Rule firing time is considered the basic information-processing step in ACT-R. Adjusting rule firing time seems a natural choice to obtain uniformly increased latencies across the whole model. Two variations using different set of values both yielded very good correlations with human data, but the model that also showed lower RMSD with the human data were 110, 90, 75, 55 and 45 ms for ages 6-10 respectively.

Accuracy: Errors can be induced in the system either through changing utility values of the error productions (Seran, Pigot, Rialle, 2007) or through inducing more noise in the system (Rehling, Lovett, Lebiere, Reder, Demiral, 2004; Ritter, Schoelles, Klein, Kase, 2007; Jones, Ritter & Wood, 2000). For inducing noise, the settings tried for the ACT-R gain noise parameter were in the range 3 to 6. Also, it is reported in the literature that children tend to make more errors due to distraction from flankers (Mezzacappa, 2004) and hence competing productions with varying utility values were used to model various likelihoods of giving either a correct answer, a random response without checking or purposely giving an incorrect answer. Both methods were applied with similar effects on correlations and RMSD implying that either noise or competing productions might contribute to erroneous behavior; both modifications are equally plausible, however, with good empirical evidence for the latter competing productions were used in the models to simulate errorful performance. The utility values for rules giving a correct, random or incorrect response are 20, 5 and 8 respectively in the adult model. For 6 year olds the random response value with the best fit is 8 and 6 for all other age groups. Incorrect response utilities decremented from 13 to 9 for ages 6-10 respectively. Correct responses held the adult value.

Alerting Network Efficiency: Alerting efficiency is higher up to age 9 reducing around age 10 and further still for adults. Although the overall longer rule firing time has the effect of increasing the latencies of all the networks, in order to fit the data the alerting network needs to be slowed down further in the younger age groups indicating there is poorer alerting efficiency at this age. This is modeled by increasing the rule firing time for the production P1 responsible for giving rise to the effect of surprise when a stimulus appears without an alerting signal. The specific firing time for P1 is set to 55 ms for age groups 6-9 compared to 40 ms in the 10 year olds and adult models.

Orienting Network Efficiency: The overall increase in rule activation time matched the orienting network score of the model with the human data; therefore no other change was required. Also the production that gives the effect of delay in the centre cue condition is not increased and takes the same time as the adult model (*notice-stimulus-with-centercue-and-shift* [P5]. This leads us to infer that not only is the orienting network well developed in the age groups modeled but also there is no effect on the capacity of shifting attention from the neutrally cued location.

Validity and Disengaging Effect: Researchers have suggested that it would be interesting to assess the effect of invalid cueing in children (Mezzacappa, 2004). Though this is not tested in the child study (Rueda et al, 2004 our adult model includes the invalid cueing extension to task (Hussain & Wood, 2009) and so by default do the child models; the invalid cueing condition was run for each age group and the effect of disengaging on validity efficiency calculated using equation 4.

Executive Control Network Efficiency: In Reuda et al's study, 6 year olds are uniquely poor compared to other age groups. This age difference was investigated by changing the utility values of the two conflicting productions [P3] and [P4] that handle incongruency to increase the likelihood of choosing the slower, less efficient P4 rule; however this did not achieve the desired result. An alternative approach is to set the rule [P4], which requires the model to refocus every time a flanker is encountered, with a longer firing time. For the model of 6 year olds only, the rule firing time for production P4 was increased to 60 ms reflecting a slightly slower capacity to refocus compared to all other productions.

Results and Evaluation

The latency data, accuracy data, efficiencies and the possible interactions of the networks are given in detail below. A series of models were run for 12 subjects each to simulate the ages 6, 7, 8, 9 and 10. Adult human for ANT-C (Rueda et al, 2004) and model data (Hussain & Wood, 2009) is also reported for baseline values (see figure 2). Results from running the same model for the invalid cueing condition are also reported.

Latency Data As observed by the human study, the model response times incrementally improve for each age group. The statistics of correlation on the mean response times over all model runs shows good correlations and RMSDs, as reported in table 1. Figure 2 shows the mean reaction times (RT) for the human study in each age group along with the simulated results from the ACT-R models.

Accuracy Data As observed in the human study, the model error rate incrementally improved for each age group. However, when the results for each individual age group from the human study were observed closely it was found that for ages 7 and 8 the errors were higher in the neutral and congruent conditions as compared to the incongruent condition (Rueda, et al, 2004) which was not the case in the model data and therefore for ages 7 and 8 there were negative correlations with the human data. The models incrementally show improvement in accuracy and a higher chance of error in the case of the incongruent condition. The models could have been fitted to simulate this anomaly; however, it did not seem logical to do so. The model is in line with child development literature which shows that children make more errors in the case of incongruency (Ahktar & Enns, 1989; Mezzacappa, 2004). Further support for the model comes from a third experiment by Rueda et al (2004) involving 7 year olds. Table 1 reports child data from experiment 3 for age 7.

