# Cognitive Modelling of Attentional Networks: Efficiencies, Interactions, Impairments and Development

Fehmida Hussain

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# Declaration

I declare that this thesis has not been submitted in whole or in part to this or any other University for the award of a degree.

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## Summary

According to the attention network theory, attention is viewed as an organ system comprising specialised networks that carry out functions of alerting, orienting and executive control. The Attention Network Test (ANT) is a simple and popular experiment that measures the efficiencies and interactions of these three sub-components of attention in a single task, and has been used for adults, children and attention deficit patients. In this thesis, cognitive modelling is used as a research tool to simulate the performance of subjects on the ANT, as well as variations of the ANT using ACT-R 6.0 cognitive architecture. All models are validated against human data using various goodness-of-fit criteria at multiple measures of the latency, accuracy and efficiency of the three networks.

Once the simulation of healthy human performance on the ANT is established, modifications inspired by psychology literature are made to simulate the performance on ANT by children and patients affected with Alzheimer's disease (AD) and mild traumatic brain injury (mTBI). The implementation of networks, their interactions and impairments in the models are shown to be theoretically grounded. Based on the simulation results and the understanding gained through model processes, a number of novel predictions are made, behaviour of the networks and a few discrepancies in human data are explained. The model predicts that in the case of Alzheimer's disease, the orienting network may be impaired and cueing may have a positive effect on conflict resolution. Also, in the case of mTBI, it was predicted that the validity effect may be impaired only in the earlier weeks after the injury. For children, a possible relationship between processing speed and mechanism of inhibitory control is predicted. It is posited that there is not always a "global clock" that controls processing speed and further different processes may be running with different processing times.

## Acknowledgements

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Special thanks to Dr. Hongbin Wang for providing me the code for ACT-R 5.0 model that I have used in this thesis and helping me understand the ACT-R 5.0 implementation of the model of ANT. The modelling tasks would not have been easy if I had not attended the ACT-R summer school at CMU and met all the wonderful people in the ACT-R group. My special thanks to Andrea Stocco, my mentor at the ACT-R summer school, 2007 for helping me get started with the modelling work and Dan Bothel who has always helped with ACT-R, responding to emails promptly.

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Dad, this thesis is for you, I know even up there you are watching over me and I want to make you proud of me!

## CONTENTS

## List of figures

## List of tables

## List of equations

# 1. Introduction

This introductory chapter begins with a motivational discussion about the meaning of attention, given its diffused nature and the role it plays in cognition. The theory of attentional networks, which is the theoretical basis for this thesis, is briefly introduced. The main objective of the thesis, which is divided into aims to be achieved, is described. The scope of the work is outlined, stating what can and cannot be expected from modelling work in this thesis. Given the central role of the attentional network task in this thesis, a detailed description of the task is also given here. Finally, a brief summary of each chapter is presented followed by a list of papers and posters published in the last three years in relation to this study.

## 1.1 Motivation

Attention is a cognitive function that deals with the overload of the sensory, visual and auditory inputs that play a vital role in our lives. Attention is responsible for choosing an object which is either of interest to us or automatically gains our attention; it keeps us vigilant to a situation or a goal and helps us to resolve a situation which may be conflicting with our expected norms. Given the diffused nature of attention, various theories of attention have attempted to explain its role in cognition. Attention theories are classified mostly on the basis of findings from psychophysical experiments that explain attention as dealing with limited capacity and selectivity, vigilance and alertness, and control of attention.

Attention researchers suggest that a single definition or a unified theory of attention is not essential, and attention can be explained as comprising of multiple components (Parasuraman, 1998). Posner was one of the most prominent proponents of the separate system view of attention. Based on a vast amount of anatomical literature, Posner and colleagues (Posner & Boies, 1971; Posner & Peterson, 1990) proposed a theory (popularly referred to as the 'theory of attentional networks') that describes attention as an organ system, with its own specific anatomy carrying out distinct psychological functions that can be influenced by specific injuries and states. According to the attentional network theory, attention involves specialised networks and carries out the functions of alerting, orienting and executive control. Alerting is associated with becoming ready for an incoming task-related event, orienting can be understood as visual-spatial selective attention, and executive control is related to conflict monitoring and resolution among thoughts, responses and emotions (Posner & Fan, 2007). Explaining attention in the context of how these networks behave and interact offers a new perspective in explaining the role of attention in cognition. This theory is supported by neuroimaging studies which show that various cognitive tasks activate a distributed set of neural areas and can correspond to specific mental areas (Corbetta & Shullman, 2002; Posner & Raichele, 1994; Posner & Fan, 2007).

From the point of view of neuropsychology and psychopathology, many disorders such as Alzheimer's disease, attention deficit disorder, schizophrenia, neglect, closed head injury, borderline personality disorders, and so on are said to be due to deficits in some attentional networks, and thus studying the specific attentional system of the brain areas allocated to anatomical areas gives us a new way of approaching such pathologies and their management.

Studies have also shown how attentional networks develop from infancy and how they influence child behaviour. It has been shown that the alerting and orienting system begins to develop in early infancy, which enables the child to stay alert and to select from visual overloads; however, the executive control network develops at a later stage in a child’s life (Posner, Sheese, Odludas & Yang, 2006; Rueda, Fan, McCandliss, Halprin, Gruber, Lercari & Posner, 2004). Enhancing our understanding of attentional networks in children is also a step towards enhancing our understanding of cognitive development.

Although these three networks have been studied using various independent behavioural tasks, a more holistic approach is to examine all three networks simultaneously in one task. According to the literature review carried out for this thesis, the Attentional Network Test (ANT) is one of the most simple and popular experiments for recording and testing the efficiencies of these three attentional networks in a single task (Fan, McCandliss, Sommer, Raz & Posner, 2002). This test has been used for adults, children and compromised subjects alike (Rueda et al., 2004; Fernandez-Duque & Black, 2006; Gooding, Braun & Studer, 2006; Posner & Rohbart, 2007; Booth, Carlson & Tucker, 2001). The ANT is described in detail in section 1.4 and also later in section 2.4.3.1.

Motivated by the importance of studying attention in the window of the attentional network theory, this thesis presents a computational modelling approach to explore the theory of attentional networks by developing cognitive models for ANTs and variations thereof. This is based on the premise that by closely examining these models we can increase our understanding of the cognitive phenomenon being modelled (Dawson, 2004). The starting point is to apply modelling to explicate how attentional networks behave in healthy humans, and then modify the model settings to simulate the behaviour of the networks in the context of various pathologies such as Alzheimer’s disease and mild traumatic brain injury. The healthy adult performance model on the ANT is also modified to simulate children's performance, the motivation for which is to understand the developmental trajectory of attentional networks in children. So, based on the modelling and data fitting process of performance on the attentional network task of healthy humans, Alzheimer's disease and mild traumatic brain injury patients and children, predictions and observations about the behaviour of the attentional networks are presented.

Therefore, as depicted in Figure 1.1, this thesis proposes to explain attention through the computational/cognitive modelling of experimental studies. The model-based predictions can be further verified through neuro-scientific studies. The two-way arrows indicate that each research method can feed into the other and vice versa.

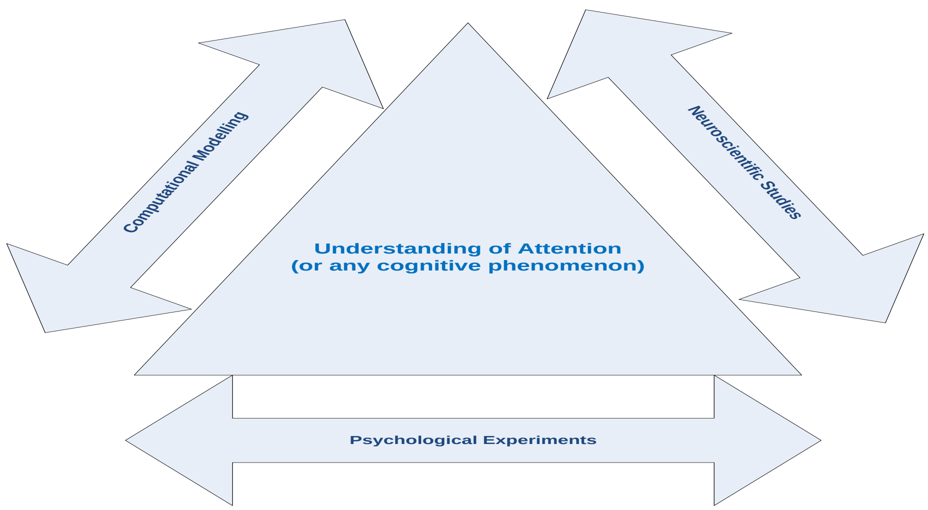



Figure 1-1: Attention (or any cognitive phenomenon) can be studied using various research methods, either independently or in conjunction with each other and also feeding into each other.

## 1.2 Objectives and aims of the thesis

As motivated by the brief discussion of attention in section 1.1, the primary objective of this thesis is to explore and advance our understanding about the theory of attentional networks specifically and, in turn, attention in general. It is proposed that the understanding of attentional networks can be subdivided mainly into explicating their efficiencies and interactions not only in healthy adults, but also in attention-related pathologies and in children. The main objective of the thesis is made up of the following aims which involve simulating:

1. Efficiencies/behaviour of attentional networks
2. Interactions of attentional networks
3. Behaviour of attentional networks in various pathologies
4. Cognitive development of attentional networks.

Investigating each of these four areas, the ultimate goal of this thesis is to gain more insight into the theory of attentional networks. To achieve this, I shall use the attentional network test (ANT) in its original form, as well as its variations, and build cognitive models to simulate the human performance on the ANT (Fan et al., 2002; Rueda et al., 2004; Callejas, Lupianez & Tudela, 2004; Callejas, Lupianez, Funes & Tudela 2005; Fernandez-Duque & Black, 2006; Halterman, Langan, Drew, Rodriguez, Osternig, Chou & van Donkelaar, 2006). Based on the lessons learnt from the data fitting process and the model results, the thesis presents observations and predictions about the behaviour and efficiencies of attentional networks, which may call for further investigation through psychophysical experiments and imaging studies. Each component is studied in detail in Chapters 5-8, as outlined below:

### 1.2.1 Efficiencies and behaviour of attentional networks

The efficiencies and behaviour of the three networks of alerting, orienting and executive control are explicated by simulating the performance of healthy adults on the ANT. This will be referred to as 'model-1', and will be used to explain the implementation and working of the operations of the three networks, showing how the design is informed by the literature.

Once model-1 is shown to be a veridical simulation of the human study (Fan et al., 2002), it will be extended to explore the effect of invalid cueing in attention, simulating a revised ANT design (Fernandez-Duque & Black, 2006), which will be referred to as 'model-2'. Model-2 explains the effects of invalid cueing in spatial orienting, simulating the subcomponents of disengagement, movement and engagement (Posner, Walker, Friedrich & Rafal, 1984; 1987).

### 1.2.2 Attentional network interactions

Although the networks are anatomically separate, they have been shown to interact with each other. Revised ANT studies extended with auditory alerting have shown various effects of the networks on each other (Callejas et al., 2004; 2005). Model-3 is implemented to simulate this human study, by explicating the modulation effects of the networks on each other. It attempts to explain how and why the networks could possibly interact and what the model predicts about the modulation effects and difference in auditory and visual alerting. Later, such network interactions are also calculated and explored in attention compromised patients and children.

### 1.2.3 Attentional network behaviour in various pathologies

Having established valid models of healthy adult performance on the ANT, model-1 and model-2 are modified and applied to understand the behaviour of attentional networks in various pathologies. Two pathologies, namely Alzheimer's disease (AD) and mild traumatic brain injury (mTBI), are looked at closely (other pathologies can be simulated using similar changes in the models). Model-2-AD simulates the performance of AD patients on the ANT (Fernandez-Duque & Black, 2006), explaining why certain networks may be impaired or affected in AD and whether the interactions of the networks change due to impairment. Model-1-mTBI simulates the performance on the ANT of patients recovering from a mild traumatic brain injury (mTBI) (Halterman, et al., 2006), offering possible explanations as to why a network may be impaired or affected, how the efficiencies improve over a recovery period and whether the interactions of the networks change due to impairment over a period of observed study. Further, applying the data fitting settings of model-1-mTBI to model-2, it is investigated how mTBI patients behave when presented with an invalid cue condition. Thus, model-2-mTBI investigates whether the injury affects disengaging capacity when oriented to a wrong location.

### 1.2.4 Cognitive development of attentional networks

Model-1 is modified and applied in understanding how attentional networks develop in children. The performance of children on a revised version of the ANT (ANT-C) (Rueda et al., 2004) is simulated by modelling the trajectory of development of these networks over various age groups. This is referred to as ‘model-1-child’. Based on the data fitting process and model results, observations are made about the behaviour and interactions of these networks over a developmental trajectory. Further, by applying the settings of model-1-child to model-2, it is predicted at what age the children’s ability to handle disengagement in the case of an invalid cue is developed. This is referred to as ‘model-2-child’.

### 1.3 Scope of the work

It is extremely important to clarify at the beginning the scope of this thesis and to demarcate between what this study is about and what it is not about. This thesis explores the theory of attentional networks in the light of producing cognitive models of human performance (healthy, AD patients, mTBI patients and children) on the attentional network test and its variations. Then, based on the modelling and data fitting processes, certain observations and predictions about the behaviour of the networks are made. It is important to note here that the theory of attentional networks is studied in the context of a specific behavioural task, namely the attentional network test (ANT). In addition, when exploring various pathologies and the cognitive development of attentional networks, it is also limited to studying performance on the ANT. So, for example, when an Alzheimer’s disease model is discussed, it is not modelling the pathology but the performance of the patients affected by the pathology, and then based on that simulation of the performance, explore the behaviour, efficiencies and interactions of the networks.

A word of caution about the word network is necessary at this point. It is my worry that usage of the word network, as it is used by Posner in presenting the theory of attentional networks, may be confusing for the reader. In this context, the use of network should not mislead the reader into expecting something about computer networks or artificial neural networks (ANN). In this study, its use simply refers to the subcomponents of attention popularly termed as ‘alerting, orienting and executive control’ (which relate to underlying parts/networks in the human brain).

Lastly, it needs to be pointed out that all the modelling work done in this thesis is limited to the cognitive architecture of ACT-R 6.0 (Anderson, 2007), and hence is in some way bounded by the underlying theories of attention embedded in ACT-R. Limiting the scope in this way actually places a useful constraint on the modelling work, as will be seen in later chapters.

## 1.4 Description of the attentional network test (ANT)

The Attentional Network Test (ANT) (Fan et al., 2002), a 30-minute reaction time test, is a combination of cueing experiments (Posner, 1980) and a flanker task (Eriksen & Eriksen, 1974). It is designed to measure the efficiencies of the alerting, orienting and executive control networks in a single task.

Visual stimuli are presented on the screen, which requires maintenance of an alert state, spatial orienting to cued stimuli and control of competing resources. Each trial begins with a fixation followed by a cue, or directly by a stimulus. If a cue is given, then it is either at the centre, top, bottom or double (that is both top and bottom). Top and bottom signify a certain location, whereas the centre and double cues dissolve the effect of cueing and give no indication about the location of the stimulus. Centre and double cues alert the subject of the appearance of the stimulus, but in the no cue condition a stimulus appears directly and, hence, no alert is given to the subject. The top and bottom cues, on the other hand, give an indication of the location of the stimulus, resulting in spatial orienting. The target may be surrounded by arrows either in the same or the opposite direction, hence giving rise to a congruency/incongruency effect. The ANT uses differences in reaction time between conditions to measure the efficiency of each network. Subtracting congruent reaction times from incongruent target trials provides a measure of conflict resolution and assesses the efficiency of the executive attention network. Subtracting reaction times obtained in the double-cue condition from the reaction time in the no-cue condition gives a measure of alerting due to the presence of a warning signal. Subtracting the reaction times of targets at the cued location (spatial cue condition) from trials using a central cue condition gives a measure of orienting, since the spatial cue, but not the central cue, provides valid information on where a target will occur. The task for the participant taking the test is to determine the direction of the target arrow, which is surrounded by distracters. The target may be surrounded by arrows either in the same or the opposite direction, hence giving rise to a congruency/incongruency effect.

Both latency and accuracy data are recorded. It was observed in the human study that reaction times are faster and accuracy rates are higher in the case of congruent and cued trials. Typical latency values are roughly in the range of 400-700 ms whereas the accuracy values are recorded as the percentage of errors made by the subject taking the test which could be anywhere from 0.5% to 10 %. The efficiencies of the three networks of alerting, orienting and executive control are calculated using equations 2.1-2.3 described later and typical values are from 40 – 90 ms (all the exact data are given in chapter 5, here the purpose of giving these ranges of values is just as an exemplar of what results are recorded). The sketch of the test and further details is given later in section 2.4.3.1.

## 1.5 Chapter summaries and outline of the thesis

Chapter 1 sets the stage by introducing the thesis, describing the motivation for conducting this research work, stating the research objectives undertaken in this thesis, the scope of the work, i.e. what can and cannot be expected from the modelling work, and an outline of the thesis.

Chapters 2 and 3 provide essential background knowledge, comprising the summary of the literature review that was conducted to inform this thesis.

Chapter 2 reviews the meaning of attention and the various theories of attention that explain its role. The theory of attentional networks is explained along with the three components of attention, the corresponding neural pathways and the network's interactions. Later, the various tasks and studies that are used to explore the phenomenon of attention in general are described, and then specifically the attentional network test (ANT) is introduced.

Chapter 3 discusses state-of-the-art computational modelling in attention and explains various modelling paradigms. Cognitive modelling is described in detail, particularly in relation to the role of cognitive architectures. ACT-R, the cognitive architecture used in this thesis, is elucidated along with how theories of attention are implemented in ACT-R. Other popular cognitive architectures such as Soar and EPIC are explained briefly and compared with ACT-R, while computational models of attention and attentional networks are also discussed.

Chapter 4 explains the research methodology and approach used in this thesis. The motivation and rationale for using cognitive modelling as a research tool, and specifically the use of the ACT-R cognitive architecture, are discussed. The literature establishes, in the context of modelling, what is meant by goodness-of-fit and how such cognitive models are evaluated statistically against human data, while specific statistical approaches used for the model validation within this thesis are explained. It is important to understand the issues with model validation in order to produce models that are faithful representations of behavioural experiments.

Chapter 5 explicates the reimplementation of an existing ACT-R 5.0 ANT model (Wang, Fan & Johnson., 2004) in ACT-R 6.0. This is referred to as ‘model-1’. Complete implementation and migration details are given to explain its working and how this implementation relates to theoretical accounts of attention. The chapter describes in detail how attentional networks are simulated and the theoretical basis for doing so. Using the model validation criteria discussed in Chapter 4, the model is then evaluated against human data. The second half of the chapter explains how a revised ANT design is modelled to incorporate the effect of invalid cueing, exploring the three components of orienting, namely disengage, move and engage (Posner, 1980; Posner, et al., 1984; 1987). This is referred to as ‘model-2’. Both model-1 and model-2 are later used in Chapters 7 and 8 in understanding attention-related pathologies such as Alzheimer’s disease, mild traumatic brain injury and the behaviour of attentional networks in children.

Chapter 6 involves further modelling to explore and study the modulation effects of attentional networks, i.e. the interactions of attentional networks (based on experiments conducted by Callejas et al., 2004; 2005). The model simulates interactions that show the effect of the inhibition or facilitation of the networks on each other. Predictions are made by, for example, increasing the efficiency of one network and exploring the effects.

Chapter 7 presents more simulation work focused on the application of cognitive modelling to the simulation of attention-related pathologies. Here, an attempt is made to model the performance of patients affected with Alzheimer's disease (Fernandez-Duque & Black, 2006) and mild traumatic brain injury (mTBI) (Halterman et al., 2006) on the attentional network test. Such models, by simulating the relevant behaviour, help to answer questions such as which networks are affected in these conditions, how does the model fit to the human data and how can these results be used in making predictions?

Chapter 8 presents another modelling application to simulate the effects of cognitive development on attentional networks in the context of simulating the performance of children on a child-friendly ANT version (Rueda, et al., 2004), the idea behind which is to enhance our understanding of the developmental trajectory of these components of attention and, based on the model results, make predictions for further investigation.

Finally, Chapter 9 concludes the thesis by revisiting the aims and objectives set out in Chapter 1 and assessing how and whether they have been met. Furthermore, this chapter summarises the main contributions of the thesis, discusses the issues and limitations of the study and finally gives guidelines for extensions and future research.

## 1.6 Naming conventions of the models implemented in this thesis

The naming conventions used for the models in this thesis are explained below:

- Model-1 is a simulation of the basic ANT (Fan et al., 2002), discussed in Chapter 5.
- Model-2 is a variation of model-1 that incorporates invalid cueing (Fernandez-Duque & Black, 2006), discussed in Chapter 5.
- Model-3 is a variation of model-1 and model-2 that mainly incorporates auditory alerting and simulates the interactions of the networks (Callejas et al., 2004; 2005), discussed in Chapter 6.

- Model-2-AD is a modified version of model-2, which is applied to simulate Alzheimer's disease patients' performances on the ANT (Fernandez-Duque & Black, 2006), discussed in Chapter 7.
- Model-1-mTBI and model-2-mTBI are model-1 and model-2 respectively, and applied to simulate the performance of mTBI patients on the ANT (Halterman et al., 2006), as discussed in Chapter 7.
- Model-1-child and model-2-child are modified from model-1 and model-2 respectively, and applied to simulate children's performance on the ANT (Rueda et al., 2004), as discussed in Chapter 8.

## 1.7 Publications

During the course of the research work carried out for this thesis over the past three years, the main chapters (5-8) of this work have been published in the sources given below (full papers and posters are attached in Appendix B):

1. Hussain, F. & Wood, S., (2009). Computational Modelling of Deficits in Attentional Networks in mild Traumatic Brain Injury: An Application in Neuropsychology. Proceedings of the 31st Annual Conference of the Cognitive Science Society, Amsterdam, Netherlands, July 2009, pp. 2675-2680 (presents Chapter 7 of the thesis).

2. Hussain, F. & Wood, S., (2009). Modelling the Performance of Children on the Attentional Network Test. The 9$^{th}$ International Conference on Cognitive Modelling, Manchester, UK, July, 2009, pp. 211-216 (presents Chapter 8 of the thesis).

3. Hussain, F. & Wood, S., (2009). Modelling the Efficiencies and Interactions of Attentional Networks, In Paletta, L., & Tsotsos, J.K. Eds., Attention in Cognitive Systems. Lecture Notes in Computer Science-LNAI 5395, pp. 139-152, Springer-Verlag, Berlin, Germany. (This was a special issue arising from the proceedings of the 5th International Workshop on Attention in Cognitive Systems (WAPCV08), Santorini, Greece, May, 2008). (Presents Chapters 5 and 6 of the thesis).

4. Hussain, F. & Wood, S., (2008). Modelling attentional networks: the modulation effects and simulation of Alzheimer's disease. Members' Abstract, Proceedings of the 30th International Conference on Cognitive Science, Washington D.C., July 2008, p. 1102 (presents Chapter 7 of the thesis).

5. Hussain, F. & Wood, S., (2008). A Cognitive Model of Attentional Networks. Proceedings of the 3rd International Workshop on Cognitive Science, Moscow, Russia, June 2008, pp. 68-70 (presents Chapter 5 of the thesis).

## 1.8 Chapter summary

Chapter 1 introduces the work carried out in this thesis. The motivation for choosing attention as a topic of investigation is given, which sets the goals that need to be achieved in this thesis. The scope of the work is clearly stated describing what can and cannot be expected from the modelling work undertaken as part of this study. A description of the attentional network test is given. An outline of each chapter is provided along with naming conventions used for all the models implemented. Finally, a list of publications is given, showing where the main chapters of this thesis were peer reviewed.

# 2. Attention and Attention Networks

From mindless neuroscience and brainless psychology to neuropsychology.

(Bunge, 1980; 1985)

The aim of this chapter is to describe attention and its role in cognition. Various theories of attention are presented based on what has been revealed from extensive research on the subject. Attentional network theory, which is the basis of this thesis, is discussed in detail. The three networks of alerting, orienting and executive control are described in terms of their functionalities and neural correlates. The attentional network test, which assesses the efficiencies of the three networks in a single task, is introduced. The behaviour of attentional networks in various attention-related pathologies and in children is also discussed, giving sufficient background knowledge for the chapters to follow.

## 2.1 Overview of attention

The word ‘attention’ is not only a common word in the English dictionary, but also a complex cognitive phenomenon which has been extensively researched in the fields of neuroscience and psychology (and other branches such as cognitive psychology, cognitive neuroscience, neuropsychology, and so on). The efforts to understand attention can be traced back to the time when William James presented his views, as follows:

> “Every one knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought” (James, 1890, pp. 403-404).

In this oft-cited quotation in the attention literature, there is a reference to the possible existence of multiplicity in the nature of attention. “Taking possession by the mind” refers to the voluntary aspect of attention, whereas “one out of what seem several” indicates the limited capacity nature of selection.

Given the multiple ways in which we make use of attention, it is not easy to give the word a single definition. Therefore, in order to understand this complex cognitive phenomenon, it is sensible to approach this by asking the question: what role does attention play in cognition? In other words, why do we require attention? After reviewing psychological literature on attention (Pashler, 1998; Parasuraman, 1998; Posner, 1978; Eyesenck & Keane, 2000), the question can be answered by examining a few main aspects of attention that deal with (1) limited capacity or selectivity, (2) vigilance or alertness and (3) attentional control.

### 2.1.1 Limited capacity or selection

From the limited capacity perspective of the human brain, it is not possible to process everything that we sense and, hence, a mechanism is required for selection. The capacity to attend may be limited in terms of not only the processing capacity (Broadbent, 1958), but also mental effort or resources (Kahneman, 1973). Consequently, attention deals with the issues of limited capacity and the selectivity of processing, which are also referred to as focused attention or selective attention (visual modality is popularly called visual attention). Focused or selective attention deals with two or more stimulus inputs, where only one is to be responded to. The source of stimulation could be any sensory modality or an internal state that guides attention.

The theories of selective attention deal with the issues of how attention deals with limited processing capacity/bottlenecks or resources and determines the locus of the bottlenecks in processing. Focused or selective attention has been studied mainly using cueing tasks and visual search tasks. In a cueing task, a subject performing the task is directed to a particular spatial location through a cue, which could be in a neutral position, valid position or invalid position (Posner, 1980). Reaction times are then recorded for each cue condition. Theories of selective attention are discussed in detail in section 2.3.1.

### 2.1.2 Vigilance or alertness

Another view about why we need attention comes from the fact that it is required to maintain a state of alertness or vigilance, which may improve the response time and accuracy of a selection (Posner, 1980; Eriksen & Yeh, 1985; Downing, 1988). Alertness is considered to be an elementary aspect of attention, which describes the wakefulness and arousal level of an individual. Vigilance is the ability of observers to maintain their focus of attention and remain alert over time which is also referred to in the attention literature as sustained attention, that is the ability to maintain alertness or vigilance in anticipation of a stimulus or action where other attentional functions are believed to rely on it (Parasuraman, Warm & See, 1998).

A number of tasks have been used to study sustained attention. The seminal studies in the area of vigilance were carried out by Mackworth (1948), followed by a number of other experiments in which tasks involved displays in which the observers had to detect the onset or conclusion of a discrete stimulus event (Warm, 1984a). Theories of vigilance and arousal deal with explaining the role of sustained attention, and are explained in detail in section 2.3.2.

### 2.1.3 Attentional control

Yet another response to why we need attention arises from the point of view of attention playing a significant role in exerting attentional control. Attentional control relates to selective attention in an effort to select from competing thoughts or actions based on internally generated goals and plans (Norman & Shallice, 1986; Desimone & Duncan, 1995). This control and monitoring function falls under the category known as divided attention. In general, divided attention requires attention to deal with multiple stimuli simultaneously; the performance commonly depends on the task difficulty and the level of practice. The concept of automaticity plays an important role in the explanation of divided attention. Automatic processes are considered to be fast, which do not reduce the capacity available for other tasks. In contrast, controlled or 'willed' processes are slower and affect the performance of other tasks.

Attentional control is explained generally in terms of a more universal term, cognitive control. Cognitive control is a term synonymous with executive functions and is used by psychologists and neuroscientists to describe a loosely defined collection of brain processes (Miller & Cohen, 2001). Many psychological tasks have been used to understand the phenomenon of cognitive control, specifically in relation to interference, conflict detection and resolution. The Stroop task, Simon effect and the flanker task (Stroop, 1935; Simon & Berbaum 1990; Eriksen & Eriksen, 1974) are a few of the more popular tasks used to study cognitive control.

Divided attention tasks deal with attentional mechanisms and their capacity where two or more stimulus inputs are given, and all must be responded to or attended to. Divided attention has been studied widely using dual-task paradigms or a psychological refractory period where the participant is given two stimuli and two responses. The task is to respond to each stimulus as quickly as possible. When the second stimulus appears shortly after the first one, there is a delay in response time to the second stimulus. This is referred to as the psychological refractory period effect (Welford, 1952). Theories of attentional/cognitive control and automatic and controlled processing explain this function of attention, and are detailed further in section 2.3.3.

### 2.1.4 Neuroscience view of attention

With the advancements in neuroscience, attention is explained from yet another perspective. Combining the conventional psychological views/functionalities of attention with research from neuro-scientific studies, attention has been viewed as an "organ system", which is divided into subsystems performing independent but interrelated functions (Corbetta & Shullman, 2002; Desimone & Duncan, 1995; Posner & Peterson, 1990). Posner and colleagues use the classic Webster's dictionary definition of an organ system, which states that:

> "An organ system may be defined as differentiated structures in animals and plants made up of various cells and tissues and adapted for the performance of some specific function and grouped with other structures into a system" (Posner & Fan, 2007, p. 2).

Attention is shown to be carried out by a network of anatomical areas, with its own distinct neuro-anatomy, neurophysiology and neurochemistry (for detailed discussion on neuro-anatomy, neurochemistry and neurophysiology of attention, see Chapters 2, 3 & 4 in the book The Attentive Brain, by Raja Parasuraman, 1998). Neuroscientists have adopted many psychophysical tasks to study the neural basis of attention using neuroimaging and neuro-physiological techniques such as functional magnetic resonance imaging (fMRI), positron emitting tomography (PET) scans and so on to monitor physically the working of the brain. Theories based on neuro-scientific studies are discussed in section 2.3.4.

## 2.2 Guidance/selection of attention

In the context of the role of attention in selectivity and limited capacity, it is important to understand how the mechanism of selection is guided and what determines what or how something gets selected. A few of the more important visual selective attention phenomena which guide the selection process are explained below.

### 2.2.1 Covert and overt attention

Under normal viewing conditions, attention and saccadic eye movements work together, in order to select things. Attentional allocation that is accompanied by saccadic eye movements is termed 'overt orientation'. Although shifts of attention are normally accompanied by eye movements, it is also possible to attend to peripheral locations of interest without moving our eyes (James, 1890), which is known as ‘covert orientation’. Covert attention is considered to be much faster than overt attention because there is no movement of eyes or head associated with it (Posner, 1980).

### 2.2.2 Bottom-up vs. top-down attention

Shifting the focus of attention, or where to look next, depends on the direction of information flow that guides and constrains the selection process. From the point of view of visual information processing and attention control, there are two execution methods: (1) bottom-up, exogenous or stimulus-driven attention and (2) top-down, endogenous or goal-oriented attention (Jonides, 1981; Müller & Rabbitt, 1989; Desimone & Duncan, 1995). Bottom-up attention is controlled by the visual stimulus and the specific attributes of the stimuli in the visual environment. On the other hand, the top-down process is directed by the subject's intentions, action and task priorities (Corbetta & Shullman, 2002). Top-down is also sometimes termed as automatic, reflexive, or peripherally cued (Posner, 1980). For example, the flash lights of an ambulance on a road immediately capture a driver’s attention; this is bottom-up attention. Conversely, if while driving a driver is looking for a petrol station to refill with fuel, he is engaged in top-down attention, which is driven by the driver’s actions or intentions.

### 2.2.3 Inhibitory mechanism of selective attention

Attention is guided not only by the enhancement of relevant information, but also by the inhibition or suppression of irrelevant information or distractors. Three inhibiting phenomena cited in the attention literature are invalid cueing, negative priming and inhibition of return (Chun & Wolfe, 2001). Invalid cueing is referred to as the condition where incorrect information regarding a cue position or location resulting in degradation of performance or the slowing down of response times. This leads further to dividing the process of orienting into three sub-components of disengage, move and engage corresponding to various sub-areas of the brain (Posner, Snyder & Davidson, 1980; Posner et al., 1984; 1987). Negative priming refers to an item-specific inhibitory effect, in which subjects respond slower to targets that were distractors in the previous trial

(Tipper, 1985). Inhibition of return refers to the phenomenon in orienting in which a recently previously attended object is inhibited. In the context of a visual search task, inhibition of return prevents an observer from continuously rechecking the same location (Klein, 1988; Klein & McInnes, 1999).

## 2.3 Theories of Attention

Theories of attention are best understood and categorised in terms of how they explain the role that attention plays in our everyday lives. Based on why we need attention and observations from various psychophysical tasks and/or neuro-scientific studies, various theories of attention have been presented by attention researchers. As briefly mentioned in section 2.1, broadly, theories of attention can be classified as dealing with (1) limited capacity and selectivity, (2) vigilance and alertness, and (3) control of attention. In addition to these, the (4) neuro-scientific view of attention and (5) mathematical models of attention are also presented in the form of theories of attention, which are described in detail below.

