Computational Modelling of Deficits in Attentional Networks in mild Traumatic Brain Injury: An Application in Neuropsychology

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Abstract

This work builds upon a model of performance for the Attentional Network Test (ANT) implemented in ACT-R 6.0 (Hussain & Wood, 2008; 2009) to simulate neglect conditions related to mild Traumatic Brain Injury (mTBI) and their effect on the attentional networks of alerting, orienting and executive control (cf. Posner & Fan, 2007). The model is evaluated against data sets for a human study of recovery in mTBI patients (Halterman, Langan, Drew, Rodriguez, Osternig, Chou & Donkelaar, 2006) and the model's fit to data is assessed statistically. A description of the mTBI model is provided, outlining how the simulation of impairment is achieved using ACT-R's[1] symbolic and subsymbolic components. The process of data fitting within the constraints of model design supports the finding that alerting remains unimpaired in mTBI and indicates that orienting network impairment is mainly due to the affect of mTBI on the ability to disengage attention. The model data further indicates that modulation effects previously observed between attentional networks (Hussain & Wood, 2008; 2009) are preserved in the mTBI model, and do not reflect the impairment observed in orienting and executive control efficiency.

Keywords: Attentional Networks; Attentional Network Test (ANT); Alerting; Orienting; Executive Control; Computational Modeling; ACT-R; mild Traumatic Brain Injury (mTBI).

Introduction: Attentional Networks

Functional neuroimaging has enabled researchers to view many cognitive processes in the window of which brain areas are activated when various attention components are working (Corbetta & Shulman, 2002; Posner & Fan, 2007; Hopfinger, Buonocore & Mangun, 2000; Fan, McCandliss, Fossella, Flombaum & Posner, 2005). There is evidence that these networks can be distinguished both at cognitive and neuroanatomical levels (Raz & Buhle, 2006). This has led to a theory of attention (Posner & Boies, 1971; Posner & Peterson, 1990) comprising three distinct anatomical areas of the brain responsible for separate aspects of attention, namely alerting, orienting and executive control.

Alerting refers to the ability to attain and sustain a vigilant state. Clinical data indicates that deficits in the associated brain network impair patients' ability to maintain alertness (Wilkins, Shallice, & McCarthy, 1987).

Orienting refers to selection of sensory information. Attention can be drawn automatically by what is referred to as an exogenous cue, or voluntarily directed to a cue, the endogenous form of orienting. Orienting deficits most commonly found in patients are the difficulty in disengaging from an invalidly cued location and then refocusing to a new location. The disengagement deficit has been found, for example, in patients suffering from stroke and Alzheimer's disease (Baddeley, Baddeley, Bucks & Wilcock, 2001) and schizophrenia (Firth, 1992).

Executive Control refers to effortful control or coordination in which, the response is not fully determined by the stimulus. It is required in tasks like task switching (Hayes, Davidson, Keele, & Rafal, 1998), conflict resolution, error detection, and so forth (Posner & Rohbart, 2007; Cater, Botvinick, & Cohen, 1990). Deficits in associated regions of the brain have been found in many pathologies including traumatic brain injury (Strum, Willmes, Orgass & Hartje, 1997), Alzheimer's disease (Baddeley et al., 2001), Parkinson's disease (Hayes, et al., 1998), and attention deficit disorder (Barkley, 1998).

Deficits in specific networks may be attributed to certain disorders and increasing our understanding of the role of each network in relation to various attentional phenomena is therefore extremely valuable.

Attentional Network Test

A paradigm for studying the separate functionality of these distinct aspects of attention is the Attentional Network Test (ANT) (Fan, McCandliss, Sommer, Raz & Posner, 2002; URL 02). ANT is a computer based reaction time test that is a combination of cueing experiments (Posner, 1980) and a flanker task (Eriksen & Eriksen, 1974). Each trial begins with a cue (or a blank interval in the no-cue condition) that informs the participant either that a target will be occurring soon, or where it will occur, or both. The target always occurs either above or below the centre screen fixation point and consists of a central arrow surrounded either by dashes (neutrals) or flanking arrows that can either point in the same direction (congruent) or in the opposite direction (incongruent). Participants respond to the direction of the target arrow, either left or right, by pressing a key on the corresponding side of the keyboard.