Age	Latency data		Accuracy data	
	r	RMSD	*r*	RMSD
6	0.79	34.7	0.93	1.28
7	0.92	34.4	0.86	1.02
8	0.88	52.5	-0.11	1.24
9	0.93	38.3	0.58	1.15
10	0.93	35	0.72	0.68

Table 1: Correlations and RMSD are used to show statistical fit of the model to the human data for age groups 6-10 years.

Efficiencies of Attentional Networks The efficiencies of the networks for each age group were calculated using equations 1-4. The efficiency data further validates the models by simulating similar values. As reported in the child study, alerting is much higher in the models for age groups 6-9; orienting scores do not show any significant difference across various age models; whereas executive control shows a high value for the model for age 6. The added finding using invalid cueing is that the validity effect is higher up to age group 10 with this increase mainly accounted for by a poorer ability to disengage from an uncued location. Correlations of the efficiencies of the networks of alerting, orienting and executive control of the model and human study for age groups 6-10 and adult data is 0.9, 0.8 and 0.9 respectively.

Interaction of Attentional Networks Once the models were shown to be veridical simulations of child performance the interactions of the networks on each other were explored. Rueda and colleagues (2004) reported no interaction effects in their paper. However, studies exploring interactions of networks in adults (Callejas et al, 2004; Fan et al, 2009) show the alerting network has an inhibitory effect on congruency (in line with Posner's idea of "clearing of consciousness" (Posner, 1994, p7401)); in contrast orienting may have a facilitating effect (Callejas et al, 2004; Fan et al, 2009). So applying the formulae in equation 6 and 7, the effect of alerting on congruency was also explored for the child models. Similar equations measured the affect of cueing on congruency.

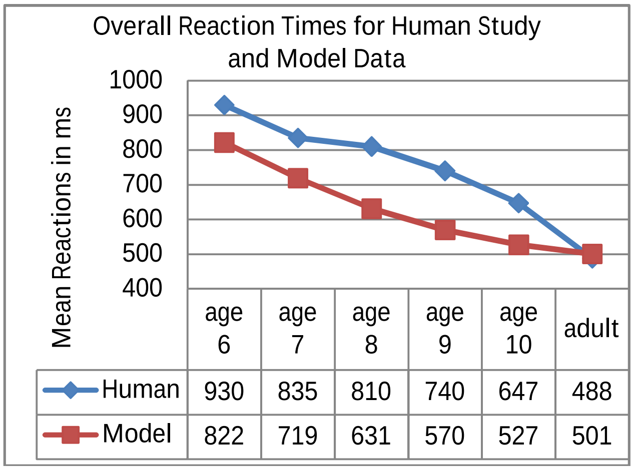

Figure 2: Mean RTs for all age groups for human data and simulation showing decreased mean reaction times.

Effect of alert on cong = (alert-incong – alert-cong)(6)
Effect of un-alert on cong=(nocue-incong–nocue-cong)(7)

The simulation of children's performance produced an inhibitory effect of alerting on congruency although of variable magnitude. This suggests that although the networks of alerting and congruency have slower efficiencies in the child models the interactions are similar to those produced in adult human studies.

General Discussion and Conclusion

The work reported in this paper is based on a reimplementation of Wang & Fan's (2004) model of attentional networks (Hussain & Wood, 2009) to simulate child performance in a study by Rueda et al, (2004), measuring various age groups on a child-friendly version of ANT (ANT-C) and projecting the trajectory of development of various attentional networks. The sequence of models simulates the child study findings well. The model fitting process in the light of relevant child development literature helps explain some of the observed age differences: (1) the overall increased latencies are accounted for by slowing down the rule firing times of all productions, which means that children take more time to process in general and tend to make more mistakes; children make more commission errors, the ones due to confusion and distraction (2) alerting network efficiency is slower than that found in healthy adult studies simulated by slowing down the firing time of the rule which induces an element of "surprise", so the ability to get alerted in the absence of a signal is slower in children under 10; (3) both orienting network efficiency and the ability to shift from center cue and move to the target location are at adult levels; (4) however, by simulating child performance after introducing an invalid cueing condition, a higher validity effect was found, improving up to age 10. This high validity efficiency was accounted for mainly due to slow disengaging ability, a component of orienting; (5) poor conflict resolution ability in age group 6 is due to a non-optimal refocusing ability when a distractor is selected; and (7) from the model results we conclude there is an inhibiting effect of alerting and facilitating effect of cueing on congruency in children as in adults (Callejas, et al, 2004; Fan et al, 2009).

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