### 2.3.1 Theories of limited capacity

This class of theories deals with the limited capacity of attention in terms of processing capacity and resource capacity. In the literature, the former have been referred to as 'structural theories' and the latter 'capacity theories', which are explained below.

#### 2.3.1.1 Processing capacity/bottleneck theories of attention

Early theories dealt with the issue of early vs. late selection of attention. The first research, called the dichotic listening study, on whether selection takes place early or later in the processing stages was performed on an auditory domain (Cherry, 1953; Cherry & Taylor, 1954). Based on the results of this study, Broadbent (1958) proposed that attention operated early in the selection process. This theory was known as a 'filter' theory because it assumed that selection was due to an all-or-none blocking mechanism (or filter) that passed only through the selected channel. However, Moray (1959), using shadowing experiments, found that people could hear their own names even in the unattended channel, which suggested that recognition of the name occurs before selection, not after. On the other hand, the late-selection view held that selection occurs only after categorisation and semantic analysis of all input has occurred (Deutsch & Deutsch, 1963; Duncan, 1980). The attenuation theory, which was considered to be a compromise between early vs. late selection views, suggested that rejected information is attenuated (reduced) rather than completely filtered or completely identified (Treisman, 1964). Thus, although the fact that there is some sort of limitation or "bottleneck" in processing capacity was agreed upon, the dispute here was over the locus of this bottleneck in the sequence of information processing.

#### 2.3.1.2 Theories of focused visual attention

Filter theory, attenuation theory and so on were presented in the context of focused auditory attention, which deals with a pattern of frequencies distributed over time. Conversely, visual information is distributed in space, so the theories of focused visual attention described what is selected, as well as the fate of the unattended stimuli. In this context, the theories of spatial orienting and visual search are described below.

##### 2.3.1.2.1 Theories of spatial orienting

One of the main issues that the theories of spatial orienting dealt with was how a region or an object is selected for attention (the spotlight vs. zoom lens metaphors in selection). According to the spotlight theory of attention (Posner, 1978), the object at the location where the spotlight of attention is focused is "illuminated" so that it can be attended to and processed. Once the object has been processed, the attentional spotlight is shifted to the next location. The spotlight could have a variable width of focus adjustable by the subject's volition or by task demands (Eriksen & St. James, 1986; Eriksen & Yeh, 1985). The alternative metaphor – the zoom lens theory – operates like the zoom lens on a camera with a variable spatial scope (Eriksen & St. James, 1986). Both metaphors can also be combined and have one thing in common inasmuch that they select a region of space. A spotlight illuminates everything which is in its spotlight, an object or parts of objects. These are focused visual attention theories.

In spatial orienting, it was shown that three distinct abilities are involved in controlling the attentional spotlight, namely:

1. Disengagement of attention from a visual stimulus
2. Shifting/moving of attention from one target stimulus to another
3. Engaging of attention to a new target location.

In experiments that distinctly study these three sub-components of orienting, Posner and colleagues (Posner, et al., 1984; 1987) administered the classic cueing task extended with an invalid cueing condition. Patients affected by various deficit conditions (Baliant's syndrome, brain damaged patients, neglect conditions, and so on) behaved differently, establishing that these three capabilities exist separately in the brain. These findings were also verified further by physiological studies (Posner & Peterson, 1990). It was pointed out that "the parietal lobe first disengages attention from its present focus, then midbrain area acts to move the index of attention to the area of the target, and the pulvinar nucleus is involved in reading out data from the indexed locations" (Posner & Peterson, 1990, p. 28). These three orienting components are explored further through modelling in Chapter 5.

2.3.1.2.2 Visual search theories

One of the most common ways in which we use focused attention in our lives is in visual search. Some theories of attention deal specifically with explaining how visual search takes place, the two most popular ones being the feature integration theory and the guided search theory.

2.3.1.2.2.1 Feature integration theory

Treisman and Gelade (1980) proposed the feature integration theory according to which attention is required to solve the "binding problem." The binding problem is defined as the problem of how the visual system correctly links up all the different features of complex objects and becomes more explicit if there is more than one object in a scene. The theory was first introduced in 1980 (Treisman & Gelade, 1980), but evolved over time (Treisman & Gormican, 1988; Treisman, 1993). Some of the changes in the initial theory involve the degree of similarity between the target and distractors, while other significant changes were based on the four kinds of attentional selection, referred to as 'selection by location', 'selection by features', 'object-defined locations' and finally an object file that controls the individual's response. The feature integration theory is considered to be one of the most influential theories in the field of attention.

2.3.1.2.2.2 Guided search theory

The guided search theory (Wolfe, 1998) is based mainly on the feature integration theory, but it refines the notion of initial serial and subsequent parallel processing. The main objective of the guided search theory is to explain visual search and associated concepts such as conjunction search, search asymmetries and so on. Unlike the feature integration theory (FIT), guided search has a complete implementation available, which has been revised periodically as guided search 1.0 (Wolfe, Cave, Franzel 1989), guided search 2.0 (Wolfe, 1994), guided search 3.0 (Wolfe & Gancarz, 1996), and guided search 4.0 (Wolfe, 2001).

2.3.1.3 Capacity theories of attention

As opposed to the filter theories, where the contention is over the locus of the bottleneck, capacity theories deal with the nature of the bottleneck, placing structural constraints on the selection process. One view, as initially proposed by Kahneman (1973), is that instead of processing limitation, there is a limitation on the resources available to perform the task, which is a limitation on the capacity to perform 'mental work.' This is based on the premise that different tasks would require different levels of demand on the limited capacity. So, if the demand of the task does not meet with what is available, i.e. the resources for processing, the task may falter. It is important to note that structural and capacity theories are not mutually exclusive; rather, they are meant to complement one another. This theory of attention is based on the idea that attention consists of a group of cognitive processes in order to deal with information overload.

### 2.3.2 Theories of vigilance or alertness

The previous section presented mainly the theories of attention that highlight the role of attention in selection and limited capacity (both processing limitation and resource overload). In this section, the theories that explain attention for dealing with alertness signals and vigilance tasks are addressed.

A number of theories of vigilance and arousal have been proposed from the perspectives of learning theories, neurological theories and psychophysical or information processing theories (Warm, 1984b). Mackworth's (1948) internal inhibition theory explains the decline in performance due to lack of rewards and incentives. The arousal, or activation, theory explains that the lack of an external stimuli leads to increased levels of drowsiness and hence reduces concentration, which explains the levels of fluctuations in the cerebral cortex of the brain, as shown by neuro-physiological studies. Channel capacity, or the filter theory, explains that during an alertness task the filter channel becomes less discriminating and allows more irrelevant signals to pass through, which leads to overloading the channel and hence losing concentration and alertness. The neurological theories of sustained attention rely on the belief that the concentration level depends on the functional states, i.e. activity in the cerebral cortex. However, other notions of adaptation (a decline in the intensity of the stimuli processed by the sensory organs) and habituation (becoming used to irrelevant stimuli) also play a significant role (for a detailed review, see Warm, 1984b).

### 2.3.3 Theories of Attentional Control

Having explained the role of attention as that of selection and dealing with alertness/vigilance, this section explains the vital role that attention plays in our lives through attentional control, the role of which is to guide thought and behaviour in accordance with internally generated goals or plans (Norman & Shallice, 1986; Desimone & Duncan, 1995). The notion of controlled and automatic processes gives rise to many well known theories. Controlled processes rely on attention for execution, whereas automatic processes can be carried out without attention (Schneider & Schiffrin, 1977). Practice also has an impact on performance inasmuch that the role of attention in this context is to reduce conflict, which provides a natural signal for the need of attentional control.

Shiffrin and Schneider's theory (1977) and Norman and Shallice's theory (1986) are the two best known models that theorise the distinctions between automatic and controlled processes and explain the working of attentional control.

2.3.3.1 Shiffrin and Schneider's theory

Shiffrin and Schneider (1977) gave a clear distinction between automatic and controlled processes. Controlled processes have limited capacity (processing or resources), hence they require attention and can be used flexibly in a dynamic environment, whereas, in contrast, automatic processes have no such processing capacity limitation, and therefore do not require attention and are not easy to modify once learned. Shiffrin and Schneider (1977) carried out multiple tasks to test this theory as well as the notion that automatic processes develop through practice.

2.3.3.2 Norman and Shallice's theory

Norman and Shallice (1986) made a further distinction between the fully automatic and partially automatic processes which operate at three levels, namely:

1. Fully automatic processing, given by schemas
2. Partially automatic processing, which involves contention scheduling without conscious control (contention scheduling deals with conflict resolution)
3. A more sophisticated, deliberate control managed by a supervisory control system.

Depending on no control or level of control, attention operates. The main distinction here is not only between automatic and controlled processes, but also fully automatic and fully controlled processes. This is also referred to in the literature as the 'schema activation' model.

### 2.3.4 Attention theories informed by neuro-scientific findings

All of the theories discussed so far are based on results from psychological experiments explaining the role of attention from different perspectives. In addition to this approach, attention has also been explained in terms of analysing and looking at the underlying brain areas that come into play that are related to different aspects of attention. Posner's three-network model (attentional network theory) and Laberge's triangular circuit theory are classic examples, and are introduced below.

2.3.4.1 Theory of attentional networks

In their seminal paper, Posner and Boies (1971) proposed attention to be comprised of three components, namely alertness, selectivity and processing capacity. This was based on the view that there are three major topics under which studies of attention are categorised. Here, alertness was referred to as the ability to develop and maintain an optimal sensitivity to external stimulation. Selectivity is the ability to select information from one source or kind, rather than the other, while limited capacity deals with interference and conflict resolution (this was also suggested by Kahneman in his book Attention and Effort (1973)). However, at that time, this distinction was not based on any neuro-physiological evidences. Later, Posner and Peterson (1990, p 26), based on neuro-scientific findings, suggested that “attention is carried out by a network of anatomical areas”, so for the first time they presented the three-network theory in the light of physiological analysis. As research progressed in cognitive neuroscience, evidence became available for the existence of separate brain areas, emphasising the anatomy of the attention system. The components of attention were renamed as the alerting, orienting and executive control networks. Since then, a vast amount of neuroimaging data has supported this theory (Posner & Fan, 2007; Hopfinger, Buonocore & Mangum, 2000; Fan, McCandliss, Fosella, Flombaum & Posner, 2005; Raz, 2004; Raz & Buhle, 2006; Posner & Raichale, 1994; Corbetta & Shullman, 2002). This theory is explored in this thesis through cognitive modelling.

#### 2.3.4.2 LaBerge’s triangular circuit theory

“If you know where something happens, you are closer to discovering how it happens” (LaBerge, 1997, p. 150). This is how Laberge describes the importance of understanding the brain areas underlying cognitive mechanisms.

According to LaBerge’s triangular circuit theory of attention (1997; 1998), attention requires the simultaneous activity of three brain regions, which are connected by a triangular circuit known as the cortical columns of attentional expression, a group of thalamic neurons that enhance activity in these columns and a set of prefrontal cortical columns for control. In addition to the three components as described by Posner, LaBerge ties up awareness in the triangular circuit.

### 2.3.5 Mathematical theories of visual attention

As opposed to psychological theories of attention that explain an experiment or part of the data at the cognitive level, some theories try to present a unified picture at a mathematical level.

Bundesen (1990) and Logan (1996) developed formal mathematical theories of visual attention. The theory of visual attention (TVA) is a powerful theory which accounts for various attention-related phenomena (Bundesen, 1990, 1998), and integrates the biased choice model for single-stimulus recognition (Luce, 1963) with a choice model for selection from multi-element displays (Bundesen, Shibuya & Larsen, 1985). Mathematically, the theory is considered tractable and has been applied widely to a number of tasks. Unlike other contemporary theories, TVA attempts to describe the mechanism of selection of attention without the aid of some "attention director" that does the selection. It derives from both the early and late selection theories of attention.

Logan's (1996) CODE theory of visual attention (CTVA) combines Bundesen's theory of visual attention (TVA) with the COntour DEtector (CODE) theory for perceptual grouping (van Oeffelen & Vos, 1982). This theory is an attempt to integrate the theories of space-based attention with theories of object-based attention (for detailed reviews, see Bundesen, 1990; Logan, 1996).

### 2.3.6 Summary and relationship between theories of attention

Attention research is not limited to psychophysical experiments, as cognitive neuroscience and mathematics have made a significant contribution in explaining attention. Section 2.3 gives an account of the theories of attention from psychological, neuro-scientific and mathematical perspectives which explain the diffused nature of attention. The classification of the theories is summarised in Figure 2.1.

The theories of attention discussed in section 2.3 seem mostly to explain one or more role of attention. However, when accounted for together, the theories put together encompass all function of attention. For example, theories of vigilance and alertness account for what happens in the case of sustained attention, or being able to stay alert or vigilant for a stimulus. Theories of spatial orienting account for the phenomenon of orienting and, finally, theories of attentional control account for the functioning of the network of executive control.

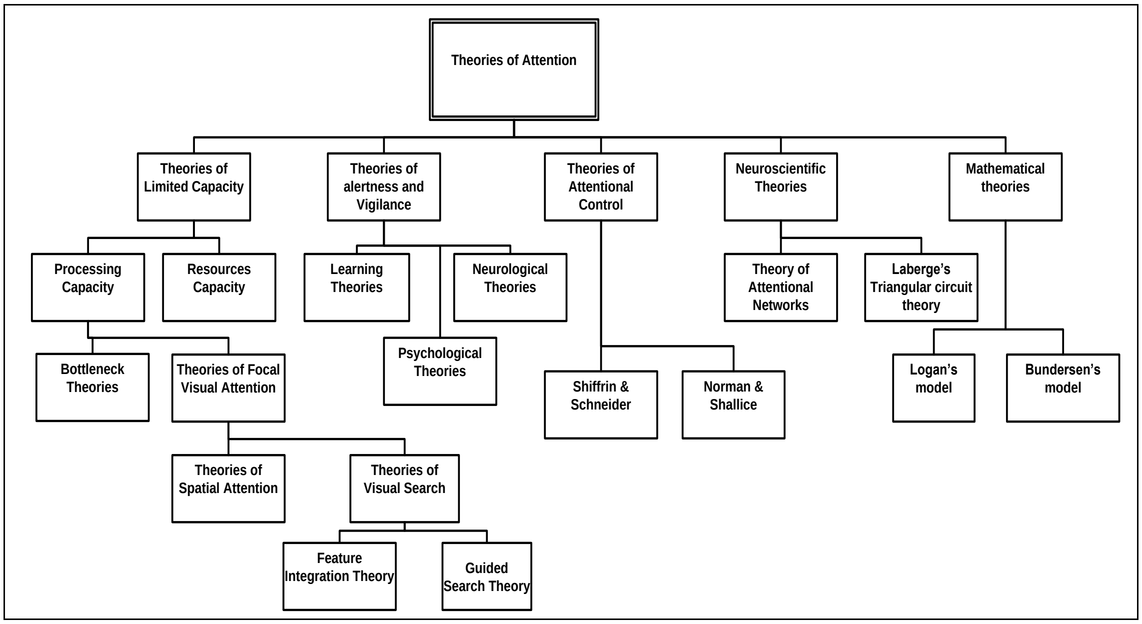



Figure 2-1: Summary of theories of attention from psychological, neuro-scientific and mathematical perspectives.

Since this thesis is based on Posner's view of attention explained as a network of three components, a relationship between Posner's view and other theories of attention is drawn. Posner's theory gives an account of attention from the perspective of psychological studies, as well as neuro-physiological and neuro-scientific approaches. It differs from other theories in the sense that some theories of attention are purely theoretical accounts, e.g. the filter theory (Broadbent, 1958), while others provide a framework, e.g. the feature integration theory (Triesman & Gelade, 1980). Furthermore, some even give computational implementations of the underlying theoretical constructs, such as the guided search theory (Wolfe, 1998). Mathematical theories attempt to give a unified picture of attention at a mathematical level. The theory of attentional networks (Posner & Peterson, 1990) brings together the disparate cognitive mechanisms which fall under the umbrella of attention, namely alerting or vigilance, orienting (also referred to as 'selection' in general attention literature) and executive control. It brings together the concepts of focused attention, divided attention and sustained attention and hence encompasses the role of attention in general in human cognition. Put together, the theory of attentional networks borrows concepts from other theories of attention, providing a more holistic picture of attention.

## 2.4 Theory of human attentional networks

Having given an overview of the function of attention and popular theories of attention, this section, which is also the theoretical basis for this thesis, describes the theory of attentional networks in detail. It provides the functionality of the three components of alerting, orienting and executive control along with the anatomical/neural basis for their existence. The attentional network test (ANT), and its variations that are simulated in this thesis, are also introduced.

### 2.4.1 Components of attentional networks

As mentioned earlier, Posner and Peterson (1990) proposed a model whereby attention can be viewed as a system of anatomical areas that is made up of three networks, namely alerting, orienting and executive control. These networks perform specialised functions that are sub-served by at least three possibly interacting attentional networks in the brain each with its distinct neuro-anatomy and neurochemistry. Imaging studies have also proved the existence of these three attentional networks in the brain (Raz, 2004; Raz & Buhle, 2006; Hopfinger et al., 2000; Fan et al., 2005; Fan, Flombaum, McCandliss, Thomas & Posner, 2003; Fan, Raz & Posner, 2003; Posner & Fan, 2007; Corbetta & Shulman, 2002; Driver, Eimer, Macaluso & Van Velzen, 2004). The functionality of the three networks[1] is described below.

#### 2.4.1.1 Alerting

Alertness or vigilance is the ability to achieve and sustain an alert state. In general, two types of tasks have been used to study alertness: warning tasks and continuous performance tasks. Tasks with a warning signal could either be exogenous (e.g. alerted by auditory sound) or endogenous (waiting to process an expected target). Continuous performance tasks, on the other hand, have either to deal with waiting for weaker target detection or are continuously responding to a task. In general, the key is that the

[1] From the perspective of cellular physiology, a network means identified neurons that connect to one another by synapses and through other means of communication (Bullock, Bennett, Johnston, Josephson, Marder & Fields, 2005).

participant must remain alert in order to avoid distraction and concentrate on the target detection.

#### 2.4.1.2 Orienting

In the psychological literature, orienting is usually referred to as ‘visual selective attention’, which has been widely referred to as the mechanism by which we can rapidly direct our gaze towards objects of interest in our visual environment, and is the most studied attentional network. Orienting itself is thought to comprise of three components, namely disengagement, movement, and engagement, each with a distinct anatomy of its own. Hence, the operation of shifting attention actually requires good coordination between these three areas of the brain, and any impairment in any of these regions, as shown by neuropsychological literature, causes difficulty in shifting attention (Posner & Peterson, 1990; Posner, et al., 1984).

#### 2.4.1.3 Executive control

Executive control falls under the broad cognitive phenomenon of executive function (EF), an umbrella term used for cognitive processes that subserve goal-directed behaviour (Botvinick, Braver, Barch, Carter & Cohen, 2001; Miller & Cohen, 2001; Norman & Shallice, 1986; Shallice, 1982). It is believed that, generally, executive function is composed of several sub-functions, namely working memory, cognitive flexibility, planning and inhibition. Working memory refers to the ability to hold information in the mind and to mentally manipulate that information, while cognitive flexibility is the ability to quickly and flexibly adapt behaviour to changing situations. Response inhibition (which is of interest in this thesis) acts on the basis of choice by resisting inappropriate behaviour and responding appropriately.

Broadly speaking, executive control is involved closely with aspects of executive functioning such as effortful control or coordination, particularly in tasks in which the response is not fully determined by the stimulus (Norman & Shallice, 1986). These tasks may involve dual tasks, task switching, conflict resolution, error detection, inhibitory control, and so on. The processes of executive control are responsible for resolving conflicts, which require the suppression of automatic responses that may interfere with target detection.

### 2.4.2 Neural mechanisms and correlates of attention networks

The neural basis of attention comprises several distinct, but interconnected pathways which carry out the multiple cognitive processes that are believed to fall under attention. These have been investigated previously by the use of techniques such as positron emission tomography (PET) and functional magnetic resonance imaging (fMRI). It has been shown by these methods that there is no single brain area that is responsible for the attentional mechanism; rather, a network of areas performs the operations related to attentional processes (Raz, 2004; Raz & Buhle, 2006; Hopfinger et al., 2000; Fan et al., 2003; 2005; Posner & Fan, 2007; Corbetta & Shulman, 2002). The alerting part of the attentional mechanism is carried out by the norepinephrine system arising in the locus coeruleus. It is believed that the orienting of attention to a stimulus is carried out by the interaction of three areas, namely the posterior parietal lobes, superior colliculus and the pulivnar of the thalamus. The posterior parietal is also responsible for disengaging the focus of attention from the present location (inhibition of return); the superior colliculus shifts the attention to a new location and the pulvinar reads out the data from the indexed location. The control network is associated with the anterior cingulated gyrus in the frontal part of the brain, and also includes the superior supplementary motor areas of the frontal lobes and portions of the basal ganglia. Figure 2.2 illustrates the cortical areas involved in the three attentional networks, and the neuro-anatomical relations and chemical relationships of these attentional networks are summarised in Table 2.1.

Table 2-1: Neuro-anatomical and chemical relationships between attentional networks (Raz, 2004).

| **Function** | **Structures** | **Chemical Modulators** |
|---|---|---|
| Alerting | Locus coeruleus, right frontal parietal cortex | Norepinephrine |
| Orienting | Superior parietal, temporal parietal junction, frontal eye fields, superior colliculus | Acetylcholine |
| Executive Control | Anterior cingulate, lateral ventral prefrontal basal ganglia | Dopamine |

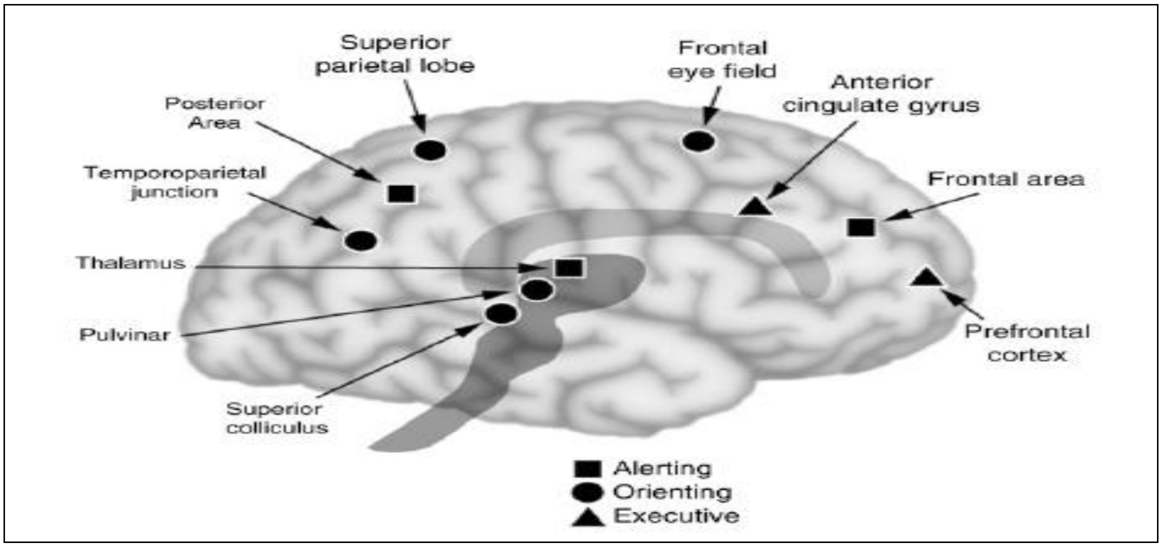



Figure 2-2: The neuro-anatomy of attentional networks (Posner & Rohbart, 2007, p. 6)

### 2.4.3 Behavioural tasks used to study attentional networks

Various psychological studies have been carried out to study the function of the networks of alerting, orienting and executive control independently. For example, alerting has been studied using alerting/vigilance tasks and warning signals. In alerting tasks, the participants are given a cue indicating that a target is going to appear shortly. However, the location of the target is not revealed. These warning cues generally decrease latency and error rates (Posner, 1980).

Orienting has been studied using visual search tasks and spatial cueing experiments. Typically, in a visual search task, participants are instructed to watch a visual display for some features (e.g. letter T, colour red and so on), or a conjunction of features (e.g. a red T). Numerous visual search experiments have been carried out (Treisman & Gelade, 1980), and some of the results showed that in the case of simple feature searches the reactions times were much faster when compared to when the participants had to do complex conjunction searches.

In a visual orienting/cueing task (Posner, 1980), participants are instructed to move attention to a cued location anticipating the appearance of a target. There is reduced latency and accuracy in the cases where the cue is in the correct location and further variation of the cueing task when the participant is given an invalid cue. In this case, the reaction time slows down, since attention is first disengaged from an invalidly cued location, and then shifted to a new location (Posner, et al., 1984; 1987).

Many psychological tasks have been used to understand the phenomenon of executive control in relation specifically to interference, conflict detection and resolution, among which are the Stroop task, Simon effect, flanker task, and so on. For example, the classic Stroop task involves a conflict between a word name and its ink colour (Stroop, 1935); however, other variations deal with more dimensions. The Simon effect deals with location and the direction of the response (Simon & Berbaum, 1990), while the flanker task deals with the identification of a stimulus surrounded by flankers, which are distracters (Eriksen & Eriksen, 1974). Most of these tasks comprise congruent, incongruent and neutral trials. Latency and accuracy rates are much higher in the case of congruent trials as opposed to the incongruent trials due to interference effects.

In the attention literature, we can also find a few experiments where two or more networks are combined in one task. For example, alerting and orienting have been studied together in a covert orienting task under different conditions of alertness. It was found that orienting has a beneficial effect from alerting (Fernandez-Duque & Posner, 1997). Similarly, to explore the effect of cueing on conflict, other studies (Vivas & Fuentes, 2001; Chen, Wei & Zhou, 2006) have used a combination of the Stroop task and cueing paradigm. Here, the cue is first presented to attract attention at a peripheral location, followed by a target either at a cued location or un-cued location, and the subjects are asked to respond to the cued location. It was reported that the reaction time at the cued location was greater than that seen for the un-cued location when the stimulus onset asynchrony (SOA) was greater than 300ms, because the inhibition of return (IOR) phenomenon can give rise to a reflexive bias in orienting and visually searching towards novel locations (Klein, 2000).

Each of the experimental paradigms discussed above mostly tap either one or sometimes two components of attention. There are only two instances of experiments that measure the efficiencies of the three networks in a single task. One of the earlier ones is the task presented by Robertson and colleagues, called the 'Everyday Test for Attention' (ETA), which uses ecological measures of attention such as map searching, looking up phone directories, listening to lottery numbers (Robertson, Ward, Ridgeway & Nimmo-Smith, 1996).

Another task, known as the attentional network task (ANT) (Fan et al., 2002), is one of the most widely used tasks for recording efficiencies of the three networks in one undertaking. The application and usability of the ANT is very diverse, and the importance can be gauged from its usage in various forms. ANT has proved to be extremely useful in evaluating attentional dysfunctions, finding correlations and interactions of the alerting, orienting and executive control networks and studying the development of the networks in children. An overview of the ANT and it variants is given in the next section. These are later modelled in Chapters 5-8.

#### 2.4.3.1 Attentional Network Test (ANT) and its variations

As introduced in section 1.4, the ANT is a combination of cueing experiments (Posner, 1980) and a flanker task (Eriksen & Eriksen, 1974). Cueing and flanker tasks are among the most extensively used paradigms in attention research. ANT is a computer-based reaction time test developed to measure the three distinct cognitive processes associated with attention, namely alerting, orienting and executive control. The duration of the test is approximately 30 minutes, for which the source code and online test are freely available (http://www.sacklerinstitute.org/users/jin.fan/). Visual stimuli are presented on the screen, which requires maintenance of an alert state, spatial orienting to cued stimuli and control of competing resources.

As given in Equations 2.1-2.3, the ANT uses differences in reaction time (RT) between conditions to measure the efficiency of each network. Subtracting reaction times for congruent from incongruent target trials provides a measure of conflict resolution and assesses the efficiency of the executive control network. Subtracting reaction times obtained in the double-cue condition from the reaction time in the no-cue condition gives a measure of alerting due to the presence of a warning signal. Subtracting the reaction times of targets at the cued location (spatial cue condition) from trials using a central cue gives a measure of orienting. It is the spatial cue and not the central cue that provides valid information about where a target will occur. A detailed description of the ANT task and an illustration is given in Chapter 5, where the ACT-R 6.0 model of the ANT is explicated.

$$Alerting = RT(no_{cue}) - RT(double_{cue}) \quad \text{Equation 2.1}$$

$$Orienting = RT(center_{cue}) - RT(spatial_{cue}) \quad \text{Equation 2.2}$$

$$Executive\ Control = RT(incongruent) - RT(congruent) \quad \text{Equation 2.3}$$

The ANT has been widely used to assess which attentional networks are affected by certain attention-related deficits (Klein, 2003; Wang, Fan, Dong, Wang, Lee & Posner, 2005; Fernandez-Duque & Black, 2006; Posner et al., 2006; Posner & Rohbart, 2007; Booth et al., 2001). It is considered to be a relatively sensitive tool for assessing attention-related disorders because it can closely determine the efficiency of individual attentional networks corresponding to distinct areas in the brain.

In addition to studying pathologies, the ANT has also been applied to assess the success of efforts to develop rehabilitation methods and attention training programmes, specifically in children (Tamm, McCandliss, Liang, Wigal, Posner & Swanson, 2007), in order to use it as an endophenotype in genetic studies exploring the heritability of each network (Fan, et al., 2003; Fan et al., 2005; Fan, Wu, Fosella & Posner, 2001).

The original attentional network test (Fan et al., 2002) has also been modified to study the development of the networks in children (Rueda et al., 2004). This test (also referred to as ‘ANT-C’) is a child-friendly version of the combination of flanker and cueing paradigms used with adults. ANT-C was adapted to make it more children-friendly by replacing the target stimuli with five colourful fish. Details of the task representation and an illustration for ANT-C are given in Chapter 8, where the ACT-R 6.0 simulation is explicated.

### 2.4.4 Interaction of attentional networks

The neural correlates of the three networks of alerting, orienting and executive control have been somewhat identified and shown to be anatomically different. However, there has also been research using both imaging and behavioural studies to explore the interactions between the networks.

For example, an inhibitory effect of alerting on congruency has been shown by neuroimaging studies, where during an alerting task a right hemisphere enhancement and a reduced signal from frontal areas such as the anterior cingulated cortex were recorded (Cohen, Semple, Gross, Holcomb, Dowling & Nordahl, 1988). This is also referred to as the "clearing of consciousness" by Posner (1994, p. 7401). The neurotransmitter (norepinephrine) also has strong connections with the posterior areas, which are related to the orienting of attention (Posner, 1978). This indicates a speeding up effect of orienting due to the presence of an alerting signal.

In addition to the above physiological/imaging studies, behavioural studies have also pointed to similar interactions between the networks. The initial study using the ANT (Fan et al., 2002) only reported interaction between orienting and executive control. The design of the experiment was such that both alerting and cueing were measured with variation of the cues, and therefore it was unclear whether the modulation effect on congruency was a result of the alerting signal or cueing. To separate out the impact of alerting and orienting, Callejas and colleagues (2004; 2005) used an auditory alerting condition to separate the cueing effect and administered the ANT experiment again to healthy adults. It was reported that alerting has an inhibiting effect on congruency, whereas cueing has a facilitating effect. These studies showed that, although alerting improves overall speed, it may have an inhibiting effect on executive control (a larger flanker-congruency effect was found where an alerting signal was present), whereas the orienting network has a positive effect on congruency (a smaller flanker effect was observed for cued as compared to un-cued trials). Furthermore, it was found that alertness seems to increase the orienting effect, resulting in a faster orienting under alertness. Fan and colleagues recently in a revised version of the ANT called the ANT-R[2] showed similar modulation effects (Fan, Xiaosi, Kevin, Xun, Fossella, Wang &

[2] As part of their revised study, Fan and colleagues (2009) re-examined the interactions of the networks of attention, using a design whereby an invalid cueing condition was introduced which did not exist in the original ANT study (Fan et al., 2002) (for details on the design of the ANT-R, refer to Fan et al., 2009).

Posner, 2009) to those produced by the Callejas and colleagues studies (2004; 2005), the simulation of which is undertaken in Chapter 6.

### 2.4.5 Attentional networks and pathologies

The attentional networks, as divided into the networks of alerting, orienting and executive control, can also be associated individually with various pathological states. For example, for patients affected with autism, it has been shown that their condition maybe related to the impairment in the orienting network. For Alzheimer's, borderline personality disorders and schizophrenia sufferers, their condition has been shown to be related to executive control (Posner et al., 2002; Posner & Rohbart, 2007). For hearing-impaired subjects (Dye, Baril & Bavelier, 2007), it is believed that there is no difference in the efficiency of alerting and orienting, but it is evident in executive control. Based on the review of the literature in this context, Table 2.2 gives a list of some of the attention-related pathologies and an account of which networks may possibly be affected by each condition. Two of these pathologies are discussed and modelled in Chapter 7. Though many of these conditions may be related to age, evidence suggests that age may not be the only factor (Fernandez-Duque & Black, 2006).