[1]For details on ACT-R refer to URL 01, Anderson, Bothell, Byrne, Douglass, Lebiere & Qin (2004) and Anderson, Matessa & Douglass (1995).

The time from the stimulus presentation to the key press is the reaction time. Figure 1 below shows the design of the original ANT experiment extended to explicitly incorporate an additional test condition in which an invalid cue appears in the location opposite to where the target will appear. It may appear that moving or shifting attention from one place to another is a very simple task but according to Posner and Peterson (1990) it is actually a three step process namely disengagement, movement and engagement. Hence the operation of shifting attention requires good coordination between the separate areas of the brain responsible and impairment in any of these regions may cause difficulty in shifting attention. The invalid cueing condition allows us to investigate the validity effect (given by equation 2) and is therefore useful in this context. This variation of ANT has been used for our model of mTBI described below.

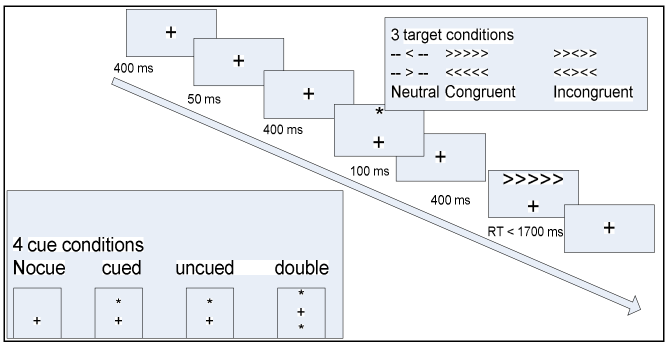

Figure 1: A sketch of the design of the original ANT extended for the invalid cueing condition.

The value of the ANT is that differences in reaction time (RT) between experimental conditions measure the efficiency of each network (see equations 1-3) in performing the one discrimination task.

Alerting efficiency = RT(no-cue) - RT(double) (1)
Orienting/validity efficiency =RT (uncued) - RT(cued) (2)
Executive control efficiency =RT(incong) - RT(cong) (3)

Simulation of Recovery from mild Traumatic Brain Injury (mTBI)

Concussion or mTBI has been defined as any transient neurological dysfunction that results from a biomechanical force to the head (Giza & Hovada, 2001). Following a mild head injury, it is seen that over a course of weeks, symptoms start to improve and attentional difficulties seem to resolve, although cases of moderate to severe injuries may take longer.

In the TBI literature, efficiencies of attentional networks have been assessed separately for each network (Cremona-Meteyard & Geffen, 1994; Ponsford & Kinsella, 1991; Gronwall, 1977). In a study to assess the efficiencies of the three networks in a single task, the ANT has been administered to post mTBI patients (Halterman et al., 2006). In this study, the rate and degree of recovery of the patient was recorded at intervals of 2, 7, 14 and 30 days after injury. The next section describes the design of a model to capture the independent time course for recovery of each network.

Design and Functionality

The model presented here simulates the recovery of mTBI patients and their performance on the ANT based on the findings of Halterman and colleagues' 2006 study. The design can be divided into two main parts: (1) the Lisp source code which sets up the experiment and (2) the ACT-R productions and parameter settings; together they enable the model to interact with the environment and make decisions based on what is presented to it

The major functionality of the model consists of four blocks of code for performing one ANT trial: (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 production (if-then) rules and associated parameter settings that combine to produce latency and accuracy data. Using equations 1-3, the efficiencies of the three networks are then calculated. The implementation of the networks in the model is explained below.

Latency Refers to the time elapsed between the appearance of a stimulus and the pressing of the key, measured in ms.

Accuracy The percentage of human-like errors made in pressing the correct key. Error is induced in the system in two ways: (1) through the ACT-R parameter *:egs* which induces noise in the system, making it non-deterministic; and (2) using production rules which mimic response errors.