Table 2-2: A summary of some of the attention-related pathologies and networks that may be possibly affected under these conditions.

| | **Pathology/Condition** | **Deficit in Alerting** | **Deficit in Orienting** | **Deficit in Control** |
|---|---|---|---|---|
| 1 | Borderline personality disorder (Posner et al., 2002) | | | ✓ |
| 2 | ADHD (Posner et al., 2006; Booth et al., 2001) | ✓ | | |
| 3 | Autism(Posner & Rohbart, 2007) | | ✓ | |
| 4 | Schizophrenia(Wang et al., 2005; Gooding et al., 2006) | | ✓ | ✓ |
| 5 | Alzheimer's (Fernandez-Duque & Black, 2006) | | ✓ | ✓ |
| 6 | Deafness (Dye et al., 2007) | | | ✓ |
| 7 | Traumatic Brain Injury (Halterman et al., 2006) | | ✓ | ✓ |
| 8 | Normal Aging (Fernandez-Duque & Black, 2006) | | | ✓ |

The assessment of attention may become very important for the purpose of attention training and designing rehabilitation programmes in neuropsychology. It has now been shown that programmes that are designed to target or rehabilitate a specific attentional network have more benefits than the more general ones. Initial attempts at attention training were geared more towards the generalised improvement of attention, and its benefits would also at times get confused with the effects of repetitive practice. Consequently, it is believed that training has to be specific and targeted towards a precise brain area or attentional network, and attention training literature has shown that basic attention functions show significant improvements after specific training (Strum, Willmes, Orgass & Hartje, 1997). For example, one rehabilitation study tested the possible interaction of alerting and orienting network by training patients to increase their self-alertness (Robertson, Tegner, Tham, Lo & Nimmo-Smith, 1995). In this experiment, the patients were made to attend to external warning signals and later during the experiments they were made to self-induce alertness. This rehabilitation had significant benefits. It has been seen that the effects of training work by repeatedly stimulating the impaired attention function. So, understanding which network is impaired, and possibly why, could be useful from the point of view of attention training.

### 2.4.6 Development of attentional networks

Research in attention development shows that children are generally, less efficient in performing attention-related tasks than adults (Enns & Cameron, 1987; Lane & Pearson, 1982). Studies have been done that show how an attentional network develops from infancy in a child and how it influences infant and child behaviour. It has been shown that alerting and orienting systems begin to develop in early infancy, which enables the child to stay alert, select from visual overload and respond to any selective sensory information with which he/she is constantly bombarded. The executive control network develops at a later stage in a child’s life; some rudimentary control capacity may develop around the age of one, but more advanced conflict resolution does not emerge until two years of age (Posner, et al., 2006). These tasks mainly involve overt/covert visual search, orienting, conflict resolution and dual tasks (Guttentag, 1985; Enns & Akhtar, 1989), and so on. Covert orienting tasks in children have revealed that the mechanism differs at different ages, while the cost of invalid cueing decreases with age (Enns & Brodeur, 1989). Developmental trajectories on executive function components have revealed that the conflict resolution ability develops with age (Huizinga, Dolan & van der Molen, 2006; Ridderinkhof & van der Molen, 1995; Enns, 1990).

The attentional network test (ANT-C) has also been administered to children to study the development of the three networks of alerting, orienting and control (Rueda et al., 2004). The children's study showed that reaction time and accuracy improved at each stage. The alerting network changed up to, and even beyond, age 10 and the orienting network was found to be stable much earlier in life, whereas the conflict resolution ability appeared stable after age 7. ANT-C has also been administered to study the developmental properties and socio-demographic relationships (Mezzacappa, 2004) in which socially advantaged children performed generally better in terms of speed, accuracy, orienting and conflict resolution. From the point of view of theories of attentional development, there are generally two explanations for this: (1) attention matures with age and experience, as it is a cognitive resource of limited capacity (Kahneman, 1973; Pascual-Leone, 1978) and (2) although children may have comparable attentional capacity in terms of size, they may have insufficient strategies (Case, 1984).

## 2.5 Chapter summary

Chapter 2 describes the meaning of attention in the context of the role that attention plays in our daily lives, and theories explaining attention from different research fields are elaborated upon. Theories of limited capacity explain attention as a process of dealing with capacity limitations in terms of processing and resources. In terms of visual-focused attention, the theories of visual search explain the role of attention in the detection of stimuli. Theories of attention that deal with control, or automaticity emphasise the role of attention in terms of the nature of processes being automatic or controlled. Theories of vigilance deal with how attention is involved in maintaining levels of arousal and an alert state. In addition to presenting theories explaining the information processing approach of attention, theories of attention which have also evolved as a result of advancements in neuroscience research are also elucidated. Mathematical models of attention are briefly mentioned.

A detailed description of the theory of attentional networks and the sub-components comprising attention is given. Furthermore, the neural correlates of attentional networks and an account of the behavioural tasks that have been used to explain the theory are discussed. Since this thesis also explores the theory of attentional networks from the point of view of pathologies and cognitive development, the behaviour of the three networks in terms of various attention-related pathologies and the development of attention networks is also examined.

The next chapter discusses the state-of-the-art computational modelling of attention and describes different modelling paradigms, specifically the use of a cognitive architecture for modelling, which is the focus of this thesis.

# 3. Computational Cognitive Modelling of Attention

> The question for me is, how can the human mind occur in the physical universe? We now know that the world is governed by physics. We now understand the way biology nestles comfortably within that. The issue is, how will the mind do that as well?

-Allen Newell, December 4, 1991, Carnegie Mellon University (http://act-r.psy.cmu.edu/misc/newellclip.mpg), (Newell, 1993)

This chapter begins with a discussion on computational modelling in general as well as various computational modelling paradigms. The role of cognitive architectures, specifically ACT-R, which is the modelling approach used in this thesis, is discussed in detail. A brief account of various cognitive architectures in the literature, along with a comparison of these, is given. Based on the various modelling approaches given, there is an account of modelling efforts related to attention studies found in the literature. Wang et al's model of ANT implemented in ACT-R 5.0 (Wang et al., 2004) which is modified in this thesis is explained in depth. So, this chapter provides background on various modelling approaches and popular cognitive architectures. Following this discussion, Chapter 4 explains the reasons for selecting cognitive modelling (as opposed to other modelling paradigms) and ACT-R 6.0 (as opposed to other cognitive architectures) as the research tool in this thesis.

## 3.1 State-of-the-art computational modelling

A computational model implemented on a computer simulates the behaviour of a participant in an experiment and measures behaviour objectively, which may then be compared with human data. In other words, computational models have a mechanistic approach to explaining descriptive or mathematical models (Schunn & Gray, 2002) and are best understood as computer algorithms or programs (Turing, 1950). Further, computational models have the advantage of explicitly exposing the computational theories, representations and algorithms underlying cognitive operations (Marr, 1982).

### 3.1.1 Computational modelling paradigms

There are many approaches to implementing computational models.[3] The two most widely used paradigms in modelling cognitive behaviour are the connectionist modelling approach and the symbolic (could also be hybrid) modelling approach. In addition to these two approaches, another type of modelling that is becoming popular (with increased computational power) in the computer vision community is the use of image-processing models. Each of these modelling paradigms is explained in turn below.

#### 3.1.1.1 Computer vision modelling

Computer vision models/filter-based models are used mainly in computer vision applications. Computer vision models are built to solve computer vision problems that aim at building computational attention systems which have applications in the fields of computer vision and robotics. Computer vision is an applied science that is concerned with providing computers with the ability to deal with what the human visual system is capable of doing. Typical applications include robot navigation, surveillance tasks, industrial control, medical imaging, and so on. It only makes sense that computer vision systems must be as biologically plausible as possible in order to produce robust and capable vision systems.

Generally, this class of computational models is based on the notion of a feature or saliency map (Koch & Ullman, 1985). A saliency map is an explicit two-dimensional

[3] Here the scope of explanation is computational models of cognition.

map that encodes for salience, i.e. stimulus conspicuity, at each location in the visual scene. Most models within this class focus on the physiological aspects of search and computer vision problems (Itti & Koch, 2001a, 2001b). There is evidence in the neuroscience literature that there is also a saliency map in the primary visual cortex-V1 (Zhaoping, 2002) and that there are regions in the brain that perform the function of collecting salient cues (Mazer & Gallant, 2003). Other examples of linear filter-based systems are also found in the literature, which share several aspects with Itti and Koch's (2001a, 2001b) models (Backer, Mertsching & Bollmann, 2001; Sun & Fisher, 2003; Heidemann, Rae, Bekel, Bax & Ritter, 2004; Hamker, 2005). Since this class of models is not the focus of this thesis, no further detail is given here.

#### 3.1.1.2 Connectionist modelling

The connectionist, or parallel distributed processing (PDP), modelling approach emerges from the discipline of neuroscience (or cognitive neuroscience), which mainly simulates the neural mechanisms of the processes of the brain. In the connectionist paradigm, networks are constructed from units that are believed to correspond roughly to neurons in the brain. Connectionist models, inspired by neural networks, have considered units at particular levels that influence each other by direct or reciprocal connections (O'Reilly & Munakata, 2000; 2003).

Connectionist models lie within a class of computational models that are composed of a large number of processing units connected by inhibitory or excitatory links. Typically, these units may sum this activity, based on which they change their state as a function of this sum (usually called a threshold function). Weights are used to modulate the activity on each connection.

A number of researchers have described the advantages of using connectionist modelling (for a review, see Sejnowski, Koch & Churchland, 1988; O'Reilly, 1998). Critical analyses and comparisons have also been extensively carried out to compare and contrast the connectionist and symbolic approaches to modelling (Fodor & Pylyshyn, 1988). Various books cover the modelling framework and environments for developing connectionist models in PDP++ (Parallel Distributed Processing), Leabra++ (local, error-driven and associative, biologically realistic algorithm), while various sources of information are available about the basics of the connectionist modelling paradigm (O'Reilly & Munakata, 2000; 2003; Rumelhart & McClelland, 1986). Since the focus of this thesis is not on connectionist modelling, no more detail is given here.

#### 3.1.1.3 Symbolic modelling

A symbolic cognitive model is an artificial system that behaves like a natural cognitive system, the goal of which is to scientifically explain the functioning and interaction of various cognitive processes. As opposed to any generic mathematical or statistical model, cognitive models are based strictly on the principles of cognition.

Symbolic models are built mainly using cognitive architectures to model various behavioural tasks in order to understand cognitive functions such as perception, memory, thinking, language, decision making, and so on. Cognitive architectures are either symbolic or a combination of symbolic and sub-symbolic components, producing what are referred to as 'hybrid' models. Symbolic models are said to be committed to a 'symbol-level of representation', and involve operations on symbols; sometimes referred to as 'language of thought' (Fodor & Pylyshyn, 1988; Newell, 1980; Fodor, 1976). An overview of cognitive architectures, along with a comparison of a few popular examples, is given in the next section.

## 3.2 Overview of cognitive architectures

A cognitive architecture refers to a set of structures, tools, techniques and methods that can support the design and construction of models of cognition (Anderson, 1993; Kieras & Meyer, 1997; Newell, 1990). Cognitive architectures not only cover the theory of human cognition and performance, but also act as a framework for developing computational models of behaviour.

According to Newell (1990), the characteristics of any type of cognitive behaviour that a cognitive architecture will cover are:

- Being goal-oriented
- Placed in a rich, complex, detailed environment

- Require a large amount of knowledge
- Require the use of symbols and abstractions
- Must be flexible and a function of the environment
- Require learning from experience/the environment

According to John Anderson:

> "Cognitive architectures are relatively complete proposals about the structure of human cognition. Just as an architect tries to provide a complete specification of a house (for a builder), so a computer or cognitive architect tries to provide a complete specification of a system. There is certain abstractness in the architect's specification, however, which leaves the concrete realisation to the builder. So, too, there is an abstraction in a cognitive or computer architecture: one does not have to specify the exact neurons in a cognitive architecture, and one does not specify the exact computing elements in a computer architecture" (Anderson, 1993, pp. 3-4).

A cognitive architecture is thought primarily to comprise of two properties: (1) a set of mechanisms that produces behaviour based on given inputs and (2) a theorisation about the commonalities of cognitive behaviours (Lehmann, Laird & Rosenbloom, 2006).

Over the past three decades, several cognitive architectures have risen, a few popular ones being ACT-R (Anderson, 1993) , Soar (Laird, Newell & Rosenbloom, 1987), EPIC (Keiras & Meyer, 1997), 4-CAPS (Just, Carpenter & Varma, 1999), COGENT (Cooper & Fox, 1998), and so on. These architectures are either purely symbolic or hybrid; however, all cognitive architectures follow the principle that symbols are the right grain size to study cognition. For example, Soar in its original form was a pure symbolic architecture, but its most recent version has added some numeric and probabilistic preferences exploring non-symbolic preferences for conflict resolution (Laird, 2008).

In the next section, ACT-R, Soar and EPIC are described. Only ACT-R is described in depth, as this is the architecture of choice for this thesis (see references for details for other architectures). However, a comparison is given between ACT-R, Soar and EPIC from the basic functionality point of view. Based on the comparisons of the popular architectures and the functionality required, in section 4.2 the reason why ACT-R was chosen for modelling work in this thesis is discussed.

### 3.2.1 ACT-R

The Adaptive Control (Character) of Thought–Rational (ACT-R) is considered to be an integrated/hybrid cognitive architecture comprising both symbolic and sub-symbolic constructs (Anderson, Bothell, Byrne, Douglass, Lebiere & Qin, 2004; Anderson & Lebeire, 1998). The beginning of the ACT-R journey can be traced back to the 1970s with the introduction of the theory of human associative memory, HAM (Anderson & Bower, 1973). It evolved from ACTE (Anderson, 1976) to ACT* (Anderson, 1983) to ACT-R 2.0 (Anderson, 1993), and finally through various version changes to its current state of ACT-R 6.0. In the acronym ACT-R, the 'R' stands for 'rational,' which is based on the principle of rational analysis. According to the principle of rational analysis, given computational limitations, each component of the architecture is optimised according to demands from the environment (Anderson, 1990). The symbolic/ sub-symbolic constructs, modular design of the architectures and embedded theories of attention are briefly given below (for reviews see Anderson, 1993; Anderson & Lebeire, 1998; Anderson et al., 2004; Anderson, Matessa, Douglass, 1995).

#### 3.2.1.1 Symbolic constructs in ACT-R

The symbolic part of the architecture is the central, goal-oriented production system which detects patterns and takes coordinated action. The production system is a module that contains a collection of if-then rules, which are also sometimes referred to as condition-action pairs for accomplishing tasks and coordinating cognition, perception and motor actions. The unit of cost in ACT-R is time. The production system decides which rule is fired at a given point in time, which by default is 50ms. Rule firing time is considered as the basic information processing step in ACT-R in which some declarative knowledge is retrieved and used to further the problem solution. The 'if' part of a production (referred to as the left-hand side or the 'condition' in the ACT-R literature) is a collection of matching patterns, whereas the 'then' part of the rule (the right-hand side or the 'action') consists of a series of actions to be taken when the rule fires. The actions are commands for the other modules or buffers.

### 3.2.1.2 Sub-symbolic constructs in ACT-R

The sub-symbolic component deals with making the system adaptive, stochastic and error prone, trying to match it with human behaviour. Two levels of parameter settings in ACT-R can be used to adjust the model's operations. SPP (set production parameters) is used to set/reset parameter values for a particular production. On a broader level, as opposed to this, SGP (set/show general parameters) is a way to generally fine tune the model using various settings. For example: (spp alertness-production :at 0.06), sets the firing time of a specific production to 60ms. On the contrary, (sgp :dat 0.050), Sets the overall rule firing time to 50ms.

In the case of multiple choices of matching productions, the internal conflict resolution mechanism of ACT-R is applied. In ACT-R, the utility module provides support for the production's sub-symbolic utility value, which is used in conflict resolution. This value is a numeric quantity associated with each production that can be learned while the model runs, or is specified in advance for each production.

Similar to making choices when productions conflict, activation functions are used to resolve memory retrieval conflicts where more than one chunk in memory matches. ACT-R has two types of memories, declarative and procedural memory components, which operate in a serial fashion. Utility and activation functions used for the conflict resolution mechanism in ACT-R are related to procedural mechanisms or memory mechanisms. It is not always the case that the production with the highest utility always gets fired, as ACT-R will choose stochastically among them, which can lead to a selection of productions that may not be well matched. Chunk activations are responsible for determining which (if any chunks) get retrieved and how long it takes to retrieve them (chunks are explained in section 3.2.1.3).

### 3.2.1.3 Modular design of ACT-R

ACT-R is built around many independent modules doing their work in parallel, some of which serve important place-keeping functions. For example, the perceptual/motor module (vision, auditory, manual) keeps our place in the world. The goal module keeps our place in the problem space and the declarative module keeps the place in our own life (memory). Information about where we are in these various spaces is made available in the buffers of the modules. A buffer – a mode of communication between modules – is used to relay requests for actions to its modules to query for its state. Since communications between the modules takes place through buffers, they cannot arbitrarily access any information. This restricts the processing to single production rule firing, but allows the modules to function in parallel. Modules may place chunks into their buffers. Chunks are elements of declarative knowledge in ACT-R and are used to communicate with buffers. A chunk is defined by chunk types, which are slot-value pairs. In short, modules can place a chunk into a buffer, modify the value of slots of a chunk, or clear the buffer.

Figure 3.1 illustrates the modular structure of the ACT-R architecture divided into three important components: ACT-R system, the environment with which the system is interacting and the iconic memory, which is a feature representation of the information on the screen. ACT-R can interact with the real world through operations like receive key or mouse press from screen and move its attention around the iconic screen.

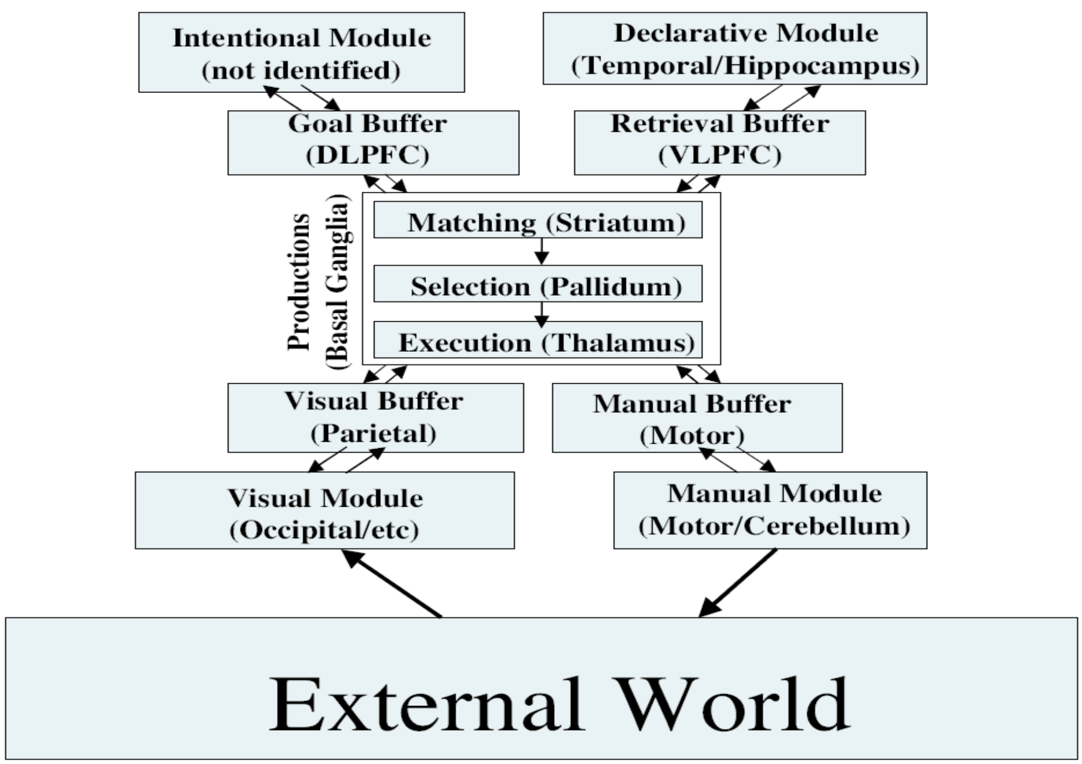



Figure 3-1: Modular design of the ACT-R architecture depicting how it interacts with the external world (Anderson et al., 2004, p.1037).

3.2.1.4 ACT-R theory and visual attention

The ACT-R theory has also been extended to include a theory of visual attention and pattern recognition, which enables production rules to direct attention to primitive visual features in the visual array. It builds upon theoretical concepts based upon the spotlight metaphor (Posner, 1980), the feature integration theory (Treisman & Gelade, 1980) and the guided search model (Wolfe, 1998). The advantage of having a theory of visual attention embedded in the architecture is twofold: (1) to model the information processing limitations in obtaining information from the screen and (2) to "remove the magical degrees of freedom in going from a description of an experiment to a cognitive model" (Anderson et al., 1995, p. 65). Both participants and the ACT-R system interact with the same experimental software (Anderson, et al., 1995). Embedding and making use of a lower level theory of visual attention or perception within a higher level theory of cognition gives any ACT-R model the power to interact and process the lower level visual interface, and hence ACT-R simulation interacts with the computer in the same way that a human subject would do. The implementation and descriptions of a few attention-related phenomena in ACT-R are discussed below (a few of these are later explored and modelled in Chapter 5):

3.2.1.4.1 Covert and overt attention

The standard ACT-R itself does not necessarily distinguish between overt and covert movements; however, there is an extension to the architecture available, called 'EMMA' (Eye Movements and Movement of Attention), which deals with eye movement data in ACT-R models (Salvucci, 2000; 2001). Using this module gives the power to record eye movements in a given task.

3.2.1.4.2 Bottom-up vs. top-down attention

The two buffers of the vision module in ACT-R 5.0 onwards, that is the visual buffer and visual location buffer, simulate the effect of the dorsal and ventral visual processing system, which is referred to as the what and the where system in attention. The automatic 'buffer stuffing' mechanism (the use of the set-visloc-default) in ACT-R 6.0 is in line with bottom-up processing. The set-visloc-default command sets the conditions that are used to place a new object into the visual-location buffer from the model's display. This means that when the visual-location buffer is empty and the model processes the display, it places one of the objects from the model's visual field into the visual-location buffer. If the default options (that is: attended new and screen-x lowest, (see section 3.2.1.4.3) are overwritten by changing the request parameters, attention can be engaged at a desired location as well, hence simulating a top-down effect.

#### 3.2.1.4.3 Inhibition of return

ACT-R itself has the ability to inhibit the system from returning to already attended objects, thus implementing the phenomenon of inhibition of return (Klein, 2000). This is achieved by using the request parameter ":attended new", which has the effect of attending to an object that has not been previously attended to.

For details on any of the ACT-R commands or mechanisms discussed here, see the ACT-R 6.0 User's Manual and Reference Manual at http://www.act-r.psy.cmu.edu.

### 3.2.1.5 ACT-R 6.0

Since this thesis converts the ACT-R 5.0 model of ANT into ACT-R 6.0, and then uses it further for exploring attentional networks, a brief description of what is new in the ACT-R version 6.0 as compared to ACT-R 5.0 is given. Chapter 5 later shows how the new features are incorporated as part of the migration from ACT-R 5.0 to ACT-R 6.0. It is important to mention here that ACT-R 6 is not backward compatible with the older versions.

ACT-R 5.0 was mainly an incorporation of the perceptual motor commands of ACT-R/PM, whereas ACT-R 6.0 now has the perceptual, motor, auditory and vocal modules fully integrated into the system. In addition, the meta process introduced in ACT-R 6.0 is essentially the system's event scheduler. It can control multiple models and holds the current simulated time and the sequence of actions to perform. Thus, there is a complete trace of every system event.

In addition, in ACT-R at any point in time multiple productions could match given the condition for selection, but due to the serial nature of processing in the architecture, only one rule can get fired, the one with the highest utility.

In ACT-R 5.0 the utility of a production is given by Equation 3.1, where Pi is an estimate of the probability that if this production is chosen, then the goal is achieved. G is the value of the goal and Cij is an estimate of the cost.

$$Ui = PiG - Cij \qquad \text{Equation 3.1}$$

In ACT-R 6.0, if there are a number of productions competing with the expected utility value Uj, then the probability of choosing production i is described by the Equation 3.2.

$$Probability(i) = \frac{e^{Ui}/\sqrt{2s}}{\Sigma_j {}^{Uj}/\sqrt{2s}} \qquad \text{Equation 3.2}$$

Here, the summation is over all productions that currently compete for firing, s is the expected gain noise, i.e. the noise added to the utility values, and e is the exponential function.

As explained by Anderson (2007), the current utility mechanism in ACT-R 6.0 "is just a simpler version that extends better to continuously varying rewards and has a clearer mapping to reinforcement learning" (p. 161, footnote 14).

#### 3.2.1.6 Applications of ACT-R

ACT-R has been used successfully in cognitive psychology, human computer interface design, education (cognitive tutoring systems) and other areas. In cognitive psychology particularly, it has been used to develop models in domains such as perception and attention, learning and memory, problem solving and decision making, language and communication, and cognitive development. In addition, ACT-R has also been used extensively to model individual differences, cognitive development and cognitive disorders (Gunzelmann, Moore, Gluck, Van Dongen & Dinges, 2008; Jongman & Taatgen, 1999; Jones & Ritter, 1998; Lovett, Reder & Lebiere, 1997; Jones, Ritter & Wood, 2000; Rehling, Lovett, Lebiere, Reder & Demiral, 2004; Ritter, Schoelles, Klein & Kase, 2007; Serna, Pigot & Rialle, 2007).

### 3.2.2 Soar

As opposed to the ACT-R architecture, which arose mainly out of an experimental psychology perspective, Soar emerged more from an artificial intelligence (AI) perspective. In the beginning, it was described as an acronym as SOAR – State, Operator And Result – but now it is just referred to as Soar (see soar FAQs, http://ritter.ist.psu.edu/soar-faq/soar-faq.html). It was created initially by John Laird, Allen Newell and Paul Rosenbloom at the Carnegie Mellon University, and the latest version (Soar-RL) is Soar Suite 9.0.

Soar is based on the theory of problem-space with certain states and goals. Behaviour is viewed as moving in the problem state by performing either internal or external actions. An internal action corresponds to desired actions, while the external action corresponds to what is observable in the environment. A goal in Soar is a desired situation, and a state is the representation of a problem solving situation. A problem space is a set of states and operators for the task and, finally, an operator transforms the state by some action. The long-term memory comprises of procedural, semantic and episodic memory. When Soar cannot proceed based on insufficient knowledge, the situation is called an impasse. Furthermore, in Soar there is no architectural conflict resolution mechanism and it is implemented through rule-based symbolic preferences (Lehmann, Laird & Rosenbloom, 2006).

Until recently, Soar was thought of as a purely symbolic architecture, but with recent changes in multiple learning mechanisms, multiple long-term memories and so on, sub-symbolism is also embedded in the architecture (Laird, 2008). Researchers have used the Soar architecture to develop sophisticated agents, one of the most popular being TAC-Air-Soar (Laird, Johnson, Jones, Koss, Lehman, Nielsen, Rosenbloom, et al., 1995; Tambe, Johnson, Jones, Koss, Laird, Rosenbloom & Schwamb, 1995), used for modelling fighter pilots' military training exercises. On the other hand, Soar has also been used to model human cognition (Miller & Laird, 1996).

For details about the architecture, see soar references. A comparison of the functionality of Soar with ACT-R and EPIC is given in 3.2.4

### 3.2.3 EPIC

In contrast to Soar and ACT-R, which are based on central cognition, the EPIC (Executive-Process Interactive Control) architecture (Keiras & Meyer, 1997) is based on peripheral cognition which determines task performance. In fact, EPIC's perceptual motor systems have also been adopted by other architectures to embed perceptual/motor capabilities.

EPIC has a central cognitive process, a production-rule interpreter, a working memory, sensors, and perceptual, auditory and occulomotor processes. The production rules make the decisions about a given cognitive task based on the content of the working memory. The cycle time has a mean of 50ms and all productions that match the conditions are fired in parallel. Thus, EPIC models are believed to have true parallel processing at the rule level. Another distinct characteristic of the architecture is a set of supervisory production rules that implement executive processes. EPIC does not have any mechanism incorporated for learning.

Like Soar, EPIC also does parallel matching and each rule that matches is allowed to fire; hence, there is no conflict resolution and it is up to the modeller to ensure that wrong things do not happen. Additionally, all processes work in parallel, so one process that is already working does not have to finish before the other process starts.

### 3.2.4 Comparison of cognitive architectures

Based on a review of the functionalities of ACT-R, Soar and EPIC described in the previous section, Table 3.1 gives a comparison of each in turn. The comparative criteria comprise of whether they are symbolic or hybrid, how they interface with the environment, the kinds of memories each architecture has, how each handles conflict, processes goals, their roots, having learning mechanism, relationship with neuroscience, error handling and other operational features (for more details on comparisons of these architectures, see reviews by Taatgen & Anderson (2008)).

Table 3-1: A functional comparison of ACT-R, Soar and EPIC.

| | **ACT-R** | **Soar** | **EPIC** |
|---|---|---|---|
| **Type** | Hybrid | Symbolic and non-symbolic | Symbolic |
| **Interface with environment** | Visual, auditory, motor modules, EMMA for eye movements | Soar I/O, links | Perceptual motor occulomotor |
| **Memories** | Procedural and declarative | Long term, working memory, episodic memory | Working memory |
| **Conflict resolution** | Utility values and activation | No architectural mechanism | No architectural mechanism |
| **Goal representation** | Goal buffer | Decision cycle | Control |
| **Processing of production** | Serial | Parallel | Parallel |
| **Learning** | Production compilation | Chunking, learning | None |
| **Relating model data with fMRI data** | BOLD Predictions module | None | None |
| **Principles of rationality** | Yes – means optimal adaptation to the environment | Yes - makes optimal use of the knowledge to achieve a goal | No |
| **Central theory** | Problem solving | Rational analysis | Embedded cognition |
| **Roots** | Cognitive/experimental psychology | Artificial intelligence | Human-computer interaction |
| **Availability of software and documentation** | Free download, tutorials, workshops, summer school | Free downloads, tutorials, workshops. | Free downloads, tutorials, workshops. |
| **Modelling environment and debugging tools** | Available Tcl/Tk | Available Tcl/Tk | Available Tcl/Tk |
| **Production/decision cycle firing time** | 50 ms default rule firing time. Firing time of individual rule can also be altered. | A decision cycle takes 50 ms | 50 ms default rule firing time |

## 3.3 Computational models of attention

Various computational models have been implemented to simulate attention-related tasks, but only the parallel distributed framework and models built using cognitive architectures are discussed in detail here (models of attention used in computer vision were briefly discussed in section 3.1.1.1).

### 3.3.1 Connectionist models of attention

There is a long list of models that have been implemented in the connectionist modelling paradigm. Neural net models based on the guided search theory are the feature-gate model (Cave, 1999) and the dynamic search model (Deco & Zhil, 2001). VISIT (Visual Search ITeratively) is another example of a connectionist model that combines the top-down and bottom-up approaches in object selection (Ahmed, 1991). Multiple Object Recognition and Attentional Selection (MORSEL) (Mozer, 1991; Mozer & Sitton, 1998) was developed to show links between visual attention and object recognition. Moreover, it was shown that MORSEL could be used to simulate other standard paradigms used in attention research such as cueing experiments (Posner, et al., 1980) and the flanker task (Eriksen & Eriksen, 1974). More connectionist models of attention examples are the SLAM – the SeLective Attention Model (Phaf, Van der Heidgen & Hudson, 1990) and SERR-SEarch via Recursive Rejection (Humphreys & Müller, 1993). The Stroop task and its variants have also been modelled in the literature using the connectionist modelling approach (Cohen, Dunbar & McClelland, 1990; Phaf, et al., 1990). For full details on any of these connectionist models, see relevant references.

In addition to using connectionist models to study normal subjects, a number of models have also been used to study neuropsychological disorders/deficits. For example, additional noise was added to Boltzman's activation function in the SERR model to show the effect of brain lesions. This is related to modelling visual agnosia, the impaired recognition of visually presented objects. Furthermore, conditions related to the effect of unilateral neglect have been modelled extensively in earlier discussed models such as SIAM, SERR and MORSEL by altering activity on one side or the other, thereby creating a spatial imbalance (Heinke & Humphreys, 2004).

### 3.3.2 Symbolic models of attention

There is an immense amount of literature which describes symbolic models of attention, but only selective models are mentioned here. The Stroop task (Stroop, 1935) is one of the most modelled tasks of conflict resolution in attention. Symbolic models of the Stroop effect have been modelled in its classic form (Altman & Davidson, 2001) and its variants (Lovett, 2005). These models simulate the Stroop interference that arises due to the conflict between the name of the colour and the ink in which the colour is written (e.g. the word 'red' printed in blue ink). Furthermore, a cognitive model of human performance on sustained attention to the response task (SART; Robertson, Manley, Andrade, Baddeley & Yiend, 1997) has been constructed (Peebles & Bothel, 2004). ACT-R Models have also been developed to simulate web page searches (Brumby &

Howes, 2004). Apart from modelling healthy human adult performance, some models simulate cognitive development transitions in children (van Rijn, van Someren & van der Maas, 2003).

## 3.4 Computational models of attentional networks

The attentional network task introduced in section 2.4.3.1 has been modelled using both the connectionist approach and cognitive architectures. A connectionist model of the ANT is based on the Leabra (local error-driven and associative, biologically realistic algorithm (O'Reilly & Munakata, (2000)) framework (Wang, Fan & Yang, 2004; Wang & Fan, 2007). A symbolic model of the ANT has been implemented using the cognitive architecture of ACT-R 5.0 (Wang et al., 2004). Both of these implementations are described briefly in the next section. The ACT-R 5.0 model of the ANT has been re-implemented and extended in this thesis to further explore the behaviour of attentional networks.

### 3.4.1 Connectionist model of attentional network test

This is a biologically inspired connectionist implementation of the attentional network test to explore the interplay of the various attentional networks from a computational perspective (Wang & Fan, 2007). This neural network model is implemented in PDP++ in the framework of Leabra (O'Reilly & Munakata, 2000).

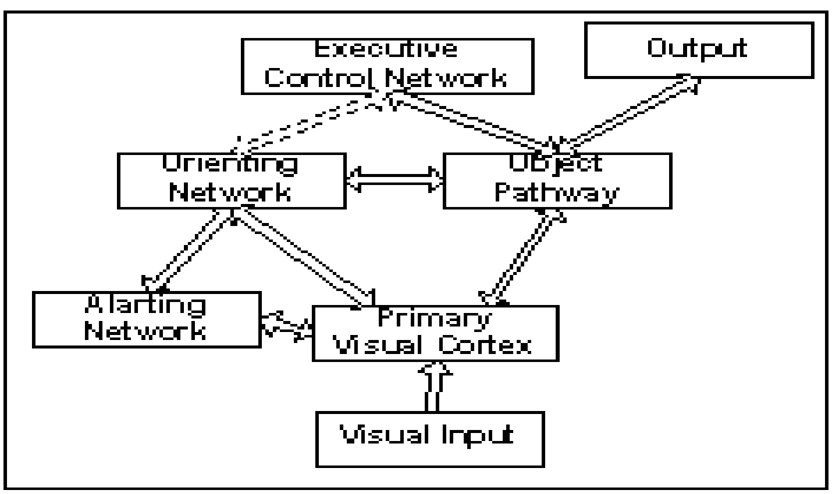



Figure 3-2: Functional components of ANT implementation on PDP++ using the Leabra framework (Wang & Fan, 2007, p. 1680). (The word 'alerting' is misspelled in the source).

The structure of the model is shown in Figure 3.2. Apart from the functional components for alerting, orienting and executive control, the modules for perception (visual input and primary visual cortex), object recognition (object pathway) and response (output) are also implemented. To describe the basic functionality, the model works as follows: a cue alerts the visual module, which later activates the orienting network to prepare it for the incoming stimulus. When a cue is a spatial cue, it will further narrow down the region of orienting, thus having another bidirectional link with the object-pathway module which actually determines the direction of the arrow. In case of conflict, that is when the stimulus is flanked, the executive control network is activated, finally producing the output. Note that all links are bidirectional except for the one from the visual input module, which obviously makes sense.

### 3.4.2 Symbolic model of the attentional network test

A symbolic model of the ANT has been previously implemented in ACT-R 5.0 (Wang et al., 2004). As the authors suggest, there are two objectives in developing the model. Firstly, the idea is to be able to see how the network behaviour can be implemented using an architecture. Secondly, presenting a symbolic implementation would also help in cross-validating the model with the earlier connectionist implementation of the test.

Looking at the design of the model, six distinct modules are involved in performing the generic ANT trial, which are depicted in the flow chart in the Figure 3.3 that shows the flow from the time of the appearance of the stimulus to the giving of a response. The design which is divided logically into six stages of processing, amalgamated to perform one generic ANT trial, is described below:

1. Fixation and cue expectation: The trial starts with a fixation “+”, indicating the beginning, which is then followed by either a cue or a direct stimulus. The cue can be one of four types – centre, top, bottom or double.
2. Cue or stimulus: In a non-alerting condition it is possible that no cue appears and a stimulus pops up directly.
3. Cue processing: Depending upon the type of cue, appropriate action needs to be taken by the model. For example, when a top cue is detected, the model determines whether there is a bottom cue as well; this means that it is a double cue. In this case, since the exact location is not known, the attention remains diffused between the two

locations. The model randomly keeps the focus of attention in one of the two places (depending upon which visual location was placed in the buffer from the visual scene). If only a top or bottom cue appears, but not both, then this is remembered as a spatial cue. In this case, attention is moved to the location of the cue and a stimulus is expected here, hence shifting attention to this particular place prior to the appearance of the target. In the case of a centre cue, there is no indication of where the stimulus will appear but there is an alert that the stimulus is coming, so attention remains at the centre.

4. Stimulus expectation: At this stage a stimulus is expected next. This is like a wait state until the event scheduler sets a flag in the task representation part of the model to indicate that it is time for the stimulus to appear. Consequently, the state ‘wait’ is reset to ‘targeting.’
5. Stimulus processing: Once the row of arrows appears, the objective is to encode the centre arrow and determine its direction. Depending on the preceding cue conditions, the focus of attention will be found. In the case of conditions other than a spatial cue, attention will have to be moved from the current location to the location of the stimulus. Due to the flanker effect, distracters could be erroneously selected and the model may have to refocus to target a location to determine the direction of the arrow. In the case of a congruent condition, the processing is simpler and quicker. In either case, once the direction of the centre arrow is determined, the model proceeds to respond.
6. Responding to stimulus: Depending upon the direction of the arrow, the key-press “f” or “j” is performed by the model. Simulating the non-deterministic behaviour of humans, the model is designed to make mistakes

These six functional components are mapped into 36 rules that cover all the possible scenarios; however, all rules are not fired in any one particular trial and will fire depending upon the cue or stimulus. In the case of multiple choices, the internal conflict resolution mechanism of ACT-R is applied. The time from stimulus presentation to the key press is recorded as the reaction time. The model is evaluated using the data set from the human ANT experiment (Fan et al., 2002).

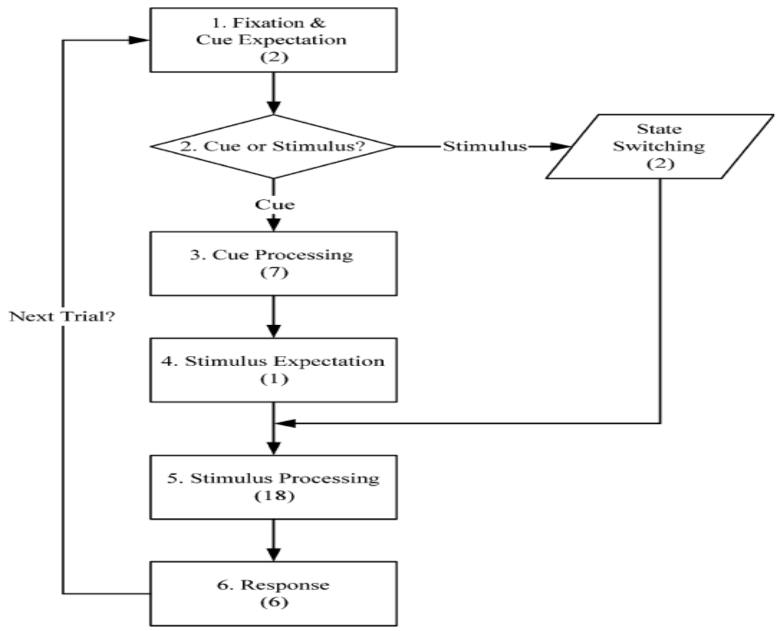



Figure 3-3: A functional decomposition of the ANT implementation on ACT-R 5.0. The numbers in the parentheses indicate the number of productions associated with each step (Wang et al., 2004, p. 124).

### 3.4.3 Comparison of connectionist and symbolic model of ANT

Wang and colleagues also attempted to primitively link and compare the two models of the ANT (Wang, Fan & Yang, 2004). Combining the two types of ANT models (ACT-R and Leabra), the authors presented a multilevel model to cross-validate the two types of modelling and looked at the computational links at each level. For example, a single-rule firing (40ms) was mapped to roughly three Leabra cycles (Wang, Fan & Yang, 2004). Furthermore, RT (ms) = 12.1 * RT (cycle); both models fitted the human data with a correlation of >= 0.94.

Table 3-2: Comparison of human data (Fan et al., 2002), ACT-R model of ANT (Wang et al., 2004) and Leabra model (Wang et al., 2007).

| | | Reaction times | | |
|---|---|---|---|---|
| Cue | Target | Human (ms) | ACT-R Model (ms) | Leabra Model (cycles) |
| No-Cue | Neutral | 525 | 545 | 44 |
| | Congruent | 528 | 580 | 45 |
| | Incongruent | 605 | 686 | 54 |
| Centre | Neutral | 480 | 495 | 41 |
| | Congruent | 485 | 526 | 39 |
| | Incongruent | 570 | 615 | 45 |
| Spatial | Neutral | 440 | 445 | 38 |
| | Congruent | 445 | 478 | 36 |
| | Incongruent | 505 | 525 | 41 |

### 3.4 Chapter summary

This chapter provides an overview of computational modelling in general and the computational modelling of attention specifically. Various approaches to computational cognitive modelling, namely computer vision modelling, connectionist paradigm and symbolic modelling, are described. An important strand of symbolic modelling is found in cognitive architectures, which are elucidated in detail. A few popular architectures like EPIC, Soar and ACT-R are explained; however, ACT-R is described in great length as it is used for modelling in this thesis. Examples from the literature are given for both connectionist and symbolic models of attention. The ACT-R 5.0 model of ANT (Wang et al., 2004) is described in detail. Extensive use of the source code for Wang et al's model, supplied by the authors, was made in developing the model presented in this thesis. A description of the source code for Wang et al's model and how it is modified and extended, and converted to ACT-R 6.0, is presented in Chapter 5. In the end, different models of the attentional network test (ANT) are described and compared.

Having introduced the different modelling paradigms and cognitive architectures, the next chapter establishes the rationale for using computational cognitive modelling as a research tool and the reasons for choosing the ACT-R architecture in this thesis.

# 4. Research Methodology

> The purpose of models is not (just) to fit data but to sharpen the questions.
>
> (Karlin, 1983)

The aim of this chapter is to establish the motivation for using cognitive modelling as the research methodology in this thesis, and ACT-R as the cognitive architecture. Further, the chapter describes, in the context of modelling, what is meant by goodness-of-fit and how cognitive models are generally evaluated statistically against human data. It is important to address and understand the issues with model validation in order to build computational models in a principled way that are faithful representations of human experiments.

## 4.1 Cognitive modelling as a useful research tool

Attention has been researched using a wide array of techniques ranging from behavioural experiments, neuroimaging studies, physiological recordings, case studies of brain damaged patients, and so on. This thesis applies the computational cognitive modelling approach towards advancing our knowledge and understanding of attention in the light of attentional network theory.

It is strongly argued in the literature that computational models are a useful tool for explaining and testing theories of cognition. It is suggested that "cognitive modelling fills the 'theoretical vacuum'" (Miller, Galanter, & Pribram, 1960, p. 11) between cognition and observable action by specifying a "detailed mechanistic process that is actually sufficient to generate the phenomena under study" (Simon & Wallach, 1999, p. 1)). The advantage of modelling is twofold: (1) to investigate the effects of experimental manipulations through simulation, and then (2) based on the insight gained from the modelling process, make predictions that may motivate new theoretically motivated experiments.

Based on the literature review, many cognitive modelling benefits have been suggested. It is believed that cognitive models do not allow ambiguity or ensure clarity and completeness in the steps of the cognitive process/behaviour. In addition, cognitive models provide a means for better evaluation, objective explorations and testable predictions of the theory being modelled. Another important characteristic of cognitive models is serendipity and emergence, which provide a whole new way of understanding and explaining the phenomenon under study. Given the objective nature of cognitive models, each concept needs to be defined specifically, which eliminates all fuzziness in a theory. In addition, creating models in the constraints of the architecture ensures that the model is not ad hoc, but inspired rather by a strong theoretical framework based on psychology theories (Dawson, 2004; Fum, Missier, Stocco, 2007; Lewandowsky, 1993; Stewart, 2005; 2006).

Furthermore, in the context of the progression/degradation of a disease or cognitive development, modelling can be utilised as a very useful tool. In psychophysical experiments, dealing either with the progression/degradation of performance of patients or monitoring and studying children's performance is considered difficult and tedious, because it may involve observations over a long span of time. Cognitive modelling can be a useful tool in such contexts, because it has the flexibility to first model some baseline behaviour on a cognitive task, and then manipulate one or more variables while reliably controlling all the other variables. Hence, a model can be used to study the impact of one developmental mechanism keeping the others constant. Researchers have shown that model behaviour can be altered by making changes to the knowledge retrieval capability of the model, the procedural rule based system, or by making plausible changes to the symbolic/sub-symbolic components of the architecture (Serna, et al., 2007). It has also been established that making changes to the cognitive model using the underlying architecture is a very useful way to "compare and test potential developmental mechanisms" (Jones, et al., 2000, p. 93).

## 4.2 Why use ACT-R in this thesis?

Various modelling approaches and cognitive architectures were discussed in Chapter 3. Section 4.1 discussed the usefulness of cognitive modelling as a research tool, but this section gives further reasons for choosing the ACT-R cognitive architecture for the modelling work carried out in this thesis.

A question that can be asked here is whether or not it is possible to construct the ANT models using a connectionist approach to computational modelling or, for that matter, any cognitive architecture other than ACT-R (the connectionist and symbolic approaches were previously explained and contrasted in section 3.1.1.2 and 3.1.1.3, and various cognitive architectures explained and compared in section 3.2). The answer to this question is twofold. Firstly, although it is possible to carry out a PDP implementation of an ANT (in fact, a basic implementation already exists in the leabra framework (Wang et al., 2007), briefly described in section 3.4.1), I chose to use symbolic modelling. It is posited here that the performance on an ANT modelled using a symbolic approach will produce enough power to simulate the components of attention at a level where productions will directly correspond to sub-processes of attention. This makes it easier to show sub-processes being mapped to one or more productions, and the timings of one or more productions can be varied to simulate different affects. Although the modelling work in this thesis could have been produced using a connectionist approach, it was by choice to use a cognitive architecture.

The second question that needs to be addressed here is why ACT-R has been chosen over other cognitive architectures. All cognitive architectures have their strengths and weaknesses. Researchers have also given useful guidelines on how to choose a cognitive architecture based on a given task (Ritter, 2004; Johnson, 1997). For example, it is suggested that Soar, for instance, provides greater support when working with larger knowledge bases, but not detailed timing predictions (Byrne, 2001).

While choosing a cognitive architecture for creating a model, it is important to consider the functionalities required by the model and what features/provisions the architecture offers for their implementation. Therefore, based on the specific functionality required in modelling the ANT performance and the comparison of the three architectures ACT-R, EPIC and Soar (given in section 3.1.4), the reasons for choosing ACT-R over other architectures are given here. The main functionality and support required from a cognitive architecture to implement a psychologically plausible simulation of performance on ANT is described below in detail.

### 4.2.1 Interface with the environment and event sequencing

Interaction with the environment in the form of auditory, visual and motor interfaces is required which are supported by the visual, auditory and motor modules of ACT-R. Initially ACT-R had embedded EPIC's perceptual/motor modules, known as ACT-R/PM, which were later made into a complete component in ACT-R 5.0 onwards (in version 6.0, even the pm suffix from the parameters was removed, e.g. pm-run became run, pm-proc-display is now only proc-display). Soar also has IO links that can be used for interfacing with the environment, and EPIC has a device window to interact with the environment, which is similar to the device window in ACT-R 6.0. In addition, in order to give a temporal sequence of events, ACT-R 6.0 has introduced an event scheduler; Soar and EPIC do not have such a feature.

### 4.2.2 Conflict resolution of competing production

According to optimality in ACT-R, in the case of a conflict or multiple choices between procedural or memory retrieval, ACT-R would choose the production/memory retrieval with the highest utility, i.e. the one with the lowest expected cost and the highest expectancy of probability of success.

Soar's approach in the context of a conflict is to find knowledge to decide between strategies. In Soar there is no architectural conflict resolution mechanism, and it is generally handled by rule-based preferences that carry out binary comparisons such as 'O1 is better than O2, O2 is not as good as O3', and so on. Conversely, ACT-R has an architectural mechanism that deals with choosing between conflicting productions and matching chunks from the memory. Nevertheless, this does not mean that Soar cannot handle conflict; it is just not a built-in mechanism of the architecture and has to be handled symbolically. EPIC also has no architectural mechanism to handle conflict. So, both Soar and EPIC do not have any architectural mechanism to handle conflict, however it can be handled symbolically.

### 4.2.3 Production processing

For modelling the performance of ANT, simple serial rule firing is required; there is no real need for parallel rule firing. It is important that only one rule fires at a time, and if there are multiple matching rules, the conflict resolution mechanism comes into play. The ability to have explicit rule firing time for each rule – and at the same time have varying rule firing times for individual productions – is also an important requirement based on the design of the model and the data fitting process. It has been said about ACT-R and Soar that ACT-R is a "mellow doer", whereas Soar is a "worried thinker" (Anderson, 2007, p. 231). Soar at each step just deliberates on what to do next, whereas ACT-R just fires a rule when it matches. Both Soar and EPIC can have multiple instantiations and can fire multiple productions at once; however this is not really required for modelling work in this thesis.

### 4.2.4 Sub-symbolic mechanisms

ACT-R is a hybrid architecture, as opposed to EPIC or Soar (Soar recently embedded some sub-symbolic components to handle memory (Laird, 2008). The sub-symbolic constructs of ACT-R, e.g. inducing noise in the system for adding stochastic behaviour for inducing errors and randomness, are some of the required features for modelling the performance on the ANT.

In psychological behaviour, errors are generally categorised as errors of omission or errors of commission. Omission errors refer to the subject's capacity to recall certain things, while commission errors refer to the subject choosing wrong things; these could be associated with memory retrieval errors or even procedural/operational errors. Utility values and random noise are used to induce errors in ACT-R models (Lebiere, Anderson & Reder, 1994; Byrne, 2003).

### 4.2.5 Architectural mechanisms to simulate attention-related phenomena

One very important feature of the ACT-R architecture is that it has explicitly embedded theories of visual attention within the theory of the architecture. For example, a mechanism in ACT-R simulates the buffer stuffing concept of attention (see section 3.2.1.1). These architectural mechanisms dealing with the theories of attention are not part of the Soar or EPIC theories.

Table 4-1: Functionality required from the architectures for modelling performance on the ANT.

| | ACT-R | Soar | EPIC |
|---|---|---|---|
| **Interface with environment** | Visual, auditory, motor modules, EMMA for eye movements | Soar I/O, links | Perceptual motor occulomotor |
| **Temporal sequence of events** | Event scheduler | None | None |
| **Conflict resolution** | Utility values and activation | Handled symbolically | None |
| **Processing of production** | Serial | Parallel | Parallel |
| **Production/decision cycle firing time** | 50ms default rule firing time. Firing time of individual rule can also be altered. Only one rule is selected for firing | A decision cycle takes 50 ms, although rules may fire in parallel | 50ms default rule firing time, but rules can fire in parallel |
| **Sub-symbolic mechanism** | Hybrid | Symbolic and non-symbolic | Symbolic |
| **Dorsal/ventral systems of visual attention** | Visual-location buffer and visual buffers | None | None |
| **Showing bottom-up/top-down process of visual attention** | Set-visloc-default function represent bottom-up processing and varying it's request parameters gives the affects of top-down processing | No such architectural feature | No such architectural feature |

The main functionality and support required from a cognitive architecture to implement a psychologically plausible simulation of performance on ANT is summarised in Table 4.1.

## 4.3 Model evaluation techniques and goodness-of-fit criteria

The main idea of discussing goodness-of-fit criteria here is to establish that the models implemented in this thesis are veridical simulations of the human studies and, hence, faithful representations of the experiments (in other words, the subject taking the test). This is one of the most important and debated aspects of cognitive modelling insofar as it addresses the problem of establishing how adequately a model (producing concrete numerical measures) implements and reflects those aspects of the real world that it is designed to model. "Exploring the match between a model and human data is an important means of understanding the human mind. Finding a good fit involves detailed explorations of mechanisms and processes – the result is a detailed understanding of what affects performance in what ways" (Sun, 2009, p 126).

The debate on the goodness-of-fit of a model was initiated by Roberts and Pashler (2000), and resulted in the exchange of many useful ideas. One of the concerns has been that the parameter fitting can be applied to fit everything and anything. Additionally, since the model is based on the theory it will have an a priori fit to the model and thus cannot say anything about the validity of the theory. Schunn and Wallach (2005), in response to Roberts and Pashler's (2000) arguments, posited that exploring and achieving a good fit to the model itself is not a trivial task. Care should be taken by the modeller to avoid over-fitting, and practice caution in using free parameters (a free parameter is the one for which there is no value from the theory). In addition, given that cognitive architectures themselves are based on extensive psychological experiments, they reduce the number of free parameters and bound the dangerous pitfalls of ad hoc theorisation. It is important that the model is based on the underlying theory and not merely a process model of the task.

It is believed that computational models should correspond to not only producing the same behavioural outcome, but also the same qualitative and quantitative behaviour seen in human performance (Sun & Ling, 1998). It is also suggested that a successful model will match the human data on multiple counts (Simon & Wallach, 1999) and that there should be a correspondence on different levels and measures of evaluation between the model and the human study, as given as follows:

- Product – perform the same ultimate objective, e.g. key press etc.
- Intermediate steps – problem solving strategies etc.
- Temporal – latency results.
- Error - accuracy results.
- Context dependency - effect of impairing the model, e.g. in a disease.
- Learning – effect of practice and rate of improvement.

For the models implemented in this thesis, parameter fitting has been undertaken with caution through recourse to theoretical evidence, wherever possible. Furthermore, models in this thesis refrain from over-fitting parameters or using too many parameters by using a minimal number of parameters. The specific use of parameters and data fitting is explained in the design and data fitting sections for each model in Chapters 5 to 8. It is apparent from the results and evaluation sections of each model in this thesis that all of the above measures have been addressed at some point or the other in the modelling work undertaken in this study.

### 4.3.1 Statistical techniques for evaluation

In relation to statistical analysis for model validation, the standard practice, as observed in the works of researchers and recommended in the modelling community (Kobayashi & Salam, 2000; Fum, et al., 2007; Stewart, 2005; 2006), is either to use linear correlations (r or $r^2$ ), root mean squared deviations (RMSD) or mean absolute deviation. Confidence intervals and equivalence testing have also been suggested (Stewart, 2005; 2007). Another measure suggested as a model validation criterion in other ACT-R models is to show that all the measures fit in a 20% interval of the human data (Card, Moran, Newell, 1993).

Correlation basically measures whether the model's behaviour varies across different measurements in a manner similar to that exhibited by human behaviour. The measurement ranges from -1 to 1, with zero meaning that there is no relationship between the two sets of data, and 1 indicating that whenever one value changes, the other also changes linearly. A negative 1 (-1) indicates that the change is in the opposite direction. Correlation (r) is calculated as follows ($r^2$ is simply the square of the value of r):

$$r = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}\sqrt{n\sum y_i^2 - (\sum y_i)^2}}$$ Equation 4.1

Another common statistical measure of model validation is calculating the mean squared difference, which represents the size of the average difference between the model and the reality. There are variations of this measure, namely Root Mean Squared Difference (RMSD), Mean Squared Deviation (MSD) and Mean Deviation (MD). This thesis uses the RMSD, which measures how different the two data sets are by taking the difference in latency between the model and subject data, squaring them, averaging them together, and then taking the square root. The formula for calculating the RMSD is given below:

$$RMSD = \sqrt{\frac{\sum (x_i - y_i)^2}{n}}$$ Equation 4.2

## 4.4 Discussion and chapter summary

In this chapter, cognitive modelling, which is used as the research method in this thesis, is argued to be an important research tool in the study of attention. Using cognitive modelling, this thesis attempts to model not only healthy adult performance on the ANT, but also modifies models to simulate the behaviour of attention-compromised patients and that of children. It is posited that the ACT-R architecture is useful for modelling human cognition and is robust in modelling traditional, experimental and psychological data, as modelled in this thesis. The discussion on why ACT-R is chosen for modelling in no way suggests that it is the only way to model performance on the ANT; rather, it seems like a more viable or appropriate choice and has therefore been used in this thesis. As part of any future work, a more sophisticated connectionist model or a Soar model could be designed and compared with the ACT-R implementation to see if more insight can be gained into the theory of attentional networks. A discussion on model validation describes how this thesis validates models against human data. Goodness-of-fit criteria and statistics used for all the model validations in this thesis are described.

The methodology adopted in the following chapters of this thesis is first to simulate the healthy adult performance on the ANT, and then to make psychologically plausible changes to the model to simulate certain effects or variances that may not have been part of the human study. Goodness-of-fit criteria, as outlined by the literature, are followed as closely as possible in this thesis. For example, multiple measures are shown to be good fits, a minimal number of parameters are used, and modification and implementation of the process models are based on theoretical grounds.

Just to recap, up to this point, Chapters 2 and 3 have given a detailed background about attention and computational modelling. Chapter 4 has established why cognitive modelling – and specifically the ACT-R cognitive architecture – is used in this thesis. The next four chapters (5-8) explain how the aims of the thesis (laid out in section 1.2) are performed through utilising the chosen research methodology.

# 5. Modelling of Attentional Networks

This chapter has two main sections. Section 5.1 explicates the implementation of the ACT-R 6.0 model of ANT (model-1), which is adapted from the earlier ACT-R 5.0 model (Wang et al., 2004). The reimplementation involves changes related to both symbolic and sub-symbolic components of the model. In addition, the psychological plausibility of the network implementation is also described. Model-1 is evaluated statistically against data from human study findings (Fan et al., 2002; Rueda et al., 2004) and further compared with the ACT-R 5.0 model data (Wang et al., 2004). Later, the model is also fitted to run with a firing time of 50ms and, based on the results, comments are made about the 50ms issue raised about Wang et al's (2004) model.

In section 5.2, model-1 is extended to incorporate the effect of invalid cueing and disengagement (Posner et al., 1984; 1987). This extended design, which is referred to as 'model-2', simulates the theory of spatial orienting (section 2.3.1.2.1), explaining how the three sub-components of orienting – disengage, move and engage – can be simulated.

Both model-1 and model-2 are used further in Chapter 6 for exploring the interactions of networks, in Chapter 7 to simulate the performance of Alzheimer's disease and mTBI patients' performance on the ANT, and in Chapter 8 to simulate children's behaviour on the ANT.

## 5.1 Model-1 - Reimplementation of the ANT in ACT-R 6.0

### 5.1.1 Task representation

As introduced in Chapter 1 (section 1.4) and described in Chapter 2 (section 2.4.3.1), the Attentional Network Test (ANT) (Fan et al., 2002), a 30-minute reaction time test, is a combination of cueing experiments (Posner, 1980) and a flanker task (Eriksen & Eriksen, 1974). It is designed to measure the efficiencies of the alerting, orienting and executive control networks in a single task. The source code and online test plus other ANT-related material are freely available at http://www.sacklerinstitute.org/users/jin.fan/.

Figure 5.1 shows a sketch of the ANT's design. After a short fixation period, 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 fixation and consists of a central arrow surrounded by flanking arrows that can either point in the same (congruent) or in the opposite direction (incongruent). The ANT uses differences in reaction time between conditions to measure the efficiency of each network. Subtracting congruent reaction times from incongruent target trials provides a measure of conflict resolution and assesses the efficiency of the executive attention network. Subtracting reaction times obtained in the double-cue condition from the reaction time in the no-cue condition gives a measure of alerting due to the presence of a warning signal. Subtracting the reaction times of targets at the cued location (spatial cue condition) from trials using a central cue condition gives a measure of orienting, since the spatial cue, but not the central cue, provides valid information on where a target will occur. Visual stimuli are presented on the screen, which requires maintenance of an alert state, spatial orienting to cued stimuli and control of competing resources. The formulae given in Equations 2.1-2.3 (section 2.4.3.1) are used to measure the efficiency of each of the three attentional networks.

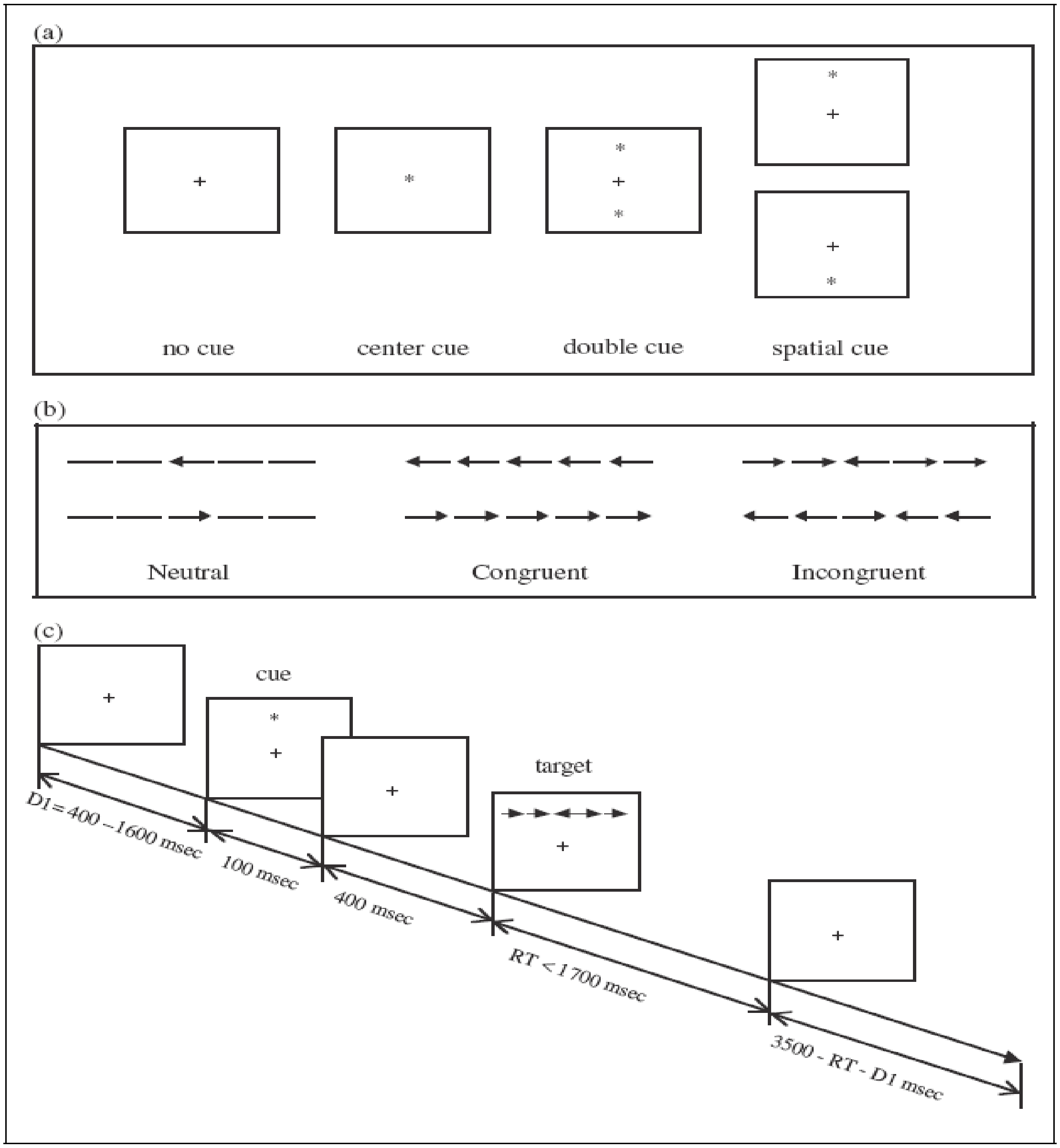



Figure 5-1: A sketch depicting the design of an ANT trial (Fan et al., 2002, p. 341).

The task for the participant taking the test is to determine the direction of the target arrow, which is surrounded by distracters. The target may be surrounded by arrows either in the same or the opposite direction, hence giving rise to a congruency/incongruency effect. Both latency and accuracy data are recorded. It was observed in the human study that reaction times are faster and accuracy rates are higher in the case of congruent and cued trials.

### 5.1.2 Design and functionality of model-1

The source code for the existing model of the ANT which is in ACT-R 5.0 (Wang et al., 2004) is modified to suit version 6.0 of ACT-R which is referred to as model-1. The major functionality of the model, remains the same as in Wang et al’s model (2004) which is briefly summarized below to facilitate the understanding of discussion of model-1 here. The design is divided logically into six stages of processing, amalgamated to perform one generic ANT trial listed below:

1. Fixation and cue expectation
2. Cue or stimulus
3. Cue processing
4. Stimulus expectation
5. Stimulus processing
6. Responding to stimulus

Figure 5.2 illustrates the state and flow diagram of an ANT trial beginning with a start state and ending at a stop state (indicated by filled black circles). All the states (S1 – S16), the flow of control between the states and the corresponding processing stages are clearly indicated. Conflict resolution mechanism is depicted as processes in rectangular boxes.

For example, if a sample trial consisted of a spatial, congruent condition, then according to Figure 5.2 and the given states, a sample trace would be:

> Start → encoding → fixating → noticespatialcue → anticipating → wait → targeting → focus → check → goahead → respond → done → refixating → stop/start.

The productions and states associated with each stage of processing are listed in Table 5.1, whereas a list of all the states that the goal buffer changes in the lifecycle of a single trial is given in Table 5.2. The six processing stages and sixteen states are the same as those used in Wang et al’s model (Wang et al., 2004). Additionally, a list and brief description of all the productions (from Wang et al's (2004) model and new productions introduced in ACT-R 6.0) are given in Table 5.3 later.