Alerting The efficiency of alerting is a difference in latency when there is no cue preceding the stimulus and when there is a double cue which only prepares the subject but does not give any spatial orienting. The element of surprise leads to the firing of an extra production *not-cue-so-switch-state-and-shift-attention* [P1] to simulate the effect of alerting or preparing for the stimulus.

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; hence it simulates the effects of various cue conditions. For example, if the cue is spatial, then this acts as a top-down mechanism to focus at the cued location. In other cases the focus is bottom up, that is, the system automatically puts an object in the visual location buffer whenever the buffer is empty; and (2) 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, the buffer is already pointing to the target.

Disengaging sub-component of Orienting To simulate the effect of invalid cueing there is a need to disengage attention from the wrongly cued location and then refocus at the stimulus location. In the model code the three step process is shown distinctly by three productions, for example, *notice-stimulus-at-uncued-bottom-location* [P2], *shift-attention-at-uncued-bottom-location* [P3] and *goahead-responding-if-it-is-the-target* [P4].

Executive Control When the target stimulus contains arrows pointing in the same direction (congruency condition) then the location is simply retrieved (harvested) and a response given based on the direction of the arrow. However, in the case of a distracting, incongruent stimulus there are two choices: either harvest the target directly (which is less costly) or refocus attention which will result in the firing of an extra production before moving attention to the target location. These are implemented using conflicting productions; which is selected depends upon their probabilities calculated on the basis of the ACT-R conflict resolution equation (equation 4) (Anderson, 2007, p160). The conflicting productions are *harvest-target-directly-if-incongruent* [P5] and *refocus-again-if-incongruent* [P6]. 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:

$$\text{Probability (i)} = \frac{e^{Ui\sqrt{2}s}}{\sum j\ e^{Uj\sqrt{2}s}} \qquad (4)$$

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

Model Fitting and Justification

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 subsymbolic components (Jones & Ritter, 1998; Jongman & Taatgen, 1999). For example, the parameter *:dat*, the *default activation time,* indicates the rule firing time for each production, having a default value of 50ms. This corresponds to the time that humans may take to execute a single processing step in the mind; changing this can simulate the slowing down or speeding up of processing steps or tasks.

The model of ANT for normal adults (Hussain & Wood, *in press*) was the starting point for the simulation of mTBI patients. To simulate performance changes in mTBI patients over the 4 time intervals (Halterman et al, 2006) the model was incrementally modified to simulate behavior exhibited in the human study, keeping to a minimum the number of modifications to parameters and production utilities given the degrees of freedom for change. Theoretical interpretation of the human study findings suggested the basis for impairments in the networks and the base model also helped explain and establish the basis for some of the observed effects. The approach used was to find a fit for the first model in the series to simulate the severest impairment at the earliest time interval. The models for subsequent test intervals are obtained through further minor adjustment of the modified parameters to find an appropriate fit. The human study showed the following variations in the mTBI patients compared to controls: (1) overall reaction times were higher reducing with time, (2) accuracy was unaffected, (3) alerting was unaffected, (4) patients regained the ability to orient effectively within one week and (5) there was no corresponding significant improvement in executive control which remained impoverished compared to controls. By modifying the model of ANT four new models were created and run for 24 subjects each to simulate the recovery process of mTBI patients over intervals of 2, 7, 14 and 30 days. Modifications to the model (summarized in table 1) and their rationale are given below.

Latency Adjusting rule firing time is a natural choice to obtain the mean RTs for each test interval. Rule firing time is considered the basic information-processing step in ACT-R in which declarative knowledge may be retrieved and used. The range of values tried for '*:dat'* started with 80ms settling on 45ms for the first interval, then varied for each interval. The best results achieved were with the values given in table 1. It was observed that only increasing *:dat* for the first interval model and keeping the default value (40ms)[1] for the other three models produced a good fit to data. This indicates that for mTBI patients, the processing time for each step returns to normal within a week and only the raised incongruency effect results in comparatively higher RTs for the next three intervals.