Table 5-1: For each processing stage, a list of associated states and productions.

| **Stages** | | **States** | **Productions** |
|---|---|---|---|
| 1 | Fixation and cue expectation | S1, S2 | P1, P2 |
| 2 | Cue or stimulus | S8, S9 | P3, P4 |
| 3 | Cue or stimulus | S3, S4, S5 | P5 – P11 |
| 4 | Stimulus expectation | S6 | P12 |
| 5 | Stimulus processing | S7, S9, S10, S11, S12, S13 | P13 – P30 (except for p25) |
| 6 | Response | S14, S15, S16 | P31-P38 |

Table 5-2: List of states used in model-1.

| | | | |
|---|---|---|---|
| S1 | Encoding | S9 | Shiftingattentiontostimulus |
| S2 | Fixating | S10 | Focus |
| S3 | Noticespatialcue | S11 | Refocus |
| S4 | Findmorecue | S12 | Check |
| S5 | Anticipating | S13 | Goahead |
| S6 | Wait | S14 | Response |
| S7 | Targeting | S15 | Done |
| S8 | Surprise | S16 | Refixating |

So, a number of productions and certain parameter settings are associated with each stage of processing above. These are responsible for controlling the execution of the model, deciding which rules are fired when, and controlling the behaviour of the system. The latency and accuracy results are produced and efficiencies calculated based on the latency results. Latency refers to the response time of the model from the time the stimulus appears to the time the response key "f" or "j" is hit, corresponding to the left and right arrow keys.  Accuracy refers to the percentage of correct responses produced by the model.

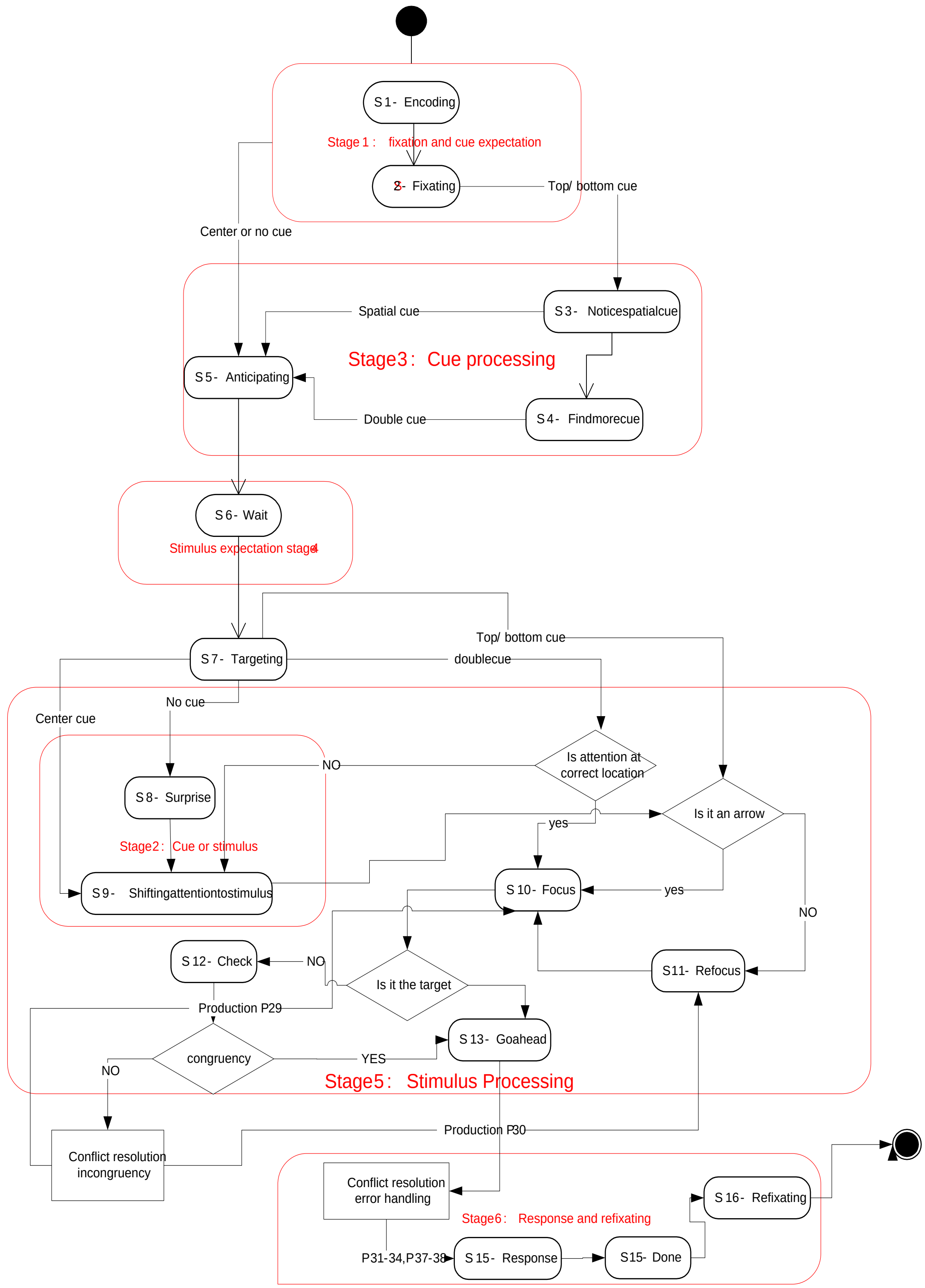



Figure 5-2: A detailed state and flow diagram for model-1. The initial and final states are indicated by generic symbols.

### 5.1.3 Implementation details of model-1: from ACT-R 5.0 to ACT-R 6.0

This section describes how the source code for the ACT-R 5.0 model (Wang et al., 2004) was adapted to suit version 6.0 of ACT-R. The changes are described in terms of (1) psychologically plausible explanations for the implementation of alerting, orienting and executive control networks, (2) symbolic production-based components, (3) sub-symbolic components of the model, (4) task setup and operational details, and finally (5) the incorporation of some new and important features of ACT-R 6.0 and their impact on the design of model-1.

#### 5.1.3.1 Implementation of the three networks

The crux of the model design which requires close examination is the implementation of the three networks of alerting, orienting and executive control. Therefore, this section describes the justification for implementing these networks based on evidence from the attention literature. Changes in the production and parameter settings in the network implementation are described in sections 5.1.3.2 and 5.1.3.3. Here, justifications from the psychological literature are provided, which were not completely found in Wang et al's model description, specifically for the executive control network (Wang et al., 2004). This gives better insight into the behaviour and working of the networks as given below:

##### 5.1.3.1.1 Alerting

Alerting is a state which helps in the preparation for perceiving a stimulus. There is evidence in the literature that an increase in alertness improves the speed of processing events (Posner, 1994; Posner & Raichele, 1990), so no alertness would result in a slowing down in response time. This slower reaction time is induced in the model through an extra production, which accounts for a state of surprise. The element of surprise leads to the firing of an extra production not-cue-so-switch-state-and-shift-attention [P4] to compensate for the effect of no alertness. As a consequence, the nocue condition corresponds to having no-alerting signal, whereas the double-cue condition alerts the model precisely of an incoming stimulus, but does not give any spatial orienting. The difference in latency between the no-cue condition and the double cue condition accounts for the efficiency of alerting for the model.

#### 5.1.3.1.2 Orienting

Orienting involves selecting specific information at the expense of ignoring others in a visual field (Posner, 1978). In the model, two properties of orienting are modelled here:

1. Based on the premise that orienting could be either bottom-up or top-down, the model simulates these two processes by making use of the buffer stuffing mechanism of ACT-R, which is implemented using the command set-visloc-default (this ACT-R feature was described in detail in section 3.2.1.4.2).

2. Another property of attention focusing applied here in the model is that if the cue type is spatially cued, then it is assumed that the focus of attention is already at that location when the stimulus appears; however, in the case of other cue types, the focus of attention has to be moved to the target location (Posner, 1980). This is simulated in the model through productions that have to shift the focus of attention in the case of non-spatial cueing.

#### 5.1.3.1.3 Executive control

In order to understand what could be a psychologically plausible way of modelling the executive control network, literature on executive functions was reviewed (discussed earlier in section 2.4.1.3). In the ANT, the control network is measured through the performance on the flanker effect, showing that at times, instead of the target, a location nearby may be selected due to distraction or even crowding of the scene (Pashler, 1998).

It is posited therefore that in modelling the flanker effect, model-1 is dealing with one component of executive function, namely response inhibition. Response inhibition (which is of interest in this thesis) is to act on the basis of choice by resisting inappropriate behaviour and responding appropriately (Davidson, Amso, Anderson, Diamond, 2006). There is evidence in the literature that, in order to explain this response inhibition, many researchers have agreed to the existence of a dual-process model that deals with two routes or pathways (de Jong, Liang & Lauber, 1994; Ridderinkhof, Scheres, Oosterlaan & Sergeant, 2005; Ridderinkhof, van der Molen & Bashore, 1995), referred to as (1) the direct response activation route and (2) the deliberate response decision process; both converging at the selective inhibition of activation as illustrated in Figure 5.3. This dual process architecture for understanding the flanker effect on target processing is the theoretical basis for implementing the executive control network in model-1.

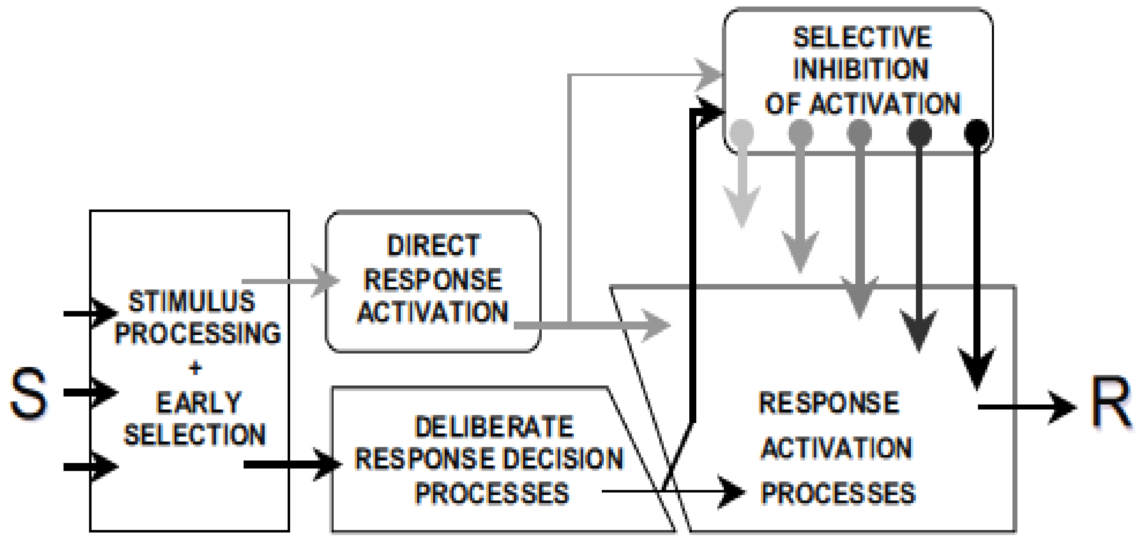



Figure 5-3: Elementary architecture of the dual-process model (Ridderinkhof et al., 2005 p. 1995).

Figure 5.4 shows the mapping of the dual-process model on the simulation of the executive control network in model-1. It shows that, accordingly, model-1 simulates the two routes of the dual-process model through two productions – [P29] and [P30] – and the selective inhibition of activation is handled through the conflict resolution ability of ACT-R (the utility values which determine the probabilities of productions being fired). The selective inhibition mechanism is associated with the ability to resolve conflict, and determines the likelihood of choosing each route. Response activation is the stage where motor programs are initiated or executed, for example in this case a key-press ‘f’ for the left arrow and ‘j’ for the right arrow.

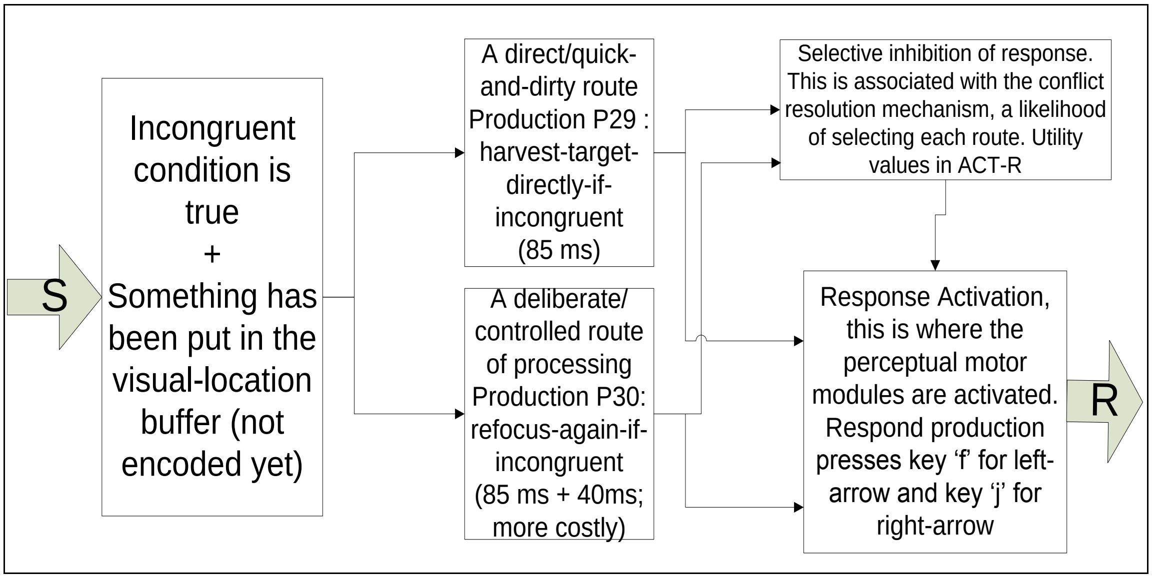



Figure 5-4: Based on the dual-process model (Figure 5.3), schematic working diagram of how executive control is implemented in model-1.

The following is how the dual-process model is applied in model-1. In the case of an incongruent condition, there are two routes: the direct route and the slower deliberate response decision process. To implement this, model-1 uses two productions with the same conditions (the same LHS) but different actions (different RHS) having two outcomes: (1) either process the target directly, using production harvest-target-directly-if-incongruent, [P29] or (2) refocus attention, which will result in the firing of an extra production, and then move attention to the target location (using production refocus-again-if-incongruent [P30]). The first strategy takes 85ms for a direct move-attention operation, whereas the second strategy costs 125ms (40ms + 85ms for an extra rule being fired for refocusing, and then move-attention). These are conflicting productions for which probabilities are set to resolve conflict and to choose which production will be fired. In the context of the dual-process model, the speed and efficiency of the response inhibition mechanism corresponds to the firing time of the two productions [P29] and [P30], and the utility values are based on which conflict is resolved. Therefore, the above guidelines from the cognitive control literature are used to implement the executive control network with conflicting productions and utility equations.

This dual-process model is also similar to that of Gratton and colleagues' (Gratton, Coles & Donchin, 1992) study, where they proposed that the processing of conflicting stimuli can take place in two phases: (1) A quick and dirty phase of processing and (2) a more controlled, focused phase in which the subjects select a particular location for processing (a costlier strategy). Gratton and colleagues (1992) also suggested that the results could be affected by the previous trial type, but model-1 does not incorporate the Gratton effect (1992) (for more details on the Gratton effect, see Gratton et al., 1992).

Having given a psychological basis for the implementation of the three networks in model-1 (the orienting and especially executive control networks were not explained like this in the Wang et al. (2004) paper), the sections to follow describe how the productions, parameters and other changes were made to reproduce model-1.

5.1.3.2 Symbolic components

This section describes which productions were retained from Wang et al's (2004) model and which were omitted. A description of the new productions, along with the details and rationales for changes made to the existing productions, is given. There are, in all, thirty-six productions in Wang et al's (2004) model. Out of these thirty-six productions, thirty-five are retained, one is omitted and two new productions are added. Table 5.3 lists all these changes in the productions in the model for each processing stage.

Production [P25] is omitted from model-1. In Wang et al's (2004) model, it was used to induce more errors and compete with production [P24], but the response times obtained in model-1's results were too high and the data did not fit with human data. This is explained further in section 5.1.3.3.2.

Furthermore, productions [P37] and [P38], which account for errors in the case of incongruent trials, are introduced, since there were no productions in Wang et al's (2004) model which induced extra errors in the case of incongruency. This is also explained further in section 5.1.3.3.4. All of the other productions remain the same with some syntactic and conceptual changes related to version 6.0 of ACT-R, as described in the section that compares the differences in the features of ACT-R 5.0 and ACT-R 6.0 given in section 3.2.1.5.

Table 5-3: List of productions for model-1 showing the same, new and deleted productions.

| Production # | ACT-R 5.0 Model Production name | Status in Model-1 |
|---|---|---|
| 1.Fixation and cue expectation stage | | |
| P1 | Notice-fixation | Same |
| P2 | Encode-fixation-and-waiting | Same |
| 2.Cue or stimulus distinction stage | | |
| P3 | Notice-something-but-not-a-cue | Same |
| P4 | Not-cue-so-switch-state-and-shift-attention | Same |
| 3. Cue processing stage | | |
| P5 | Notice-a-centre-cue | Same |
| P6 | Notice-a-top-cue | Same |
| P7 | Notice-a-bottom-cue | Same |
| P8 | Given-a-top-cue-find-a-bottom-cue | Same |
| P9 | Given-a-bottom-cue-find-a-top-cue | Same |
| P10 | Find-no-more-cue-so-spatialcue | Same |
| P11 | Find-no-more-cue-so-doublecue | Same |
| 4.Stimulus expectation stage | | |
| P12 | Anticipating-the-stimulus | Same |
| 5.Stimulus processing stage | | |
| P13 | Notice-stimulus-at-cued-top-location-and-attend | Same |
| P14 | Notice-stimulus-at-cued-top-location-but-a-neutral-item-is-selected | Same |
| P15 | Notice-stimulus-at-cued-bottom-location-and-attend | Same |
| P16 | Notice-stimulus-at-cued-bottom-location-but-a-neutral-item-is-selected | Same |
| P17 | Notice-stimulus-with-centercue-and-shift | Same |
| P18 | Notice-stimulus-with-doublecue-and-shift | Same |
| P19 | Notice-stimulus-with-doublecue-and-an-arrow-is-focused-on-so-attend | Same |
| P20 | Notice-stimulus-with-doublecue-but-a-neutral-item-is-focused-on-so-shift | Same |
| P21 | Attend-to-at-large-target | Same |
| P22 | Shift-to-at-large-target-from-a-neutral-item | Same |
| P23 | Harvest-target | Same |
| P24 | Goahead-responding-if-it-is-the-target | Same |
| P25 | Hurryup-responding-no-matter-whether-target-or-not | Production deleted |
| P26 | Attended-item-is-left-to-the-target | Same |
| P27 | Attended-item-is-left-to-the-target | Same |
| P28 | Goahead—responding-if-congruent | Same |
| P29 | Refocus-again-if-incongruent | Same |
| P30 | Harvest-target-directly-if-incongruent | Same |
| 6.Response stage | | |
| P31 | Decide-left | Same |
| P32 | Decide-right | Same |
| P33 | Random-left | Same |
| P34 | Random-right | Same |
| P35 | Respond | Same |
| P36 | Refixating-and-wait-for-next-trial | Same |
| P37 | Error-left | New production |
| P38 | Error-right | New production |

5.1.3.3 Sub-symbolic components

This section explains data fitting in terms of the fine tuning of parameters and the use of ACT-R's conflict resolution mechanism. It explains which parameters are retained, which are deleted and which are introduced and why. The difference in how the conflicting productions are handled in ACT-R 6.0 is elucidated. A separate sub-section on error modelling explains in detail how errors are handled differently from Wang's model (2004), and why.

5.1.3.3.1 Parameter fitting

The sub-symbolic part of ACT-R 6.0 model comprises various parameters such as rule firing time, noise to induce randomness, utility values set to deal with conflicting productions, and so on. Table 5.4 gives a list of all the changes in model-1 related to parameter fitting and the rationale for doing so (for a detailed description of each parameter, refer to ACT-R reference manual at http:// act-r.psy.cmu.edu/).

In model-1, non deterministic behaviour is induced through three parameters, namely 's', 'er' and 'esc.'. Parameter, 's' – the expected gain noise – is used to induce noise in the system. It defaults to 0, which means there is no noise in utilities; in model-1 the value used is 3. This standard is used in most of the ACT-R models found in the literature to induce noise. The enable randomness parameter, 'er', specifies how modules should operate deterministically. It can be set to t, which means act non-deterministically, or nil, which means act deterministically. The default value is nil. It specifies what methods should be used to break "ties" during conflict resolution and memory retrievals. The enable sub-symbolic computation parameter, 'esc', specifies whether or not modules should work in a purely symbolic fashion. The default value is nil, which means that modules should be purely symbolic. If it is set to t, then modules should use whatever sub-symbolic computations they provide (for example, a utility for production selection in the procedural module and activation for chunk selection from the declarative module).

The default action time 'dat' parameter specifies the default time that it takes to fire a production in milliseconds. The default value is normally 50ms, but in model-1 it is set to a faster firing time of 40ms[4], the reasons for which are discussed in detail in section 5.1.7. Some obsolete parameters that inform ACT-R 5.0 version were removed.

Table 5-4: Changes in parameter settings migrating from the ACT-R 5.0 model (Wang et al., 2004) to the ACT-R 6.0 model (model-1).

| **Parameter fitting from ACT-R 5.0 to ACT-R 6.0 of model of ANT Performance** | | |
|---|---|---|
| **ACT-R 5.0 model (Wang et al, 2004)** | | **ACT-R 6.0 model (model-1)** |
| Parameter name | Parameter description | Status in model-1 |
| :v t | Verbose, | Same |
| :er t | Enable randomness | Same |
| :dat 0.04 | Default action time, | Same |
| :egs 3 | Expected gain noise | Same |
| :pm t | Perceptual motor | Omitted, does not exist in ACT-R 6 |
| :act nil | Activation trace | Omitted, not needed, this is related to memory retrieval |
| :era t | Enable rational analysis | Omitted, does not exist in Act-R 6.0 |
| :esc t | Enable sub-symbolic computations | Same |
| :ans 0.3 | Related to activation equation in memory retrieval | Omitted, this is for randomness in activation, not required in this model |
| :ut -100 | Utility threshold to add randomness to system | Omitted, does not exist in ACT-R 6.0 |
| :p values | Probability values for handling conflict | Omitted, does not exist in ACT-R 6.0 |
| :u values | Utility values for handling conflict. | Used in place of :p values to resolve values, described in detail in section 3.2.1.5. |

#### 5.1.3.3.2 Conflict resolution and learning mechanisms

Utility values are used in conflicting productions that implement the executive control network in model-1. In section 3.2.1.5, the differences in representing and calculating utility values in both ACT-R 5.0 and ACT-R 6.0 are explained. In this section only the probabilities in Wang's model (2004) and how they are calculated in the ACT-R 6.0 model are described.

As shown in Table 5.4, the p values parameter is omitted. Instead, in ACT-R 6.0, utility values are calculated based on the formula given in Equation 3.2. The conflicting productions are [P29] and [P30] for incongruency and productions [P31]-[P34] and [P37],[P38] for modelling error.

[4] This is also the setting used by Wang and colleagues (2004) in the ACT-R 5.0 model, and my justification for retaining this is given in section 5.1.7

In Wang's (2004) model, the productions [P29] and [P30] have firing odds of 1:3. However, in model-1, fitting the human data, best values were produced with the following

```
(spp harvest-target-directly-if-incongruent :u 7)
(spp refocus-again-if-incongruent :u 15)
```

Here, the utility values of 7 and 15, according to Equation 3.2, correspond to probabilities of 0.125 and 0.875, or odds of 1:8. So, according to the data fitting, model-1 shows a greater probability of interference compared to Wang's model (Wang et al., 2004). The workings of productions [P29] and [P30] are explained below:

```
[P29] (P harvest-target-directly-if-
incongruent
 =goal>
    ISA        do-ant
    state      check
  =visual-location>
    ISA        visual-location
  =visual>
    ISA        text
    value      =value
    !eval! (notequal-arrow =value)
==>
  =goal>
    state      focuson
  +visual>
    ISA        move-attention
    screen-pos  =visual-location
  =visual-location>   )
```

[P29] checks the goal state which indicates that the goal state is 'check' and both visual-location and visual buffers are active. The action corresponds to the direct route of the dual-process model (Figure 5.4) where the state changes to 'focus' and 'move-attention' operation takes place.

This is the less costly option that takes 85ms to encode the location and then proceeds to respond; eval is a lisp macro which checks for the inequality of arrow directions.

```
[P30] (P refocus-again-if-incongruent
=goal>
    ISA        do-ant
    state      check
  =visual-location>
    ISA        visual-location
  =visual>
    ISA        text
    value      =value
     !eval! (notequal-arrow =value)
==>
  =goal>
    state      refocuson
  +visual-location>
    ISA        visual-location
  > screen-x    80
  < screen-x    100)
```

[P30] has exactly the same LHS as production [P29] but the RHS is different. Here a deliberate strategy is chosen where the model needs to explicitly refocus to the target location (that is fire another production) before performing the move-attention. This corresponds to the deliberate route of Figure 5.4.

This is the costlier option which takes 40 ms for an additional production fire and then 85 ms to move-attention before the model can proceed to respond.

To contrast what happens in the congruent condition, the production goahead-responding-if-congruent [P24] fires and proceeds to encode the object as follows:

```
[P24](P goahead-responding-if-congruent
  =goal>
    ISA       do-ant
    state     check
    =visual-location>
    ISA       visual-location
     =visual>
     ISA       text
     value     =value
     !eval! (equal-arrow =value)
==>
  =goal>
  state     goahead
  =visual>)
```

The arrow in the visual buffer and the target has the same value (congruency condition). The model is directed to respond left or right by firing the production goahead-responding-if-target, [P25], which checks the direction of the arrow and proceeds to encode the object.

5.1.3.3.4 Modelling error

For error handling, Wang's (2004) model uses conflict in two productions – [P24] and [P25] – and p values of 0.3 (competing with odds of 1:3). This production is omitted from model-1 because of extremely fast response times that did not match the human data.[5] In addition, the random-left and random-right productions compete with decide-left and decide right, while the p value parameter is set as 0.05, which corresponds to odds of 1:20.

Model-1 handles the error in two ways:

1. In the case of congruent trials, only {random-left, decide-left} and {random-right, decide-right} compete with probabilities of 0.02 and 0.97 (odds of 1:38, almost half of Wang's (2004) model's p values).
2. In the case of incongruency, the productions error-left and error-right also join the competition, so the productions {random-left, error-left and decide-left} and similarly {random-right, error-right and decide-right} compete with utility values of 5, 8 and 20. This corresponds roughly to the probabilities of 0.03, 0.05 and 0.92 respectively. These participate in the conflict when the flanker is incongruent, hence

[5] In the model code for ACT-R 5.0 the production *hurryup-responding-no-matter-whether-target-or-not* is commented out, but the paper (Wang et al., 2004) mentions that it is used, so there is some doubt about its use.

increasing the chances of error in the case of incongruency, which competes with the other error-related productions. Productions [P37] and [P38] compete with a low probability with the productions that produce correct responses. This is done based on observation of the human data and evidence from the literature, which indicate that in the incongruent condition the error rates were much higher as compared to neutral or congruent conditions (Eriksen, & Schultz, 1979). The new productions [P37] and [P38] are described:

| | |
|---|---|
| [P37] (P error-left<br>=goal><br>ISA do-ant<br>state goahead<br>=visual><br>ISA text<br>value "<"<br>!eval! *incong-condition*<br>==><br>=goal><br>state response<br>response "j") | [P37] checks on the LHS of the production if the goal state indicates that the model is ready to goahead, the encoded value in the visual buffer is a left arrow and that the flanker condition for this trial is incongruent. In that case the response given is ‘j’ which means right arrow; this is a deliberate incorrect answer. |
| [P38] (P error-right<br>=goal><br>ISA do-ant<br>state goahead<br>=visual><br>ISA text<br>value ">"<br>!eval! *incong-condition*<br>==><br>=goal><br>state response<br>response "f") | [P38] checks on the LHS of the production if the goal state indicates that the model is ready to go ahead the encoded value in the visual buffer is a right arrow and the flanker condition for this trial is incongruent. In that case the response given is ‘f’ which means left arrow; this is a deliberate incorrect answer. |

Different utility values were tried, most of which gave good correlations, but efforts were made to bring the RMSD down as low as possible. The utility values of random-left and random-right varied from 5 to 10, the values of error-left and error-right varied from 5 to 15, and the values of decide-left and decide-right varied from 10 to 30. Looking at the utility values of error and random productions, it is evident that the utility values of error productions [P37] and [P38] are higher than the utility values of random productions [P33] and [P34], which indicates that there is a lesser chance of responding randomly rather than making a mistake due to incongruency. Moreover, incongruency generally results in less accurate responses, as shown by the use of error productions.

Figure 5.5 demonstrates how random-right and decide-right productions compete, by giving a snapshot of the error handling in model-1. The left-hand side of both productions is the same, except that decide-right specifically checks the right arrow and random-right will respond randomly without doing a check. Which one of these productions is fired depends upon the utility values. All other modules are shown – the vision module interacting with the visual buffer, the motor module handling the key-press interacting with the motor module, and the device window. The goal buffer is shown to have a current goal state and the event scheduler is running continuously in the background. This diagram, however, does not show the error-right productions, assuming that the flanker condition in this trial is congruent.

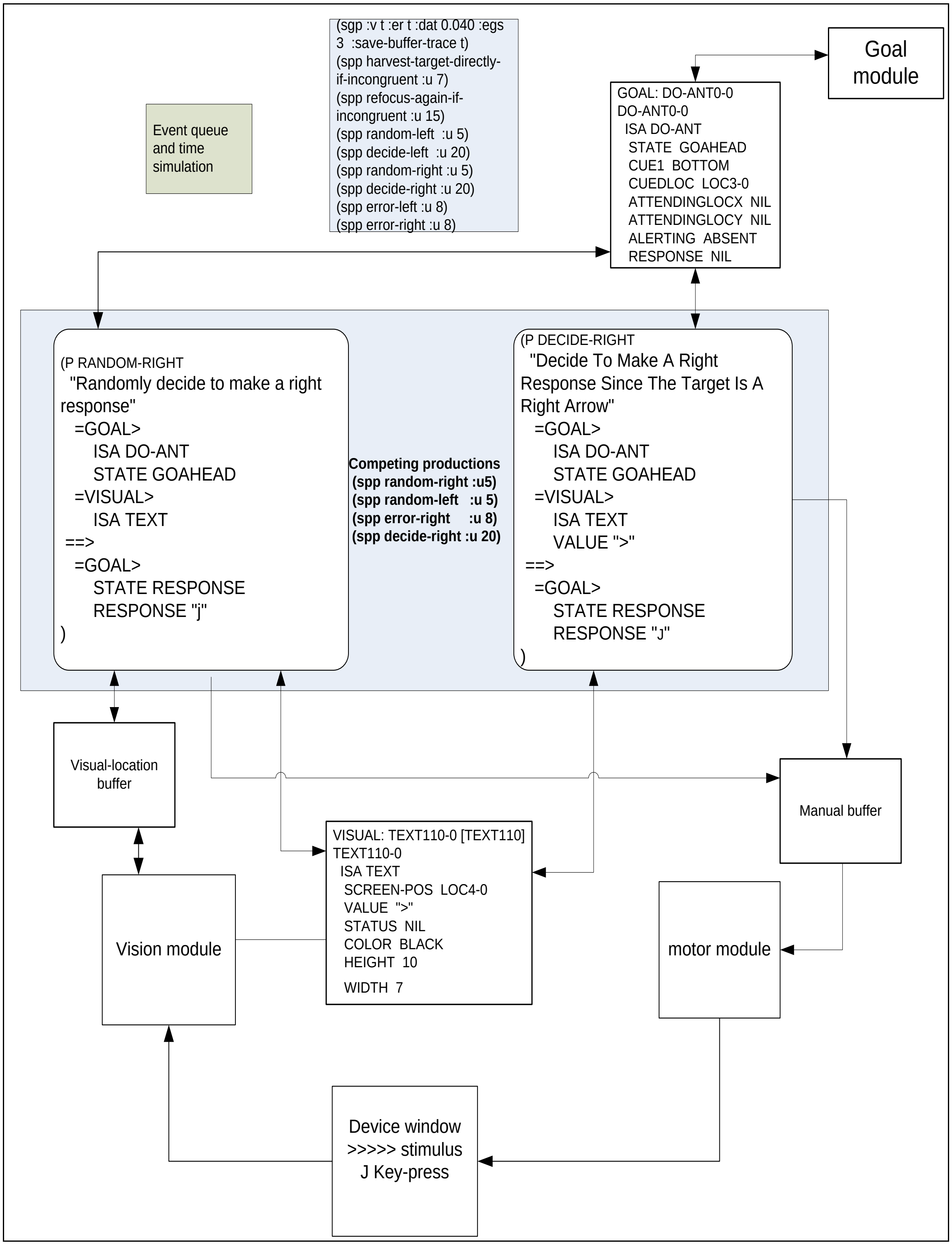



Figure 5-5: Snapshot of model-1 illustrating how productions [P32] and [P34] compete to produce erroneous behaviour.

5.1.3.4 Model-1 task setup and operational details

The task setup is rewritten completely in Lisp making use of the event scheduler of ACT-R 6.0. The meta-process, described in section 3.2.1.5, is used for explicitly sequencing and scheduling the sequence of events in the model. This provides for the scheduling of events occurring at a desired time on a timeline. The device window interacts with the model in a similar way to how a participant taking the test would interact with the computer screen. The event scheduler is a new feature of ACT-R 6.0 and was not a part of previous versions. Most of the AGI (ACT-R Graphical Interface) functions are the same as in ACT-R 5.0. The operational details which involved recording, calculating and printing mean response times, mean accuracy rates and efficiencies produced from the model results were modified according to the ACL 8.1 version changes (Allegro common Lisp).

A screenshot of the window that interfaces with the perceptual motor modules of ACT-R is given in figure 5.6. It shows that, after fixation and a no-cue condition, the congruent stimulus appears at the bottom location.

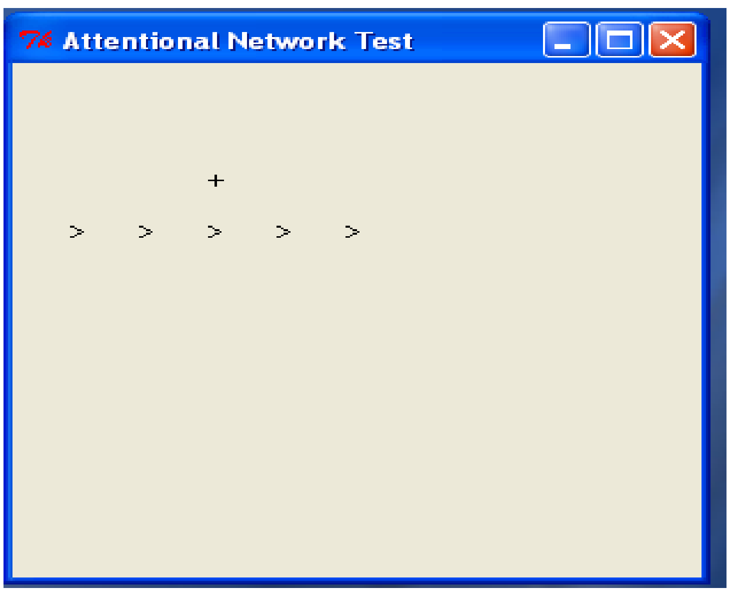



Figure 5-6: Screenshot of the window with which model-1 interacts.

5.1.3.5 New ACT-R 6.0 features and their impact on the design of model-1

A few significant changes introduced in model-1 were based on new ACT-R 6.0 features, as outlined below:

Strict harvesting is a new feature in ACT-R 6.0, which means that if the chunk in a buffer is tested on the LHS of a production, and if that buffer is not modified on the RHS, then that buffer is automatically cleared. By default, this happens for all buffers except for the goal buffer. However, this has no direct implication on the design of model-1, and buffer clearing does not need to be done manually, which used to be the case in ACT-R 5.0.

Buffer stuffing using the command set-visloc-default is a new feature, which (as explained in section 3.2.1.4.2) is utilised to simulate both the bottom-up and top-down processing of visual attention in model-1. Wang's model uses a user-defined function (defmethod stuff-visloc-buffer (vis-mod vision-module)), which manually performs the buffer stuffing (for details, see code for Wang's model, (http://www.sacklerinstitute.org/users/jin.fan/).

Model-1 explicitly makes use of the two buffers, visual-location and visual, denoting the where and what system (the dorsal and ventral systems in vision) indicating the location and the contents of the visual object. Visual-location represents the coordinates of the object, whereas visual buffer can tell the contents of the buffer. Although these two buffers also existed in ACT-R 5.0, it was possible to look at the value slot of the visual-location buffer and know what was contained at that location. However, in ACT-R 6.0, it is not until the object is placed in the visual buffer that the content of the object is known. A move-attention command is required to place the object in the visual buffer. In ACT-R 5.0, this is indeed syntactically different, as shown below, but the time to shift attention remains at 85ms.

| ACT-R 5.0 Syntax | ACT-R 6.0 Syntax |
|---|---|
| +visual><br>ISA visual-object<br>Screen-pos =visual-location | +visual><br>ISA move-attention<br>Screen-pos =visual-location |

### 5.1.4 Sample trace of an ANT trial

In this section, Figure 5.7 illustrates a sample trace produced by the ACT-R environment for a single trial stepping through the timing calculation of latency. It illustrates at what time in the execution in the model various events take place and which production(s) are engaged. For example, at 900ms the production notice-stimulus-with-double-cue [P24] is fired, which leads later to the firing of other productions that determine the direction of the arrow, and finally at time 1450ms the key-press module is engaged and a response is given. The time elapsed between the appearance of the stimulus and the key-press is 550ms (1450ms -900ms), and so on.

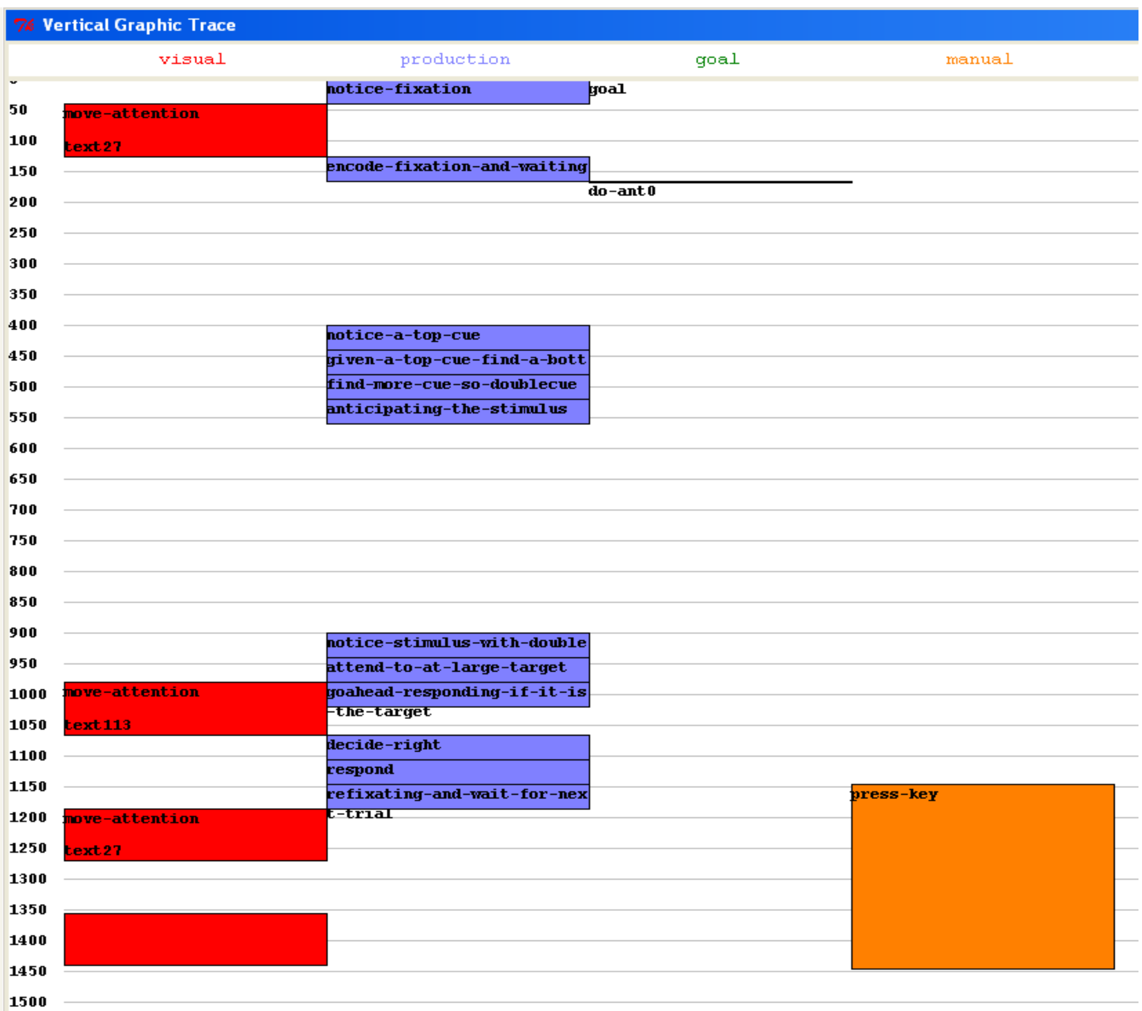



Figure 5-7: A vertical buffer trace produced by ACT-R's tracing utility – part of the GUI module run from the control panel of the environment for a model-1trial.

A user manual on how to start the Lisp application and load ACT-R 6.0, as well as a sample run of a trial stepping through the trace of the trial to show the working and functionality of model-1, is shown in Appendix A.

### 5.1.5 Results

This section reports the results obtained after running the model as an experiment for twenty subjects. Each subject run consists of ninety six trials, four cue conditions (no-cue, centre-cue, double-cue and spatial cue), two target locations (upper and lower); two target directions (left and right); three flanker conditions (neutral, congruent, incongruent)], and repeats the process twice.

The tables and graphs in this section report the results produced by model-1 compared with the human data (Fan et al., 2002) and the ACT-R 5.0 (Wang et al., 2004) model. Latency and accuracy data are collected for each subject, while the efficiency of attentional networks is calculated using Equations 2.1-2.3. Statistical correlation and root mean squared deviations are computed based on the two sets of data (human study and model-1) to determine the model's fit to the human data. The model validation criteria discussed in section 4.3.1 are applied.

#### 5.1.5.1 Latency data

The time between the stimulus appearing and a response key being hit is called the 'response time' or 'reaction time'. This is averaged for all subjects for each cue and flanker type. In Table 5.5, latency data are compared against human data (Fan et al., 2002) as well as the ACT-R 5.0 model (Wang et al., 2004). The graph in Figure 5.8 plots the reaction time data for the human data (Fan et al., 2002) and for model-1 data. The correlations and RMSD for model-1 validated against human data (Fan et al., 2002) is 0.99 and 10.95. For comparison the correlation and RMSD for Wang et al.'s model (Wang et al., 2004) and human data (Fan et al., 2002) is 0.99 and 7.88 as given in Table 5.6. These results could lead the reader to deduce that Wang et al.'s model has a better fit to the human data as compared to model-1. However the process of obtaining the fits and why model-1 is the best possible fit of the ANT model in ACT-R 6.0 is shown later in section 5.1.8.

The latency results reported in Table 5.5 and illustrated in Figure 5.8 show that the mean reaction times are highest for the incongruent condition across all flanker conditions and lowest for spatial cue conditions among every cue condition. Similar to the ACT-R 5.0 model data (Wang et al., 2004), the data produced from model-1 also do not produce a high variance. Although model-1 did exhibit non-deterministic behaviour, the variance in data or individual differences was not simulated explicitly in model-1, because even in the human study (Fan et al., 2002) there was no comment on the significance of the variance and, hence, the model was not complicated by this effect.

Table 5-5: Comparison of mean reaction times produced by model-1 with human data (Fan et al., (2002) study and the ACT-R 5.0 model (Wang et al., 2004). Standard deviations are given in brackets.

| **Latencies of human and model data (and standard deviations)** | | | |
|---|---|---|---|
| **Cue and flanker conditions** | **ACT-R 6 model** | **Human data from Fan study** | **ACT-R 5.0 model** |
| Nocueneutral | 520 (5) | 529 ( 47) | 527 (3) |
| Centerneutral | 482 (4) | 483 (46) | 487 (3) |
| Doubleneutral | 464 (6) | 472 (44) | 467 (5) |
| Spatialneutral | 441 (4) | 442 (39) | 441 (4) |
| Nocuecongruent | 521 (6) | 530 (49) | 526 (4) |
| Centercongruent | 483 (5) | 490 (48) | 486 (3) |
| Doublecongruent | 459 (5) | 479 (45) | 466 (6) |
| Spatialcongruent | 441 (4) | 446 (41) | 441 (4) |
| Nocueincongruent | 592 (14) | 605 (59) | 621 (14) |
| Centerincongruent | 557 (20) | 585 (57) | 580 (14) |
| Doubleincongruent | 531 (16) | 574 (57) | 562 (15) |
| Spatialincongruent | 527(20) | 515 (58) | 522 (16) |

Table 5-6: Summary of correlations and RMSD of latency data for human data (Fan et al., 2002), ACT-R 5.0 model results (Wang et al., 2004) and ACT-R 6.0 model-1 results.

| **Data sets compared** | **Correlation** | **RMSD** |
|---|---|---|
| Human – ACT-R 5.0 model | 0.99 | 7.88 |
| Human – ACT-R 6.0 model | 0.99 | 10.95 |
| ACT-R 6.0 – ACT-R 5.0 model | 0.97 | 10.46 |

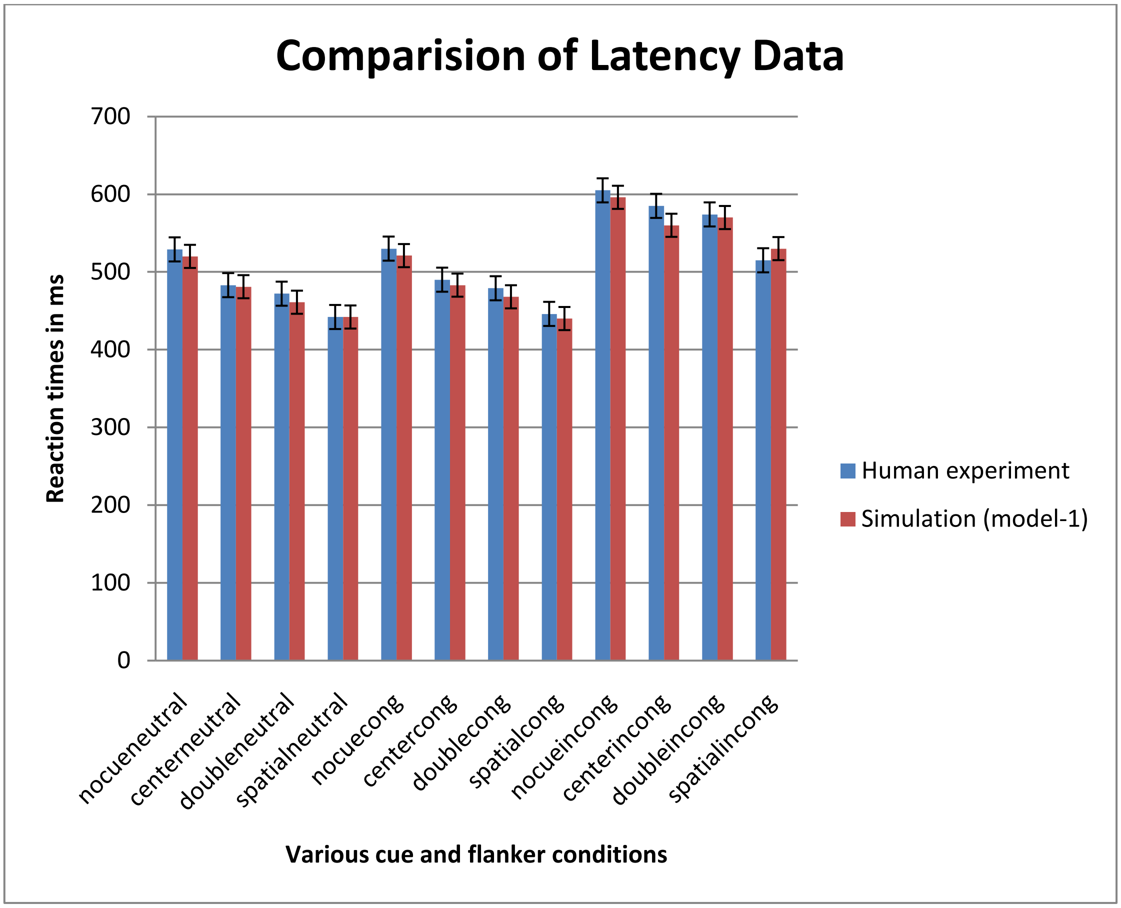



Figure 5-8: Latency results for all cue and flanker conditions from human experiment (Fan et al., 2002) and produced by model-1. Error bars indicate standard error.

5.1.5.2 Accuracy data

Accuracy also plays an important role in this task. Same statistical measures of correlations, standard deviations and RMSDs are computed. Table 5.7 records the percentage of errors for each cue and flanker condition from model-1, the human data (Fan et al., 2002) and the ACT-R 5.0 model (Wang et al., 2004). The accuracy data in Table 5.7 also shows that errors are highest in incongruent conditions when compared to other flanker conditions.

Table 5-7: Comparison of error rates produced by model-1 with the human study (Fan et al., 2002) and ACT-R 5.0 model (Wang et al., 2004). Standard deviations are given in brackets.

| Accuracies of human and model data (and standard deviations) | | | |
|---|---|---|---|
| **Cue and Flanker conditions** | **Model-1** | **Human data** | **ACT-R 5.0 model[6]** |
| Nocueneutral | 1.3(2.6) | 1.17(0.33) | 0.96 |
| Centerneutral | 0.9(2.3) | 0.93(0.22) | 0.92 |
| Doubleneutral | 0.3(1.4) | 1.56(0.29) | 0.71 |
| Spatialneutral | 0.9(2.3) | 0.78(0.23) | 0.79 |
| Nocuecongruent | 1.9(2.9) | 0.73(0.21) | 0.75 |
| Centercongruent | 1.6(4.0) | 0.54(0.19) | 1 |
| Doublecongruent | 2.8(5.2) | 0.59(0.19) | 0.79 |
| Spatialcongruent | 0.9(2.3) | 0.44(0.18) | 0.83 |
| Nocueincongruent | 3.4(4.3) | 3.49(0.67) | 3.25 |
| Centerincongruent | 4.7(5.3) | 4.88(0.68) | 3.79 |
| Doubleincongruent | 4.1(6.2) | 4.27(0.70) | 3.5 |
| Spatialincongruent | 3.4(4.3) | 3.51(0.47) | 2.67 |
| Correlation | | 0.85 | 0.97 |
| RMSD | | 0.88 | 0.56 |

#### 5.1.5.3 Efficiencies of attentional networks

Since one of the main objectives here is to study the efficiencies of the networks and later use these efficiencies to study their interactions, it is equally important to ensure that the model fits this data as well. Efficiencies calculated using Equations 2.1-2.3 are given in Table 5.8.

Table 5-8: Efficiencies of the networks calculated by subtracting reaction times in various cue and flanker conditions. Correlation and RMSD of the efficiency data of model-1 are calculated against the human study (Fan et al., 2002) and the ACT-R 5.0 model (Wang et al., 2004).

| Efficiencies of Attentional Networks | | | | | |
|---|---|---|---|---|---|
| **Mean effects** | **Alerting** | **Orienting** | **Executive control** | **Correlations** | **RMSD** |
| Model-1 | 46 | 38 | 86 | | |
| Human data | 47 | 51 | 84 | 0.94 | 3.4 |
| ACT-R 5.0 Model | 55 | 45 | 86 | 0.97 | 4.4 |

[6] Standard deviation of error for Wang's model (2004) not available.

### 5.1.6 Summary of results and model validation

The correlation and RMSD statistics are given in Table 5.6 for latency data, Table 5.7 for accuracy and efficiencies in Table 5.8. The network efficiencies between model-1, the human study (Fan et al., 2002) and the ACT-R 5.0 model (Wang et al., 2004) indicate a faithful reimplementation of the original ACT-R 5.0 model, as well as reproducing a veridical simulation of the human data set. The correlations and RMSD for the human data (Fan et al., 2002) and model-1 are summarised in Table 5.9.

Table 5-9: Summary of the correlations and root mean square deviations for the latency, accuracy and efficiency data of model-1 compared with the human data (Fan et al., 2002).

| Model-1/Human Data | Correlations ( r ) | Root Mean Square Deviation (RMSD) |
|---|---|---|
| Latency | 0.99 | 10.95 |
| Accuracy | 0.85 | 0.88 |
| Efficiencies of networks | 0.97 | 4.4 |

All three measures of latency, accuracy and the efficiencies are also shown to be in a 20% interval (explained in section 4.3) of the human data, as given in Table 5.10.

Table 5-10: Values falling within a 20% range of all the measures of latency, accuracy and each network efficiency, showing a good fit of model-1 data to the human study (Fan et al., 2002).

| **Mean effect** | **Latency** | **Accuracy** | **Alerting** | **Orienting** | **Executive control** |
|---|---|---|---|---|---|
| Human | 515 | 1.9 | 47 | 51 | 84 |
| 20%range | 412-618 | 1.52-2.28 | 37-57 | 41-61 | 69-100 |
| Model-1 | 513 | 2.2 | 46 | 38 | 86 |

In addition to the standard practice of using correlation and RMSD for model-1 validation, the data were also analysed by means of repeated measures within subject ANOVA. The response times for all twenty subjects for each cue and flanker condition were entered into a 4 x 3 within subject ANOVA table. Statistically significant cue and flanker condition effects were found – the responses were faster in cued trials ($F_{(3,57)} = 204.92$; $p < 0.0001$) and in congruent trials ($F_{(2,38)} = 73.39$; $p < 0.0001$). These significant effects were the same as those found in the human study, further validating the model-1 results.

### 5.1.7 Rule firing time (50ms) issue

This section addresses the issue raised about the ACT-R 5.0 model (Wang et al., 2004) regarding altering the default rule firing time from 50ms to 40ms. The aim is to explore whether this had any significant differences in results. As stated in their paper: "One criticism of our model is that this parameter (rule firing time) is widely accepted as one of a few of ACT-R's fundamental architectural primitives, and changing it is indicative of a misuse of the architecture" (Wang et al., 2004, p. 129). Although the authors had their own reasons to back this up, here, in order to verify this statistically, model-1 was run with a rule firing time of 50ms instead of 40ms, and then the reaction times, accuracy rates and efficiencies of the networks were observed. The data collected are reported in Tables 5.11, 5.12 and 5.13. The correlations are good but the RMSDs are higher than the data reported in section 5.1.5, where the rule firing time used was 40ms. However, the cue fixation time had to be increased from 100ms to 200ms.

Table 5-11: Comparison of latency results of the human study (Fan et al., 2002) with model-1, where the rule firing time is modified to 50ms. Standard deviations are given in brackets.

| **Flanker type** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No cue | | Centre | | Double | | Valid | |
| | Human | Model | Human | Model | Human | Model | Human | Model |
| Neutral | 529(47) | 580(4.7) | 483(46) | 529(8) | 472(44) | 476(5) | 442(39) | 482(6) |
| Congruent | 530(49) | 576(5) | 490(48) | 529(6) | 479(45) | 495(0) | 446(41) | 479(8) |
| Incongruent | 605(59) | 659(25) | 585(57) | 614(14) | 574(57) | 624(6) | 515(58) | 570(17) |
| **Correlations** | 0.97 | | | | | | | |
| **RMSD** | 41 | | | | | | | |

Table 5-12: Comparison of accuracy results of the human study (Fan et al., 2002) with model-1, where the rule firing time is modified to 50ms. Standard deviations are given in brackets.

| **Flanker type** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No cue | | Centre | | Double | | Valid | |
| | Human | Model | Human | Model | Human | Model | Human | Model |
| Neutral | 1.17(0.3) | 1.9(3) | 0.93(0.2) | 1.9(3) | 1.56(0.3) | 0(0) | 0.78(0.3) | 0(0) |
| Congruent | 0.73(0.2) | 0.6(2) | 0.54(.2) | 0.6(2) | 0.59(0.2) | 1.3(2.6) | 0.44(0.2) | 0.6(2) |
| Incongruent | 3.49(0.7) | 5.6(7) | 4.88(0.7) | 2.6(4) | 4.27(0.7) | 4.4(6) | 3.51(0.5) | 2.5(4) |
| **Correlations** | 0.8 | | | | | | | |
| **RMSD** | 1.1 | | | | | | | |

Table 5-13: Efficiencies produced by model-1, where the rule firing time is changed to a default of 50ms compared with the human data (Fan et al., 2002).

| **Efficiency in ms** | **Alerting** | **Orienting** | **Exec control** |
|---|---|---|---|
| Human Data | 47 | 51 | 84 |
| Model Simulation | 73 | 47 | 97 |
| **Correlation** | 0.8 | | |
| **RMSD** | 9.8 | | |

In addition to showing good correlations and RMSD in Tables 5.11-5.13, a few reasons for retaining the value of a 40ms firing time in model-1 are as follows: (1) the ANT is a relatively simple and trivial experiment, and it makes sense to assume that subjects will perform relatively quicker than in any other cognitive task which may be more complex; (2) although the reaction times will go up by 10ms each for a rule fired, which will reflect in the reaction time, when we subtract to calculate the efficiency of alerting, orienting and executive control, the net effect will not be overly large; and (3) if we look at the original experimental results, they show a higher standard deviation, so the reaction time can vary in that range.

### 5.1.8 Obtaining best-fit of model-1

Having given the results produced by model-1 in section 5.16 (validated against human data to be faithful representations of the human experiment) and a detailed discussion of the 50 ms rule firing time issue in section 5.1.7, this section demonstrates the process of obtaining the best fits. For example, the results are explicated for a range of values for the rule firing times, ranging from 40 ms to 50 ms, and the utility values of productions P29 and P30, ranging from 1 to 22. Four data sets for latency are shown below along with the correlations and RMSD when compared to human data (Fan et al., 2002).

Table 5.14 shows seven columns. The first column describes the type of cue and flanker condition. The second column shows the human data (Fan et al., 2002), the third column shows the best fit produced by model-1 and columns four to seven show variations of some of the utility values being tried. The correlations for all data sets are good however the RMSD vary as the utility values are varied (it was desirable to achieve a minimum RMSD value). It is reminded here that the best RMSD was with the values used for model-1, that is, utility values of 7 and 15 for productions P29 and P30 respectively.

Similarly, Table 5.15 shows how the RMSD changes when the rule firing time is varied from 50 ms to 40 ms providing an illustration and justification for the process of obtaining best fits. Note the RMSD values improve as the value for rule firing time approaches 40 ms.

Table 5-14: An exemplar of how the best fit was obtained for latency value by changing the utility values of conflicting productions P29 and P30.

| Cue and Flanker conditions | Human Data | Model-1 utility values 7,15 | utility values 4,15 | utility values 7,18 | utility values 7,22 | utility values 1 ,15 |
|---|---|---|---|---|---|---|
| Nocueneutral | 529 | 520 | 523 | 512 | 521 | 522 |
| Centerneutral | 483 | 481 | 480 | 475 | 481 | 484 |
| Doubleneutral | 472 | 461 | 458 | 455 | 459 | 461 |
| Spatialneutral | 442 | 442 | 443 | 442 | 441 | 443 |
| Nocuecong | 530 | 521 | 518 | 525 | 520 | 523 |
| Centercong | 490 | 483 | 481 | 487 | 479 | 481 |
| Doublecong | 479 | 468 | 465 | 465 | 468 | 476 |
| Spatialcong | 446 | 440 | 444 | 440 | 442 | 441 |
| Nocueincong | 605 | 596 | 597 | 634 | 590 | 580 |
| Centerincong | 585 | 560 | 572 | 589 | 567 | 564 |
| Doubleincong | 574 | 570 | 564 | 579 | 568 | 574 |
| Spatialincong | 512 | 530 | 540 | 515 | 542 | 540 |
| Correlation | | 0.99 | 0.98 | 0.99 | 0.98 | 0.97 |
| RMSD | | 10.95 | 11.64 | 12.21 | 12.62 | 13.00 |

Table 5-15: An exemplar of how the best fit was obtained for latency value by varying the rule firing time from 50 ms to 40 ms

| Cue and Flanker conditions | Human Data | Model-1 Rule firing 40 ms | Rule firing 43 ms | Rule firing 45 ms | Rule firing 47 ms | Rule firing 50 ms |
|---|---|---|---|---|---|---|
| Nocueneutral | 529 | 520 | 534 | 545 | 565 | 579 |
| Centerneutral | 483 | 481 | 494 | 491 | 512 | 529 |
| doubleneutral | 472 | 461 | 483 | 472 | 489 | 476 |
| spatialneutral | 442 | 442 | 454 | 464 | 462 | 482 |
| Nocuecong | 530 | 521 | 540 | 543 | 568 | 576 |
| Centercong | 490 | 483 | 499 | 506 | 509 | 530 |
| Doublecong | 479 | 468 | 483 | 495 | 512 | 495 |
| Spatialcong | 446 | 440 | 456 | 453 | 471 | 479 |
| Nocueincong | 605 | 596 | 644 | 629 | 620 | 659 |
| Centerincong | 585 | 560 | 571 | 562 | 567 | 614 |
| Doubleincong | 574 | 570 | 579 | 608 | 608 | 624 |
| Spatialincong | 512 | 530 | 528 | 536 | 569 | 570 |
| Correlation | | 0.99 | 0.97 | 0.97 | **0.95** | 0.97 |
| RMSD | | 10.95 | 14.77 | 18.79 | 30.23 | 41 |

### 5.1.9 Discussion

Changes were made to the source code of ACT-R 5.0 model (Wang et al., 2004) to produce model-1. To reiterate the discussion of section 5.1.3, the changes involved in migration were related to (1) finding psychological explanations for modelling the networks' efficiencies, (2) the symbolic rules, (3) sub-symbolic changes related to parameters for conflict resolution and error handling, (4) task representation to interact with ACT-R devices, and finally (5) a few miscellaneous changes related to new ACT-R 6.0 features.

The parameter/production settings which had to be fitted to produce best fit were (1) the utility values of the congruency handling productions and the error productions, (2) the spread of visual attention in the case of various cueing conditions, i.e. x-values for the set-visloc-default command, and (3) the rule firing time as done in the ACT-R 5.0 model (Wang et al., 2004). To find the optimal values for these settings, the idea was to start with a value or pair of values for a single parameter, vary it across a wide range, and then observe the way the statistics fitted to the changed data. In this fashion, all values were varied, and then the effects on reaction time, error rates and efficiencies observed. As part of the data fitting process, a wide range of values were tried, and those that produced the best possible fit are reported in this thesis. A demonstration of this related to latency value is given in section 5.1.8.

Based on detailed results and a statistical analysis, model-1 was shown to be a valid simulation of human adult performance on the ANT. In the rest of the thesis, model-1 is extended and used to further explain the interactions of the networks and the behaviour in various pathologies and in children.

In the next section of this chapter, model-1 is extended to simulate performance on a variant of the original ANT incorporating invalid cueing.

## 5.2 Model 2 – Simulating the effect of invalid cueing in ANT performance

Section 5.1 fully explicates the working and results of model-1 that simulate the performance of healthy adults on an ANT in ACT-R 6.0. In this section, model-1 is extended to incorporate the theory of spatial orienting as part of the implementation of the orienting network. The three components of spatial orienting, namely disengage, move and engage, are introduced in model-1. This extended model is referred to as 'model-2'. The motivation for introducing this invalid cueing condition is to obtain a more precise measure of the shift of attention from an unexpected to an expected location, which will also allow us to measure the three elementary operations of orienting (Posner et al., 1984; 1987).

The disengagement deficit (the difference between the reaction time for invalid and valid cues) has been observed in clinical populations suffering from stroke, Alzheimer's and schizophrenia. Therefore, it was useful to model this effect, which is later used in the modelling of attention-related deficits in Chapter 7.

### 5.2.1 Task representation

The original ANT study (Fan et al., 2002) did not incorporate an invalid cue condition and the orienting effect was calculated as a difference of the centre cue and spatial cue conditions. However, in another study, a variant of the ANT design which was used to study the performance of elderly and Alzheimer's disease subjects did incorporate invalid cueing (Fernandez-Duque & Black, 2006). The design of this experiment is given in Figure 5.9. Extending the basic design of the ANT, in addition to a no-cue, cued and double-cue condition, an invalid cue condition is added to the types of cues. An invalid cue condition means that a cue can also appear in a location opposite to the target location, giving incorrect spatial information.

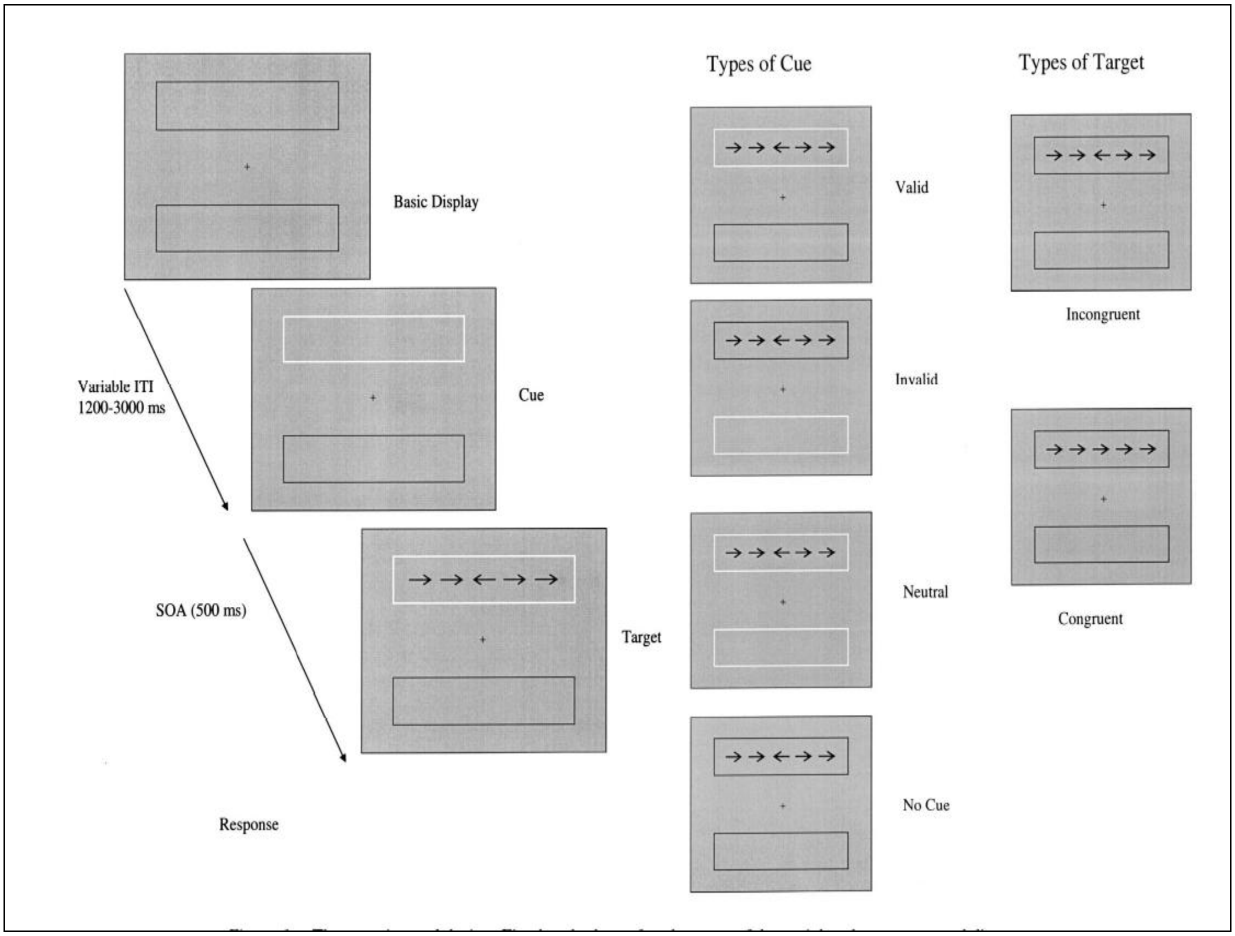



Figure 5-9: A sketch of the design of Fernandez-Duque and Black's (2006, p. 135) experiment incorporating the invalid cue condition.