Accuracy The human study did not report a significant group or testing day effect implying that both controls and patients were equally accurate across the trials and the within subject variability was similar. To simulate this effect nothing was changed within the model with respect to producing errors.

Alerting Network Efficiency A consequence of increasing the overall rule firing time in the model was an increased alerting effect, but this was not observed in the human study. We believe the reason for this owed to the blanket increase in rule-firing rate, so that the extra production (P1) responsible for giving the effect of surprise (in the no-cue condition) is also fired at the slower rate as if alerting gain is increased (refer equation 1). To keep the alerting effect unchanged we kept the firing time for P1 at 40ms. The production rules are responsible for governing the model behavior in performing the task, but only P1 is involved in calculating alerting efficiency and by implication reflective of associated brain regions. The different treatment of this part of the model is consistent with the view that the alerting network (and therefore alerting efficiency) is not impaired in mTBI.

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[1]Wang & Fan (2004) have reasoned and established that the original model of ANT is best simulated with a *:dat* of 40ms and that is carried over in all our models of ANT.

Orienting Network Efficiency As suggested by the human study, the reason for impaired orienting efficiency in the first week could be due to two reasons: (1) impaired ability to disengage, shift and re-engage attention back to the cued location indicating injury affects the brain regions associated with spatial orienting of attention; or (2) being oriented to a location other than the stimulus and then being made to refocus again. In the model, we considered modifying each behavior in turn. In (1) to simulate the initial slow down in disengaging from an incorrect cue location and refocusing at the correct location, a slower activation time (disengage time) for productions *shift-attention-at-uncued-top-location* [P8] *and shift-attention-at-uncued-bottom-location* [P9] is used in test interval 1 reverting to the default for each subsequent test interval (see table 1). In (2) the *set-visloc-default* command controlling the buffer stuffing mechanism is narrowed for each test interval. For example, if we state *set-visloc-default (x-value within (50, 140))*, then anything in the model's visual field (scene) between the x coordinates 50 and 140 can be selected for attention as a result of being placed in the visual buffer, increasing the likelihood of selecting a non-target for attention and thus inducing refocusing; anything outside that range will not be attended. By narrowing the x-values, focusing more closely on the target, the probability of choosing the target arrow increases. It was observed from the model results that changing the disengaging time gave a better fit to the data (thus adopted in the model) than altering the buffer stuffing mechanism. This leads us to believe that the disengaging effect may have a major role to play in affecting patients' orienting network efficiency in the case of mTBI.

Executive Control Network Efficiency Again there were two possible ways of handling this behavior: (1) using the healthy adult model as a benchmark, change the relative utility values of the two conflicting productions P5 and P6 that handle incongruency; each have the same goal state and the probability of either one firing depends upon their utility values. The probability of selecting the first production was set relatively high for interval 1. Alternatively, (2) increasing the value of the noise parameter *:egs* also results in a higher incongruency effect. In utility equation 4,*'s'* is set by the value for the parameter :egs which induces noise in the system and hence more non-deterministic behavior. Based on the model results we are unable to say one is better than the other, both induce a non-deterministic behavior in conflict resolving ability. So both approaches are used in the model. The original model was implemented with 7 and 15 for P5 and P6 respectively giving probabilities of 5-10% and 90-95% for P5 and P6. We explored varying the value of noise between 3-5, utility values for P5 from 3-7 and P6 from 10-20. The final values used in this model giving the best fit are shown in table 1.

A consequence of increasing the congruency effect was that all the intervals had increased utility and noise values which also results in an overall increase in RTs.

Table 1: Model parameter setting variations for simulating the efficiencies of attentional networks in mTBI patients.