After the reaction times are recorded, similar to calculating the network efficiencies of alerting, orienting and executive control using Equations 2.1-2.3 (section 2.4.3.1), the difference between the reaction times of uncued and cued trials is calculated using Equation 5.2 (derived from Equation 5.1, which shows all the cue and flanker states).

$$\begin{aligned} Validity\ effect &= \{(RT(uncued_{congruent}) + RT(uncued_{incongruent})) - (RT(cued_{congruent}) \\ &+ RT(cued_{incongruent}))\} \div 2 \end{aligned} \quad \text{Equation 5.1}$$

$$Validity\ effect = RT(invalid\_cue) - RT(valid\_cue) \quad \text{Equation 5.2}$$

This difference is called the validity effect. Recall that Equation 2.2, calculating the difference in reaction times between double-cue and spatial-cue conditions, is referred to as the 'orienting effect'.

### 5.2.2 Design and functionality of model-2

Model-1 is modified to incorporate the uncued condition, i.e. when the cue appears in the opposite location of the stimulus. According to the literature on spatial orienting, in the case of invalid cueing, what is required is a disengagement from the uncued location, an attentional movement and an engagement at the target location (Posner et al., 1984). Based on the task representation and the insights gained from the psychological literature on this scenario, modifications are made to model-1 which involved changes in the symbolic components and in the task setup, as explained below.

#### 5.2.2.1 Symbolic components

New productions are introduced at the stimulus processing and response stages of the model design. These include productions for processing the invalid-cue condition, in order to handle the disengagement effect and refocus attention at the target location. The new productions and states are listed in Tables 5.16 and 5.17. The complete flow of control is illustrated in Figure 5.10, showing how the invalid cueing condition is added to model-1 using extra states and productions, which were required for disengaging from the uncued location and moving attention to the cued location. The boxes and arrows in blue (filled states) represent modifications to model-1.

Table 5-16: New productions added to model-1 to create model-2 for simulating invalid cueing.

| **New productions added in Model-1 to create model-2 which simulates the invalid cueing condition** | | |
|---|---|---|
| Number | Name | Description |
| P39 | Notice-stimulus-at-uncued-top-location | Added in the stimulus-processing stage to handle a stimulus at an invalid cue location |
| P40 | Notice-stimulus-at-uncued-bottom-location | Same as [P39], only the invalid cue location is bottom instead of top |
| P41 | Disengage-production | Production to disengage attention from the invalidly cued location to correct location |
| P42 | Shift-attention-at-uncued-top-location | Engage attention to the correct stimulus location(move-attention) |
| P43 | Shift-attention-at-uncued-bottom-location | Same as [P42], only the invalid cue is at bottom instead of top |

Table 5-17: New states added to model-1 to create model-2 for simulating an invalid cueing effect and the new productions associated with these states.

| State number | State description | New productions |
|---|---|---|
| Stimulus processing stage | | |
| S17 | Disengage | P39,P40.P42,P43 |
| S18 | Shiftingattentionfromuncuedstimulus | P41 |

The three-step process of disengage-move-engage is explained. The production notice-stimulus-at-uncued-top-location [P39] determines that the stimulus appears at an uncued location. The goal state changes to state disengage, which leads to firing the disengage-production [P41]. As a result, another location is requested (item from the screen) to be placed in the visual-location buffer. This is followed by firing the production shift-attention-at-uncued-top-location [P42], which moves attention to the location in the visual-location and proceeds to focus and engage attention.

The above example is explained for an invalid top cue, with the same set of productions repeated for handling an invalidly cued bottom location (using P40, P43). In the case of an invalid cue condition, there is a need to disengage attention from the wrongly cued location, and then refocus at the stimulus location. The extra production to disengage attention from the invalidly cued location gives rise to an extra processing step, inducing the effect of higher reaction times and increased error rates (Posner, Snyder & Davidson, 1980). New productions are explained below:

```
[P39] (P notice-stimulus-at-uncued-top-location
        =goal>
                ISA        do-ant
                state      targeting
                cue1       bottom
                =visual-location>
                ISA        visual-location
                screen-y   40
        ==>
        =goal>
        state      disengage
                =visual-location>   )
```

The production notice-stimulus-at-uncued-top-location [P39] determines that cue1 slot specifies that the indicated location is bottom but the cue appears at screen-y location 40 which is the top. So, the goal state sets a flag to remember that this is an invalid cue.

```
[P41] (P  disengage-production
          =goal>
```

The production disengage-production, [P41],

```
            ISA         do-ant
            state       disengage
      ==>
      =goal>
            state
shiftingattentiontouncuedstimulus
      +visual-location>
            ISA         visual-location
            :attended   new
            > screen-x   30
            < screen-x   150 )
```

checks the goal state and finds out that attention is fixated at an incorrect location so there is a need to disengage attention and places a new object in the visual-location buffer for processing.

```
[P42] (P shift-attention-at-uncued-top-location
       =goal>
      ISA         do-ant
      state       shiftingattentiontouncuedstimulus
            cue1        bottom
            =visual-location>
            ISA         visual-location
            screen-y   40
      ==>
            =goal>
            state       focuson
            +visual>
            ISA         move-attention
            screen-pos  =visual-location
            =visual-location>)
```

The production shift-attention-at-uncued-top-location [P42] moves attention to the newly selected object and then engages attention at that location.

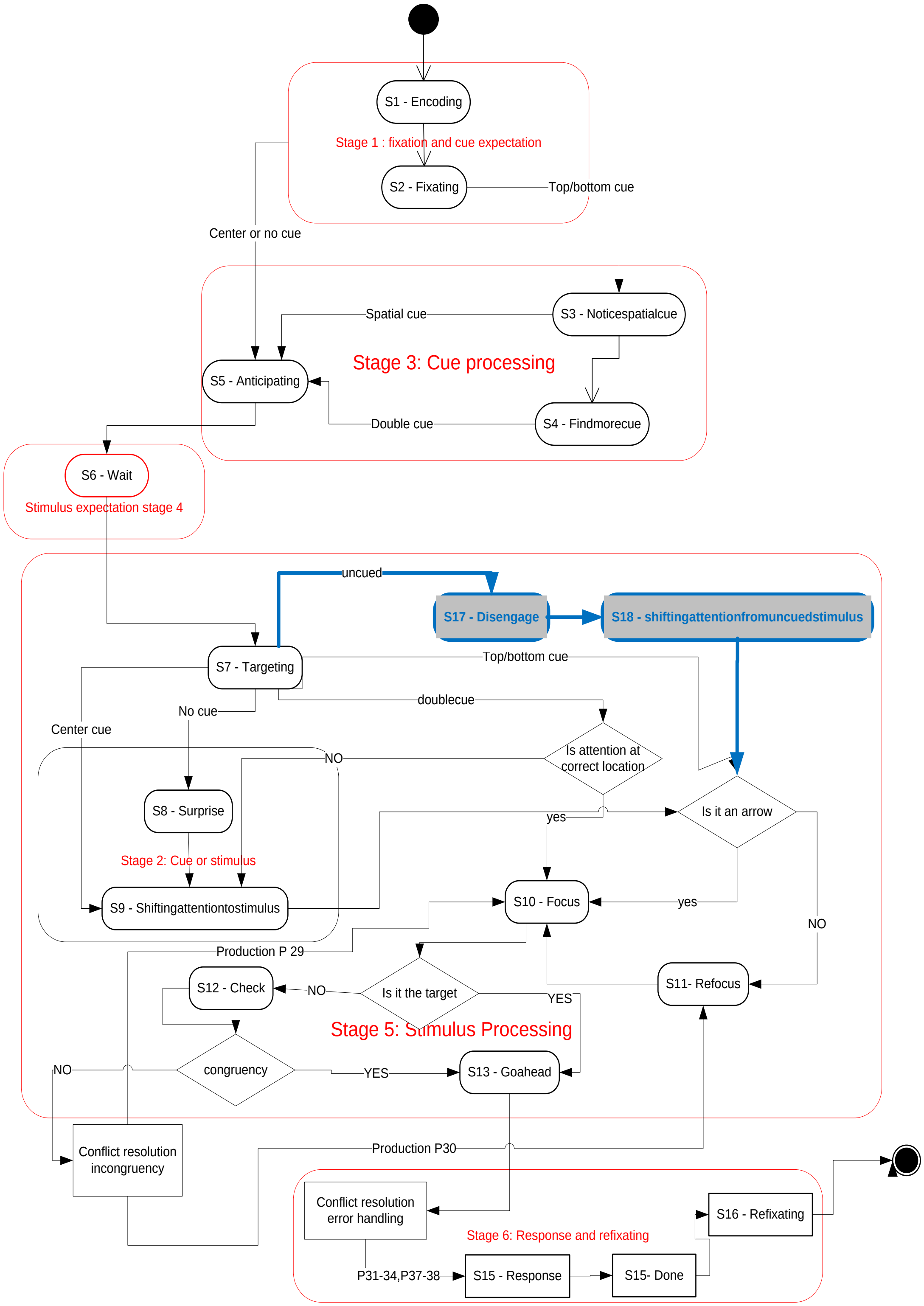



Figure 5-10: A modified state/flow diagram for model-2. The blue lines and shaded boxes represent new states and transitions added to Figure 5.2.

5.2.2.2 Task setup

The experimental setup which communicates with ACT-R's visual module is also modified to incorporate the new invalid cue condition. The design of the experiment (given in Figure 5.10) indicates cueing by the use of highlighted boxes, but model-2 uses "*" as the cues (as done in model-1). It was assumed that, for the model, the use of '*' or highlighted boxes would not have an impact on the latency or accuracy data, since the response time was calculated based on the time between the appearance of the target and a key-press, based on the direction of the arrow. The neutral flanker condition was not used in the human study (Fernandez-Duque & Black, 2006) (it was observed from the latency and accuracy results of model-1 that the neutral and congruent condition results were not too different from one another). The rest of the design and the functionality was the same as that of model-1.

### 5.2.3 Results

This section reports the results obtained after running model-2 with thirteen subjects. Each subject run consists of sixty-four trials [four cue conditions (no-cue, double-cue, spatial cue and un-cued), two flanker conditions (congruent, incongruent), two target locations (upper and lower), two target directions (left and right)], and a repeating of the process twice. Fernandez-Duque and Black (2006) recorded not only the performance of Alzheimer's disease (AD) patients and ageing subjects, but also recorded data from healthy subjects, which are used here to validate the model-2 data. Recently, Fan and colleagues (2009) conducted a revised ANT study (ANT-R) to explore the effect of invalid cueing. Since these new results also became available after data-fitting the model, they were also incorporated for model validation in this chapter[7] (for details on the ANT-R, see Fan et al., 2009). Reported and described below are the latency data, accuracy data, efficiencies of the three networks, and the relationship between efficiencies of validity and orienting of the model compared with human studies. For each measure, a summary of the statistical analysis and model validation is given to show goodness-of-fit.

[7] This paper is a 2009 publication and was not part of the initial literature review for this thesis; however, since the new data became available, they were used for additional model validation and included in the thesis in the final stages of writing.

5.2.3.1 Latency data

The latency data produced by model-2 are compared with both (1) the healthy participant data of Fernandez-Duque & Black's (2006) study and (2) data from the revised ANT design (Fan et al., 2009). Table 5.18 gives the model data validated against Fernandez-Duque and Black's (2006) study, while Table 5.19 compares the model data with the latest Fan et al. (2009) study on the ANT-R. Correlations and root mean squared deviations are used to show goodness-of-fit. Numbers in parentheses are standard deviation. Figure 5.11 illustrates the comparison of latency data for human experiment (Fernandez-Duque & Black, 2006 and model-2 data.

Table 5-18: Latency data for model-2 compared with human data taken form Fernandez-Duque and Black's (2006) study.

| **Flanker type** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No cue | | Double | | Valid | | Invalid | |
| | Human | Model | Human | Model | Human | Model | Human | Model |
| Congruent | 493(46) | 523(5) | 455(47) | 469(5) | 429(44) | 443(3) | 495(53) | 526(3) |
| Incongruent | 574(40) | 603(9) | 566(39) | 570(9) | 538(40) | 514(18) | 600(52) | 617(12) |
| **Correlations** | 0.96 | | | | | | | |
| **RMSD** | 22 | | | | | | | |

Table 5-19: Latency data for model-2 compared with the human data produced from Fan et al.'s (2009) recent ANT-R study.

| **Flanker type** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No cue | | Double | | Valid | | Invalid | |
| | Human | Model | Human | Model | Human | Model | Human | Model |
| Congruent | 558(67) | 523(5) | 480(47) | 469(5) | 453(51) | 443(3) | 563(73) | 526(3) |
| Incongruent | 687(83) | 603(9) | 685(91) | 570(9) | 581(72) | 514(18) | 740(94) | 617(12) |
| **Correlations** | 0.98 | | | | | | | |
| **RMSD** | 85 | | | | | | | |

The correlation of the latency data compared to Fernandez-Duque and Black's (2006) study is 0.96, and for Fan et al.'s (2009) study 0.99, which shows a decent fit to human data. The results show that, in the case of invalid cueing, the reaction times are higher when compared to valid cueing, which was expected because the disengaging effect leads to a longer RT. This is in support of the view that spatial orienting has three components namely disengage, move and engage (Posner et al., 1987). The RMSD from

Fan et al.'s (2009) data is much higher, possibly because the ANT-R design is more complex than an ANT with two levels of interference.

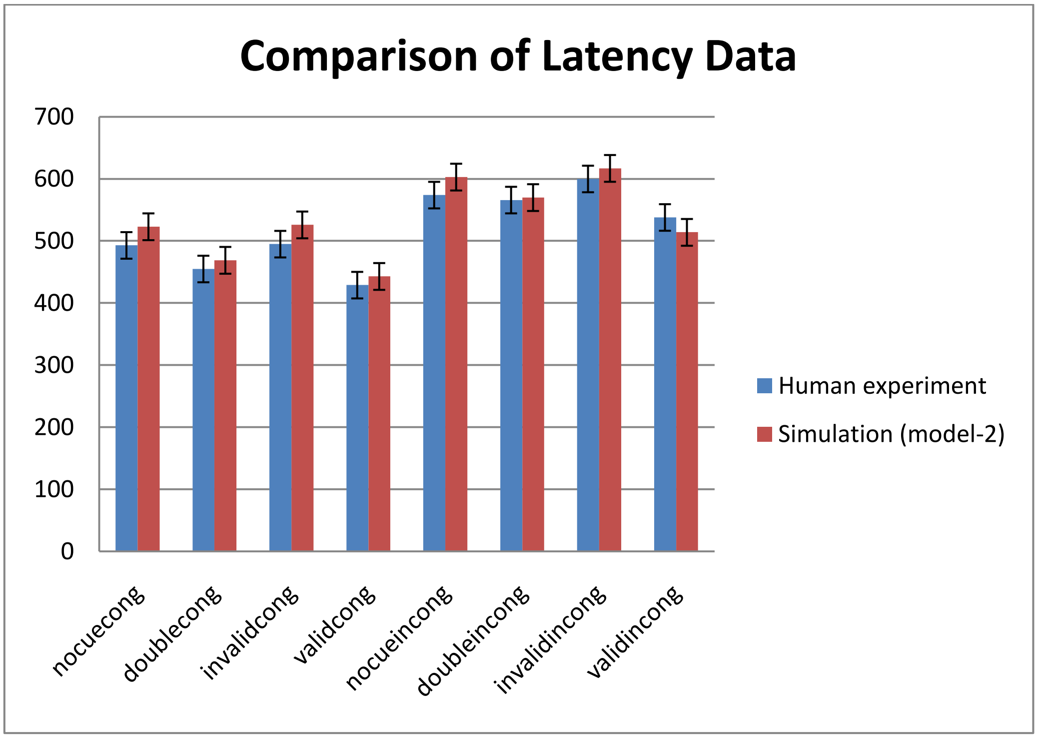



Figure 5-11: Comparison of latency data for the human experiment (Fernandez-Duque & Black, 2006) and model-2 results for all cue and flanker conditions.

#### 5.2.3.2 Accuracy data

In addition to the latency data, the percentage of errors is also recorded. Table 5.20 below shows the accuracy data evaluated against the Fernandez-Duque and Black study (2006), and subsequently Table 5.21 shows data compared against the ANT-R (Fan et al., 2009). The correlations and RMSDs are better in Table 5.20 compared to Table 5.21.

Table 5-20: Accuracy data produced from model-2 validated against the human data from Fernandez-Duque and Black's (2006) study.

| **Flanker type** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No cue | | Double | | Valid | | Invalid | |
| | Human | Model | Human | Model | Human | Model | Human | Model |
| Congruent | 1.2(3.0) | 3.8(5) | 1.9(3.3) | 0.8(2) | 0.4(1.4) | 2.5(4) | 1.5(3.1) | 1.7(3) |
| Incongruent | 5.5(6.1) | 6.3(5) | 8.1(8.8) | 5(5) | 7.6(6.3) | 6.3(4) | 6.2(6.3) | 8.8(6) |
| **Correlations** | 0.8 | | | | | | | |
| **RMSD** | 1.9 | | | | | | | |

Table 5-21: The accuracy data produced from model-2 validated against the human data from Fan et al.'s recent study (2009) based on the ANT-R.

| **Flanker type** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | No cue | | Double | | Valid | | Invalid | |
| | Human | Model | Human | Model | Human | Model | Human | Model |
| Congruent | 3 (6) | 3.8(5) | 3 (9) | 0.8(2) | 1 (3) | 2.5(4) | 0 (0) | 1.7(3) |
| Incongruent | 7 (8) | 6.3(5) | 20(20) | 5(5) | 6(8) | 6.3(4) | 17 (23) | 8.8(6) |
| **Correlations** | 0.7 | | | | | | | |
| **RMSD** | 6 | | | | | | | |

#### 5.2.3.3 Efficiencies of the attentional networks

Efficiency data plotted in Figure 5.12 use the formulae in Equations 2.1, 2.2, 2.3 and 5.2. The difference in the efficiencies of orienting and validity are accounted for by the extra disengage operation, which is required in the case of an invalid cue condition. The efficiencies of alerting and control are not of concern here, but fit fairly well with the human data. Human1 represents the Fernandez-Duque and Black (2006) study and human2 denotes the Fan et al. (2009) study. The possible reason for longer executive control network efficiency from human2 could be because this is run on ANT-R (Fan et al., 2009), which has a more complex design and two levels of incongruency. Note that the validity and orienting effects are roughly apart by the time that the disengaging effect is simulated.

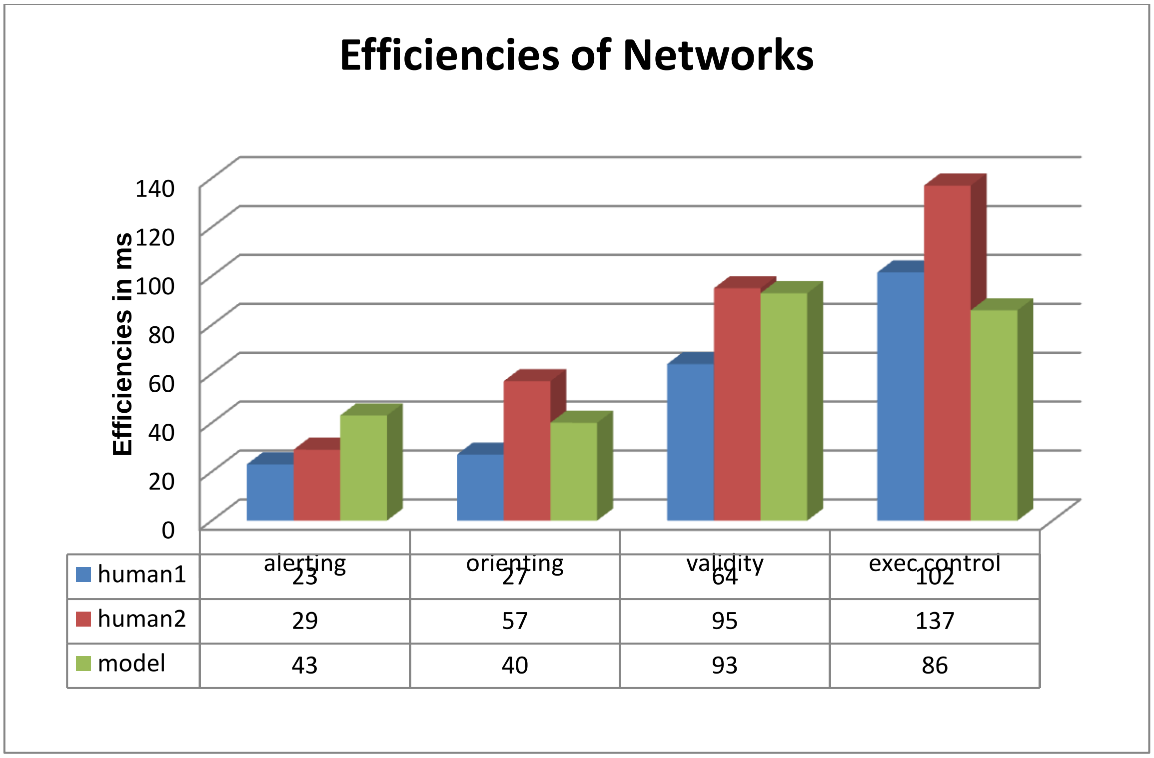
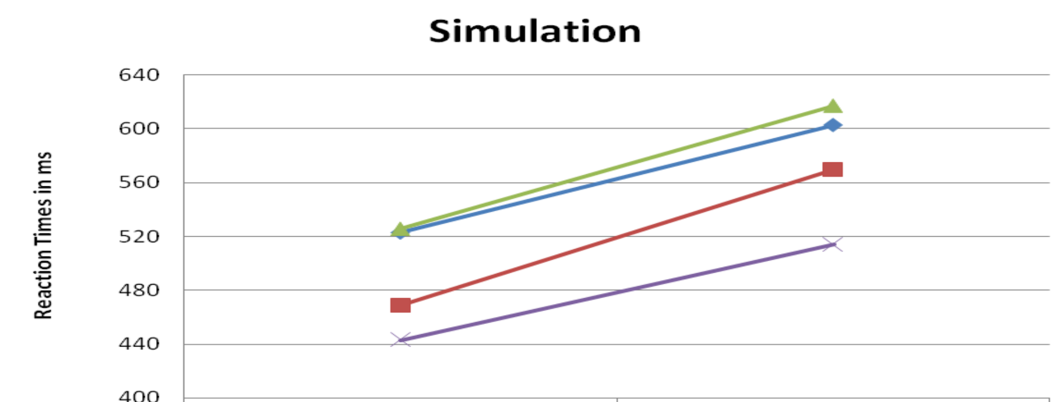



Figure 5-12: Efficiency of attentional networks produced by model-2, including an invalid cue condition in order to measure the validity effect. Human1 denotes the Fernandez-Duque and Black (2006) study and human2 denotes the Fan et al. (2009) study.

5.2.3.4 Relationship between orienting and validity effects (efficiencies)

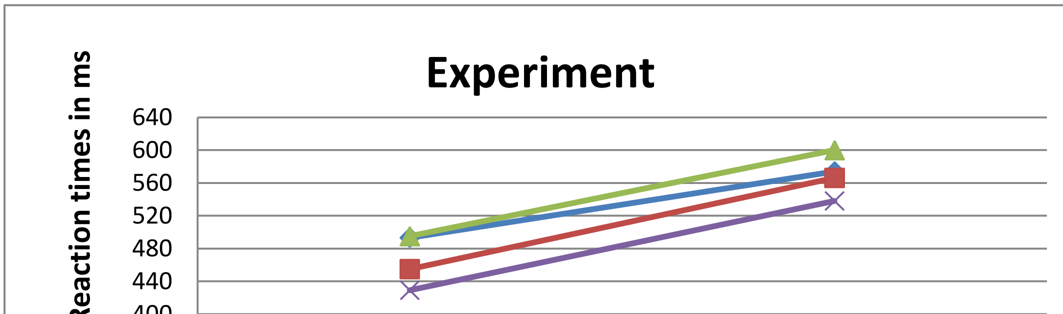
The graph in Figure 5.13 depicts all four cue conditions, showing the reaction times for each flanker condition and including the newly introduced invalid cue condition. For comparison, the human data for healthy participants from Fernandez-Duque and Black (2006) are plotted in Figure 5.14.

From the lines in the graphs in Figures 5.13 and 5.14, it is evident that the red and green lines depicting the double and invalid cues are different due to an additional disengage step. However, another observation is that the nocue and uncued (blue and green) lines are almost overlapping. Nocue is the condition when the target appears without an alerting signal. Although the networks involved with alerting and uncueing are separate, these close reaction time data might mean that the effect of a delay in the reaction time due to uncueing is similar to the slowdown in response time due to un-alerting.




| | congruent | incongruent |
|---|---|---|
| nocue | 523 | 603 |
| double | 469 | 570 |
| invalid | 526 | 617 |
| valid | 443 | 514 |

Figure 5-13: Mean reaction times for all cue and flanker conditions for model-2, incorporating an invalid cueing condition.




| | congruent | incongruent |
|---|---|---|
| nocue | 493 | 574 |
| double | 455 | 566 |
| invalid | 495 | 600 |
| valid | 429 | 538 |

Figure 5-14: Mean reaction times from the human study (Fernandez-Duque & Black, 2006) and model-2.

### 5.2.4 Summary of the results and model validation

The correlation of the latency data compared to Fernandez-Duque and Black's (2006) study is 0.96, and 0.98 against the Fan et al., (2009) study, which indicates a good fit to the human data. The results show that, in the case of invalid cueing, the latency data are higher than valid cueing, which is as expected because the disengaging effect leads to a longer reaction time. This is in support of Posner's three components of disengage, move and engage paradigm. The correlation and RMSD of the accuracy data are 0.8 and 1.6 with the Fernandez-Duque and Black study (2006) and 0.7 and 5 with the Fan et al., (2009) study, which also show a good fit to the available human data.

The RMSD from Fan et al.'s (2009) data is much higher, possibly because the design of the ANT-R is more complex than that of the ANT. In addition, the efficiencies of the networks in this study compared with the model show similar trend magnitudes, which again establish the validity of the model. All the values are summarised in Table 5.22.

Table 5-22: Summary of the correlations and RMSD for the latency, accuracy and efficiency data of model-2 compared with human data (Fernandez-Duque & Black, 2006 is referred to as human1 and Fan et al., 2009 as human2).

| | Correlations ( r ) | | Root mean square deviations (RMSD) | |
|---|---|---|---|---|
| | Human1 | Human2 | Human1 | Human2 |
| Latency | 0.96 | 0.98 | 22 | 85 |
| Accuracy | 0.8 | 0.7 | 1.6 | 5 |
| Efficiencies of networks | 0.86 | 10 | 0.84 | 14 |

In addition to using the standard measures of correlations and RMSD for model validation, the latency data from all subjects were entered into a 4 X 2 within subject repeated measures ANOVA. Statistically significant cue and flanker condition effects were found – the responses were faster in cued trials ($F_{(3,72)} = 88.89$; $p < 0.0001$) and in congruent trials ($F_{(1,24)} = 655.06$; $p < 0.0001$).

### 5.2.5 Discussion

In section 5.2, in order to incorporate invalid cueing in model-1, its functionality was enhanced by adding extra productions to process an additional cue condition called uncued. This simulated the situation whereby the target appears in the location opposite to the cue. In this case, attention has to disengage from the wrongly cued location to the correct location, and finally focus attention on the target location. In model-1, there is no invalid cue condition, and the orienting effect is calculated by subtracting the reaction time of the center-cue from the reaction time of the spatial-cue (the spatial cue is always valid). Model-2 is a more explicit representation, where the validity effect is calculated as a difference of the reaction times under uncued and cued conditions using Equation 5.2.

So, by working of model-2 it is shown how the three-step process of disengage-move-engage is broken down and implemented in the model. By simulating the steps separating the operations related to attention, when studying deficits in the orienting network, it is now possible to simulate and explore which particular sub-operation (disengage, move or engage) could be impaired by a pathological condition. For example, a deficit in disengaging attention can be attributed to the longer validity effect and simulated in the model by slowing down the production that disengages attention from an invalid cue location [P41]). A deficit in moving or engaging attention can be attributed to the slowing down of reaction times, irrespective of where attention was engaged prior to the appearance of the stimulus. This can be simulated in the model by slowing down the reaction time for the productions [P42] and [P43] which move attention and re-engage it, no matter where the focus was before the target appeared.

### 5.3 Chapter summary

Chapter 5 explicates the working of model-1 and model-2. Model-1, which is the reimplementation of the ACT-R 5.0 model for ANT performance (Wang et al., 2004), involved changes in the symbolic and sub-symbolic constructs, task setup and a few miscellaneous changes related to ACT-R 6.0. The rationale for implementing the three networks, based on the psychological literature, is provided. The design decisions are discussed and the process of data fitting is justified. Latency, accuracy and efficiency results produced by model-1 are validated against human data (Fan et al., 2002) and the ACT-R 5.0 model (Wang et al., 2004) of ANT performance.

Extending the functionality of model-1, model-2 implements the effect of invalid cueing in the ANT paradigm. Model-2 is a more explicit representation of what happens when a cue is at an incorrect location. It is demonstrated how the three-step process of disengage-move-engage is broken down and implemented in model-2. By simulating the steps that separate the operations related to attention, when studying deficits in the orienting network it will now be possible to simulate and explore which particular sub-operations (disengage, move or engage) may be impaired by a pathological condition.

This chapter represents the groundwork that has been done for the other modelling tasks in this thesis. In the chapters to follow, model-1 and model-2 are extended further and used to explore the interactions of the attentional networks, various attentional-related disorders and cognitive development in children with respect to the attentional networks of alerting, orienting and executive control in the context of the attentional network test.

# 6. Modelling the Modulation Effects of Attentional Networks

The aim of this chapter is to explore the interactions of attentional networks through computational modelling. In this effort, model-2 (section 5.2) is extended to simulate an extended ANT study which was used to explicitly explore the modulation effects of attentional networks (Callejas et al., 2005). The effects of an inhibition or the facilitation of a network are simulated, and then, based on the design of the model and data fitting process, observations are made. How the model's behaviour changes is investigated, and whether these effects are varied is determined. This ACT-R 6.0 model is referred to as 'model-3'. Detailed findings from neuroimaging and behavioural studies about the investigation of interactions of the attentional networks were discussed in section 2.4.4.

## 6.1 Model-3 – Modelling interactions of attentional networks using the ANT

### 6.1.1 Task representation

The original ANT experiment (Fan et al., 2002) only reported the possibility of an interaction between orienting and executive control. The design of the experiment was such that both alerting and cueing were measured with cue variations, and therefore it was unclear whether the modulation effect on congruency was a result of the alerting signal or cueing. Recall that the alerting effect is measured as the difference between the response times between no-cue and double cue conditions, whereas the orienting effect is measured using the subtraction of response times between the centre-cue and spatial cue conditions. Since spatial cueing is used for orienting but temporal cueing is used for alerting, there is no explicit alerting signal.

To separate out the impact of alerting and orienting, Callejas and colleagues (Callejas, et al., 2004; 2005) used an auditory alerting condition to separate the cueing effect, and then administered the revised ANT experiment to healthy adults. Here, an auditory tone was used to alert and restrict the use of spatial cueing, but only for measuring the orienting effect. Consequently, both are measured independently by using two separate modalities, i.e. an auditory sound for alerting and visual cueing for orienting.

The revised ANT design (Callejas et al., 2004; 2005), illustrated in Figure 6.1, involves two auditory signals (present, absent), three visual cues (nocue, cued and uncued) and three congruency conditions (neutral, congruent, incongruent). Nocue is the condition where a stimulus is not preceded by a cue (in the original ANT experiment (Fan et al., 2002), nocue was used for showing no alertness condition, but here it is just a cue condition). In the cued condition a spatial cue is presented in the location where the stimulus is expected, while uncued refers to the condition where a cue appears in a location opposite to the location of the stimulus (uncued, that is invalid cueing).