Time (days)	Rule fire[1]	Alert effect[2]	Disengage Time[3]	Noise (egs)[4]	Util. values[5]
1 (2)	45	40	50	4.2	5,18
2 (7)	40	40	40	4	5,15
3 (14)	40	40	40	4	6,15
4 (30)	40	40	40	3.5	6,15
Control	40	40	40	3	7,15

Results and Evaluation

The model was run to simulate 24 participants, similar to the original study (Halterman et al, 2006). The experimental design comprised a block of 4 cues (nocue, cued, uncued and double) X 3 flanker (neutral, congruent, incongruent) X 2 directions (left, right) X 2 locations (top, bottom). Each block was run twice, totaling 96 trials for every run. The model was run 4 times, each time with a different setting (see table 1). The latency data, efficiencies and the interactions of the networks are discussed in detail below.

Latency Data The model was run for each interval to simulate the incremental change in performance over a period of one month and reaction time data was recorded on each run. The median reaction time was calculated for each run for each time interval for the simulated mTBI subject. Figure 2 plots and records the median reaction times over the 4 intervals for the controls (both human and model), human mTBI patients and simulated subjects[6]. These show overall improvement in latency over time. The correlations and root mean square deviations (RMSD)[7] are 0.88 and 41 for controls and 0.98 and 15 for mTBI, showing a good fit to the experimental data. Note that in both controls and mTBI the RTs go as low as 440 and 475 ms whereas those for the models are comparatively higher; even in the original ANT experiment (Fan et al, 2002) with normal subjects, the mean RT is 511ms with a standard deviation of 44. The model was not purposely made to fit this low RT outlier data, getting a good correlation was taken to be sufficient.

Efficiencies of Attentional Networks The efficiencies of each modeled network were calculated using equations 1-3. Figure 3 illustrates the efficiencies of the alerting, orienting and control networks. The efficiency of the orienting network improves markedly for each test interval. Executive control, though reducing for each modeled interval, like the mTBI patient is still not close to the control data, whereas the simulated alerting network remained unchanged.

[1] Value of *:dat*, overall rule firing time in ms.
[2] Value of *:at* for the production P1 alerting effect.
[3] Value of *:at* for the productions P2 and P3 disengaging effect.
[4] Value for noise (*:egs*) parameter for inducing more randomness.
[5] For congruency, the utility values are for P5 and P6.
[6] Data for human study obtained from graphs (Halterman et al, 2006). (Attempts to obtain original data have been unsuccessful).
[7] It is standard practice in ACT-R modeling to use correlations and root mean square deviations (RMSD) to show goodness-of-fit.

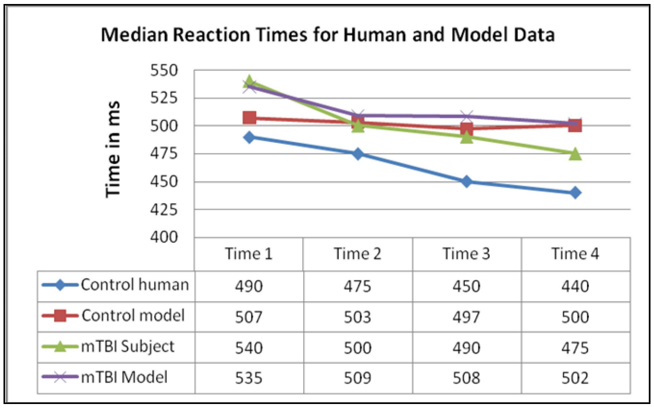

Figure 2: Median reactions times for human control, model control, mTBI patients and the model simulation of mTBI.

In addition to the results reported above, the modulation effects between networks for the model of mTBI impairment were also analyzed. A study by Callejas, Lupianez and Tudela (2004) exploring interaction effects between networks and modeled in Hussain & Wood, (2008; 2009) showed the alerting network has an inhibitory effect on the congruency network, orienting has a facilitating effect on congruency, and alerting has a speeding up effect on orienting efficiency. The same approach has been applied here to study the interactions of the network using data from the mTBI model. The correlations and root mean square deviations for mTBI subject and mTBI model are 0.74 and 9 for alerting, 0.87 and 4 for orienting and 0.97 and 9 for executive control.

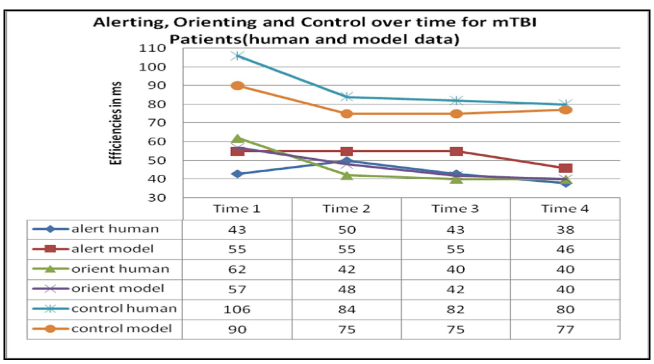

Figure 3: The efficiencies of the three networks for mTBI patients and mTBI models.

Based on the modulation data plotted in figure 4, as calculated using formulae 6-9, it can be inferred that, as for the previous study, the alerting network has an inhibitory effect on congruency whereas the orienting network has a facilitating effect or no effect on congruency. The interesting part is that these interactions remain stable over each test interval under study and no changes in the interactions have been observed, particularly the alerting network. This suggests that, although mTBI affects the efficiency of both the orienting and executive control networks, there is no impairment to, or variation in, the interactions between networks.

effect of alert on cong = (alerted-incong - alerted-cong) (6)
effect of un-alert on cong = (nocue-incong - nocue-cong)(7)
effect of cue on cong = (cued-incong - cued- cong) (8)
effect of uncue on cong = (uncued-incong - uncued-cong)(9)

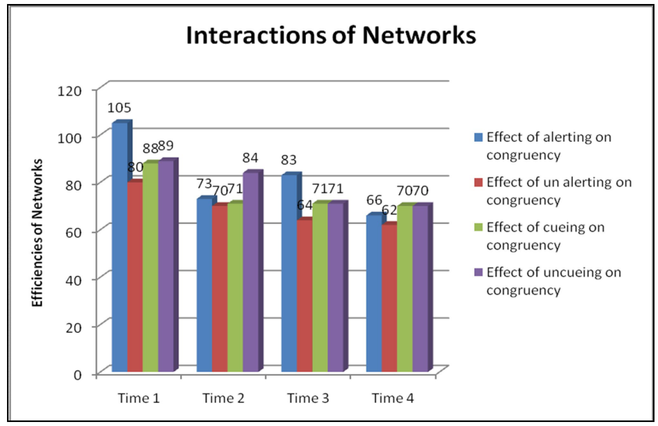

Figure 4: Graph plotting the interactions of alerting and cueing on congruency.

Conclusions and Future Work

The work reported in this paper is based on a reimplementation of Wang & Fan's (2004) model of attentional networks (Hussain & Wood, 2009) incorporating an invalid priming condition to explore the subcomponents of orienting. The model has been used to simulate a study by Halterman et al, (2006) which tracks the recovery of mTBI patients over a 30 day period, achieving a good correlation in replicating the human study data. The model was run four times to simulate the intervals at which the mTBI patients were reassessed for recovery, in the original experiment. The changes in network efficiency were shown to be effectively simulated by (1) altering the overall rule firing time to achieve an overall slow down in performance, (2) impairing the orienting network by further altering the rule firing time for productions involved in modeling the disengaging effect of invalid priming to achieve a poorer orienting efficiency, (3) retaining the firing time of the alerting production to maintain no affect on alerting and (4) simulating deficit in the control network by changing utility values of the productions for responding to incongruent targets and varying the noise parameter (*:egs*) that handles distraction.

Further analysis of the modeled data suggested by an earlier study of network modulation (Hussain & Wood, 2009) indicates that throughout the recovery period, alerting has an inhibitory effect on the control network whereas orienting has a facilitating effect or no effect on the control network. In addition, the results suggest that, despite variation in network efficiency, interactions between networks do not show any variation over time.

It would be interesting to confirm this finding through further study of mTBI patient data using the invalid cueing version of ANT. Confirmation of this observation, perhaps in conjunction with fMRI studies, may assist in informing the design of attention network-specific attention training programmes for mTBI patients (cf. Strum et al, 1997).

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