The remaining details of the experiment stayed the same as the original ANT (Fan et al., 2002), where the target stimulus consisted of a left or right arrow flanked by two arrows on each side, either in the same (congruent condition) or opposite direction (incongruent condition). The task for the subject was to report on the direction of the arrow and press the ‘f’ key for left arrow and the ‘j’ key for right arrow.

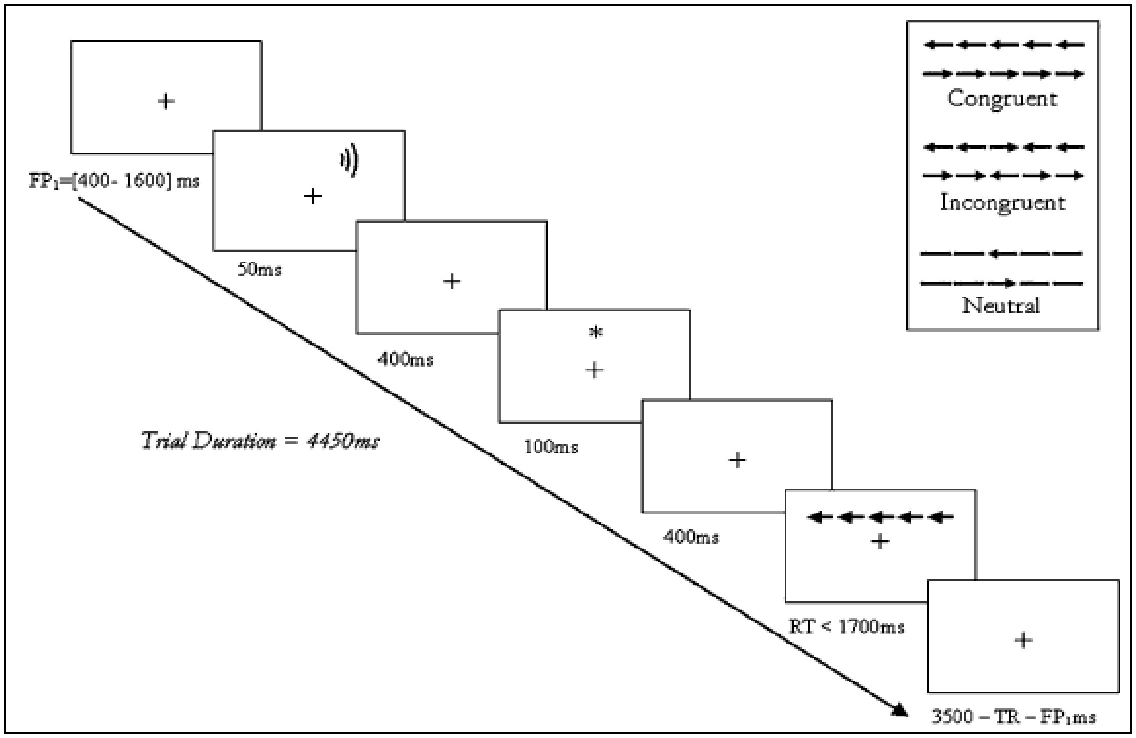



Figure 6-1: A revised ANT design extended with an auditory alerting condition (Callejas, et al., 2005, p. 30).

Accounting for every cue and flanker condition under alertness and no alertness, Equations 6.1-6.3 give the detailed formulae for calculating the efficiencies of the three networks (based on Equations 2.1, 2.3 and 5.2). Alerting efficiency is the difference between the sums of the reaction times for all cue and flanker conditions under no alertness, and the same under alertness. The cueing effect is calculated by taking the average difference of the mean reaction times for un-cued trials and cued trials, irrespective of being alerted or not. Finally, the congruency effect is calculated by taking the difference of the mean reaction times for every incongruent and congruent trial. Complete formulae are given in Equations 6.1-6.3:

$$\begin{aligned}&Alerting\\&= \{\boldsymbol{s}um\ of(RT\ of\ all\ cue\ and\ flanker\ conditions\ under\ no\_alertness)\\&-\ \boldsymbol{s}um\ of(RT\ of all\ cue\ and\ flanker\ conditions\ under\ alerntess)\} \div 6\end{aligned}$$ Equation 6.1

$$\begin{aligned}&Orienting\ or\ validity\\&= \{sum\ of(RT\ of\ uncued\ under\ alerting\ for\ both\ congruent\ and\ incongruent)\\&+\ sum\ of\ (RT\ of\ uncued\ under\ no_{alertness} for\ both\ congruent\ and\ uncongruent)\\&-\ sum\ of\ (RT\ of cued\ under\ alerting\ for\ both\ congruent\ and\ incongruent)\\&-\ sum\ of(RT\ of\ cued\ under\ no_{alertness} for\ both\ congruent\ and\ uncongruent)\}\\&\div\ 4\end{aligned}$$ Equation 6.2

$$\begin{aligned}&Executive\ control\\&= \{sum\ of(RT\ of\ incongruent\ for\ all\ cue\ conditions\ under\ alertness)\\&+\ sum\ of\ (RT\ of\ incongruent\ for\ all\ cue\ conditions\ under\ no\_alertness\ )\\&-\ sum\ of\ (RT\ of\ congruent\ for\ all\ cue\ conditions\ under\ alertness)\\&- sum\ of\ (RT\ of\ congruent\ for\ all\ cue\ conditions\ for\ under\ no\_alertness\ )\ \}\\&\div 6\end{aligned}$$ Equation 6.3

### 6.1.2 Design and functionality of model-3

In order to simulate the revised ANT experiment (Callejas et al., 2004; 2005) and explore further how the interaction affects the attentional networks, model-3 is implemented by making use of the basic design of model-2 (section 5.2.2). The modifications to model-2 were related to modifying (1) the implementation of the networks, (2) the simulation of interactions of the networks, (3) the symbolic components introducing new productions to handle changes at the symbolic level, (4) adjusting sub-symbolic components for data fitting, and (5) modifying the task setup specifically for auditory alerting.

#### 6.1.2.1 Implementation of the networks

The alerting network is now initiated through an auditory signal. The auditory module of ACT-R is used for this purpose. When an alerting sound is detected, a flag is set to remember whether alertness is present or absent. This information is used later in the stimulus processing stage. If there is no-alerting sound, then an extra production no-alertness is fired, which induces the element of surprise in the case of a no-alerting sound. The justification is the same as used in implementing alertness in model-1 (see section 5.1.3.1.1). The implementation of the orienting network is the same as in model 2 (see section 5.2.2), while the executive control network is the same as used for both model-1 and model-2 (see section 5.1.3.1.3.). Therefore, the only change is in the implementation of the alerting network.

#### 6.1.2.2 Interactions of networks

It was reported in the human study that alerting has an inhibitory effect on congruency, whereas cueing has a facilitating effect. Furthermore, alerting seems to speed up the orienting process. These effects were introduced in model-3 based on some guidance from the attention literature. As a consequence, under alerting, the model was simulated to have a longer reaction time for incongruent conditions. Similarly, when a valid cue was encountered before the appearance of the stimulus, model-3 was fitted to benefit from the valid cue condition.

Model-3 induces these effects by varying the spread of visual attention, making use of ACT-R 6.0 buffer stuffing mechanism (see section 3.2.1.4.2). This – in theory – corresponds to making use of the spatial spread of visual attention and the idea that any object falling within that range only will receive a processing advantage. This is based on evidence from the attention literature on how the narrowing of attention of the zoom-lens or the spotlight width reduces the effect of distraction and increases the cueing effect (van der Lubbe & Keuss, 2001; LaBerge, Brown, Carter, Bash & Hartley, 1991). The simulation of these interactions is described in detail below.

##### 6.1.2.2.1 Alerting by congruency effect

In the case of alerting, model-3 is adjusted to exhibit a wider focus of attention, which results in a greater chance of distraction, whereas in the case of no-alerting a narrow range of attention spread simulates less chance of distraction. Varying the range of values made available for selection, depending upon alerting or no-alerting, gives rise to the inhibiting and facilitation effect of alerting on congruency. Hence, controlling the level of distraction in alerting and no-alerting conditions by increasing and decreasing zoom of the focus produces these effects.

To exhibit a wider range of values, new productions are added, which perform the same main function but are now under a no-alerting condition. For example, recall in model-2 that the production [P41] disengages attention in the case of an invalid cue condition. Now, under the no-alerting condition, the newly introduced production, disengage-production-unalert, is the same as [P41], but note that the x-values are between 30 and

150 instead of 20 and 180. The new productions are described in detail in section 6.1.2.3 (the x coordinate for the target arrow is 90).

```
(p  disengage-production
   =goal>
     ISA        do-ant
     state      disengage
   =visual-location>
     ISA        visual-location
   ==>
   =goal>
     state
shiftingattentiontouncuedstimulus

   +visual-location>
     ISA        visual-location
     :attended    new
   > screen-x    20
   < screen-x    180)
```

```
(p  disengage-production-unalert
   =goal>
     ISA        do-ant
     state      disengage-unalerted
   =visual-location>
     ISA        visual-location
==>
   =goal>
     state
shiftingattentiontouncuedstimulus-unalerted
   +visual-location>
     ISA        visual-location
     :attended    new
   > screen-x    30
   < screen-x    150)
```

6.1.2.2.2. Validity by congruency effect

In the simulation, controlling the amount of distraction modulates not only the effects of alerting on congruency, but also cueing on congruency. In other words, if an object is selected for attention from a wider range of values from the visual scene (the visicon in the case of the ACT-R model), then there is more chance of a distracter being focused instead of the target. On the other hand, if the focus is narrower, then there is less chance of distraction and a better chance of focusing directly on the target. This is implemented in model-3, again manipulating the buffer stuffing mechanism such that, in the case of spatial cueing, a narrow focus of attention is simulated by using x-values closer to the target location, whereas in other cue conditions, a wider focus of attention is simulated using a wider range of x-values. The condition is given below:

```
    (if  the cue is a spatial-cue then
            (set-visloc-default :screen-x (within 40 130) :attended new)
  else for all other cue types, (set-visloc-default :screen-x (within 20 180)).
```

#### 6.1.2.3 Symbolic components

New productions are added to model-2 at various processing stages to create model-3. At the stage of cue processing, these new productions process the auditory cue for alertness (P44-P46). Similarly, at the stimulus processing stage, productions (P47-P53) are added that process the stimuli under no alertness and simulate the observed interactions of the networks, as explained in section 6.1.2.2.

Similar to buffers such as visual-location and visual buffers, the usage of which is described in model-1 (section 5.1), an aural-location buffer is used to hold the location of an aural message and an aural buffer is used to hold the sound that is attended to (the working of ACT-R buffers is explained in section 3.2.1). If a new sound appears and the aural-location buffer is empty, then the audio-event for that sound, the auditory equivalent of visual-location, is placed into the buffer automatically.

A list of all the new productions, along with a brief description, is given in Table 6.1, while the new states that were added to the model-2 are given in Table 6.2.

Table 6-1: New productions added to model-2 to create model-3 for simulating the auditory alerting and interactions of networks.

| Number | Name | Description |
|---|---|---|
| P44 | Detected-sound | Detect and put an auditory sound when the aural buffer is free. |
| P45 | Alerting present | If the sound frequency is 2000 hz, then set the flag alerting as present |
| P46 | Alerting-absent | If the sound frequency is 1000 hz, then set the flag alerting as absent |
| P47 | No-alertness | Extra production which induces an effect of no-alerting signal |
| P48 | Notice-stimulus-at-cued-top-location-unalerted | Same as [P13] but the goal state is different which accounts for firing of an extra production for no alertness. |
| P49 | Notice-stimulus-at-uncued-top-location-unalerted | Same as [P39] except that the spread of attention is reduced as explained in section 6.1.2.2. |
| P50 | Notice-stimulus-at-cued-bottom-location-unalerted | Same as [P15] but the goal state is different which accounts for firing of an extra production for no alertness. |
| P51 | Notice-stimulus-at-uncued-bottom-location-unalerted | Same as [P40] except that the spread of attention is reduced as explained in section 6.1.2.2. |
| P52 | Disengage-production-unalert | Same as [P41] except that the spread of attention is reduced as explained in section 6.1.2.2. |
| P53 | notice-something-but-not-a-cue-unalerted | Same as [P3] but set the state S22 to indicate for later that this cue condition was under no alertness. Hence, the spread of attention is narrower as compared to alerting condition. |

Table 6-2: New states added to model-2 to create model-3 for simulating the auditory alerting and interactions of networks.

| State number | State description | Associated new productions |
|---|---|---|
| Stimulus processing stage | | |
| S19 | Shiftingtocue | P47 |
| S20 | Disengage-unalerted | P49, P51 |
| S21 | Shiftingtouncuedstimulus-unalerted | P52 |
| S22 | Surprise-unalert | P53 |

The state and flow diagram in Figure 6.2 describes how the states change and the control flows in model-3. For example, in the case of no-alerting sound, model-3 implements an extra production, which makes the system perform an additional state change – increasing the overall reaction time. In the case of an alerting signal, no such state switching is required. Shaded boxes denote changes to model-2 flow to create model-3.

To further explain the working of model-3, Figure 6.3 illustrates the working of the model by showing the state of the buffers and parameter settings under a certain cue – a flanker and alerting condition – thus capturing a snapshot of model-3. It also shows the simultaneous interaction of the visual and auditory modules with the device window, and depending upon the state of the goal buffer and the contents of the visual and aural buffer, the productions that match are fired. The event scheduler is running in the background and the parameter settings are shown.

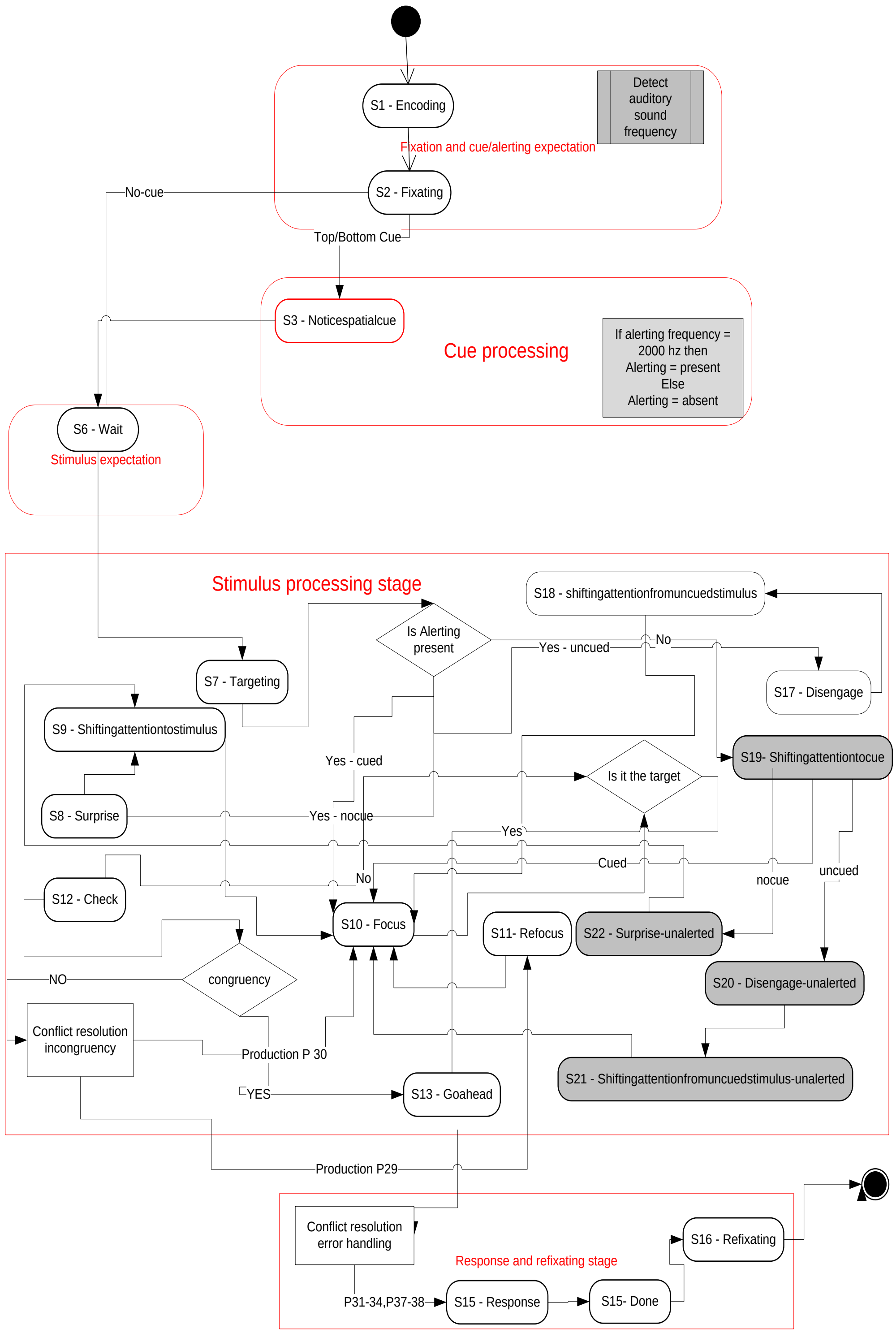



Figure 6-2: State and flow diagram for model-3.The shaded boxes are the new states and processes added to model-2 to create model-3.

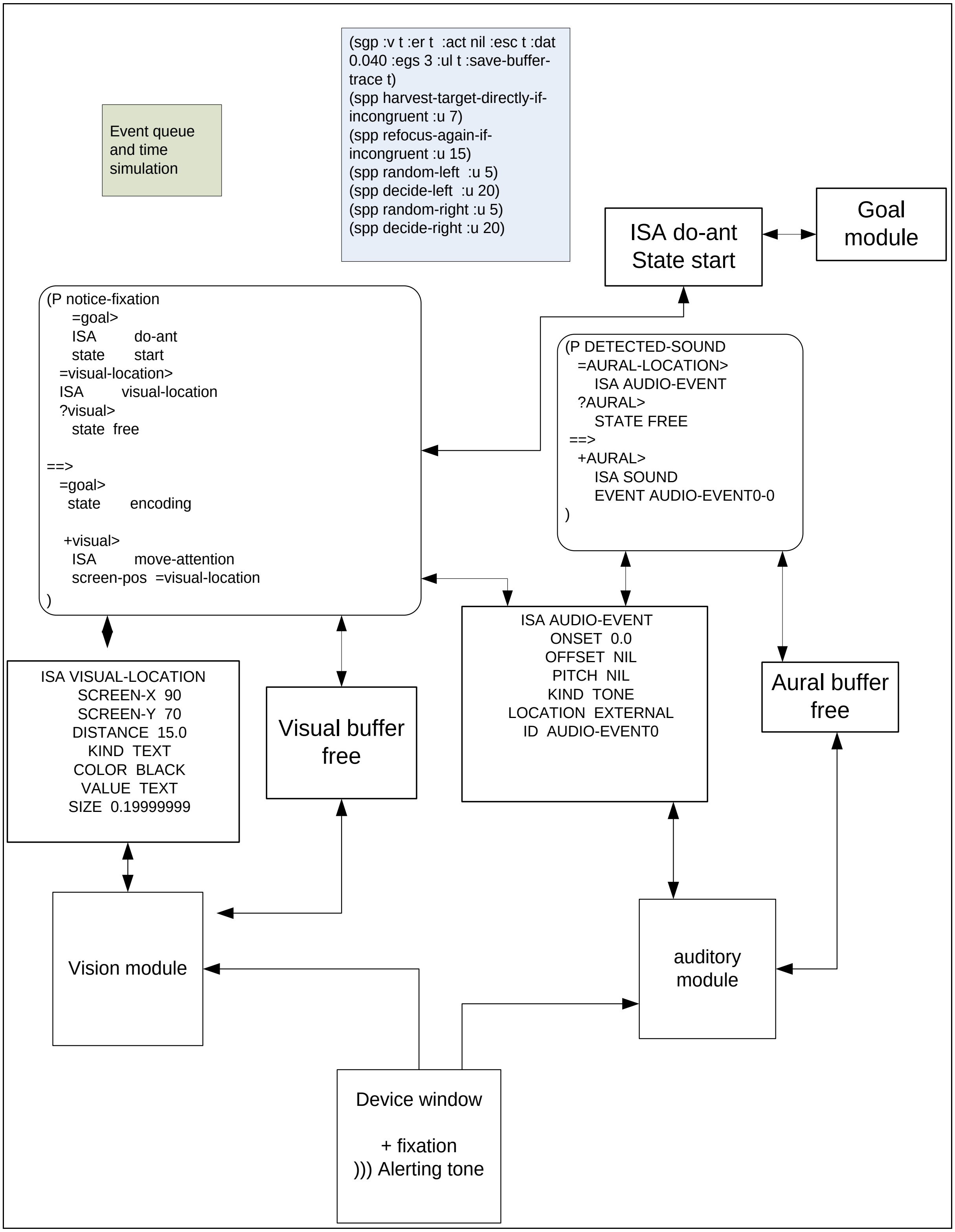



Figure 6-3: A snapshot of the cue and auditory signal processing stage showing the working of visual and auditory modules, along with interactions with the device window.

#### 6.1.2.4 Sub-symbolic components

In the human study (Callejas et al., 2004; 2005), it was observed that the alerting efficiency value is faster than reported in the original Fan et al., (2002) experiment, which may indicate that auditory alerting is much quicker and far more effective. To explore this change in auditory alerting efficiency, the alerting effect was made quicker by altering the rule firing time of the single production [P47], no-alertness from 40ms to 20ms (the range of values tried were between 10ms and 40ms using the command spp no-alertness: at 0.020). This data fitting revealed that, although auditory alerting may be quicker than visual alerting, once the state of alertness was achieved, the behaviour of the rest of the system remained the same. In other words, the orienting and executive efficiencies were similar, and even the interactions of the networks did not change. A detailed discussion on this and the reaction time data is given in the results section 6.1.4.1.

#### 6.1.2.5 Task setup

In order to deal with the auditory alerting condition, some changes were also made to the task setup of model-2. For example, the auditory module of ACT-R was used to produce alerting sounds, and then based on the frequency tone produced, a flag was set indicating whether alerting was present or absent. Model-3 is capable of handling an auditory sound which is processed by adding the following functionality to the experimental setup of the model: (new-tone-sound (case *tone* (0 2000) (1 1000) ) .5 onset-time). This function, new-tone-sound, takes two required parameters and a third optional parameter. The first parameter is the frequency of the tone to be presented to the model (2000 Hz or 1000 Hz), the second is the duration of the tone in seconds (0.5 seconds), and the third parameter, if specified, gives the time when sound is to be produced and, if omitted, the tone is to be presented immediately. The high frequency here, which is interpreted by the model as a ‘present’ alerting sound, is 2000Hz, whereas the lower sound is treated as alerting ‘absent’ and lasts for 0.5 s.

### 6.1.3 Calculating the behavioural interactions of networks: operational definitions[8]

The interaction effects of the networks on each other are calculated by comparing the effects under given cue and flanker conditions. Equations 6.4-6.18 give the calculations involved for calculating the effect of alerting on congruency, cueing on congruency and alerting on cueing. The net effects indicate whether the effect of one network on the other was positive or negative.

6.1.3.1 Alerting by congruency effect

The effect of alerting on congruency is calculated using Equations 6.4-6.5, which demonstrate the sum of the differences averaged for reaction times for all cueing and flanker conditions under alerting and no-alerting. The net effect is given in Equation 6.6.

$$\begin{aligned} Effect\ of\ alerting\ on\ congruency &= \{(RTalert, uncued, incong - RTalert, uncued, cong) \\ &+ (RTalert, cued, incong - RTalert, cued, cong) \\ &+ (RTalert, nocue, incong - RTalert, nocue, cong)\ \} \div 3 \end{aligned}$$ Equation 6.4

$$\begin{aligned} Effect\ of\ noalerting\ on\ congruency &= \{(RTnoalert, uncued, incong - RTnoalert, uncued, cong) \\ &+ (RTnoalert, cued, incong - RTnoalert, cued, cong) \\ &+ (RTnoalert, nocue, incong - RTnoalert, nocue, cong)\ \} \div 3 \end{aligned}$$ Equation 6.5

$$\begin{aligned} Net\ effect\ of\ alerting\ on\ congruency &= effect\ of\ noalerting\ on\ congruency \\ &- effect\ of\ alerting\ on\ congruency \end{aligned}$$ Equation 6.6

6.1.3.2 Cueing by congruency effect

The effect of cueing on congruency is calculated using Equations 6.7-6.8, showing the difference of the reaction times averaged for alerting/no-alerting for all flanker conditions for uncued and cued trials. The net effect is shown by Equation 6.9.

$$\begin{aligned} Effect\ of\ cueing\ on\ congruency &= \{(RTnoalert, cued, incong - RTnoalert, cued, cong) \\ &+ (RTalert, cued, incong - RTalert, cued, cong)\ \} \div 2 \end{aligned}$$ Equation 6.7

[8] The term ‘operational definitions’ was used by Fan and colleagues in their recent ANT study (Fan et al., 2009) and is borrowed from there.

$$Effect\ of\ uncueing\ on\ congruency \\ = \{(RTnoalert, uncued, incong - RTnoalert, uncued, cong \\ + (RTalert, uncued, incong - RTalert, uncued, cong)\} \div 2$$ Equation 6.8

$$Net\ effect\ of\ cueing\ on\ congruency \\ = (effect\ of\ uncueing\ on\ congruency \\ - effect\ of\ cueing\ on\ congruency)$$ Equation 6.9

6.1.3.3 Alerting by cueing effect

The effect of alerting by cueing is given by Equations 6.10-6.11, which show the difference of reaction times for uncued and cued trials for both flanker conditions. The net effect is given in Equation 6.12.

$$Effect\ of\ alerting\ on\ cueing \\ = \{(RTalert, uncued, incong - RTalert, cued, incong) \\ + (RTalert, uncued, cong - RTalert, cued, cong)\} \div 2$$ Equation 6.10

$$Effect\ of\ noalerting\ on\ cueing \\ = \{(RTnoalert, uncued, incong - RTnoalert, cued, incon \\ + (RTnoalert, uncued, cong - RTnoalert, cued, cong)\} \div$$ Equation 6.11

$$Net\ effect\ of\ alerting\ on\ cueing \\ = effect\ of\ noalerting\ on\ cueing - effect\ on\ alerting$$ Equation 6.12

### 6.1.4 Results

The model was run twenty-four times to simulate the human study (Callejas et al., 2005). Each trial was based on two auditory signals, three visual cues, two congruency conditions, two locations and two directions. The model's performance was compared against the human data (Callejas et al., 2005) (Experiment 1 data),[9] latency data, accuracy data, and efficiencies of the networks, and the interactions are given in detail in the subsections to follow.

[9] Callejas et al. (2005) conducted three experiments as part of this study, using two levels of stimulus onset asynchrony (SOA). It was also shown in the experiment that the effect of an auditory signal on the visual cue is only found when the stimulus onset asynchrony (SOA) is shorter. However, model-3 is not simulating the effect of variable SOA between cue and target. The way the model is set up is that the time the target appears to the time the response is made is recorded as the reaction time and thus no impact of SOA can be captured in the model.

#### 6.1.4.1 Latency data

The latency results produced by model-3, given in Table 6.3, show that the reaction times are reduced under all cue and flanker conditions when there is an explicit alerting signal present, as opposed to the condition where there is no-alerting signal present (Posner, 1978). Moreover, the reaction times are smaller when there is valid cueing provided before the appearance of the targets. These are expected results, and there is no deviation from the human study results.

Table 6-3: Reaction times generated by model-3 validated against human data (Callejas et al., 2005), given in brackets.

| | **No-alerting tone** | | | **Alerting tone** | | |
|---|---|---|---|---|---|---|
| | No cue | Cued | Uncued | No cue | Cued | Uncued |
| Congruent | 572 (561 ) | 499 (482) | 550( 561) | 522 (528 ) | 491 ( 442) | 538 ( 528) |
| Incongruent | 633 ( 649) | 562 (545 ) | 627 (639 ) | 606 ( 623) | 550 (528) | 627 (625 ) |
| Correlation | 0.98 | | | | | |
| RMSD | 10 | | | | | |

Figure 6.4 demonstrates that, under alerting, the average reaction times are lower compared to a no-alerting condition, in line with the human findings.

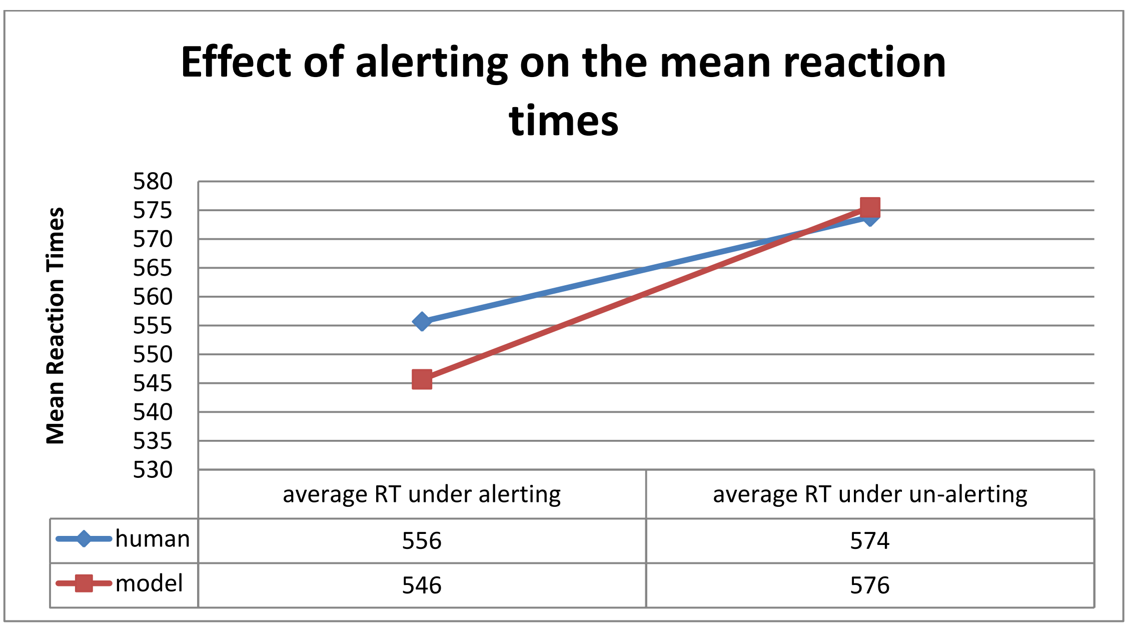



Figure 6-4: The mean reaction times for alerting and no-alerting for both the human study (Callejas et al., 2005) and model-3.

Figures 6.5 illustrates the mean reaction times under all cue and flanker conditions for alerting and no-alerting states for model-3 and the human study (Callejas et al., 2005).

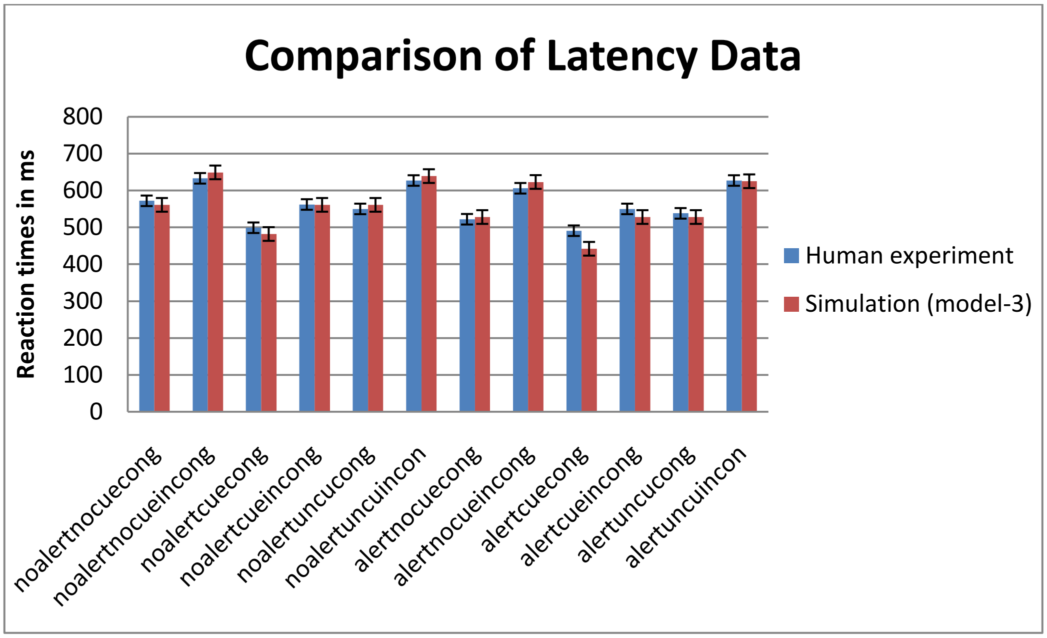



Figure 6-5: Comparison of latency data for human experiment (Callejas, et al., 2005) and model-3 results.

### 6.1.4.2 Effect of auditory alerting

Table 6.4 shows the difference in reaction times when model-3 is fitted to suit the reduced alerting efficiency by altering the rule firing time of the alerting-related production [P47] to 20ms.

Table 6-4: Results generated by model-3 along with human data (Callejas et al., 2005), given in brackets. Here the alerting production's firing time is set to 20ms.

| | **No-alerting tone** | | | **Alerting tone** | | |
|---|---|---|---|---|---|---|
| | **No cue** | **Cued** | **Uncued** | **No cue** | **Cued** | **Uncued** |
| **Congruent** | 572 (542 ) | 499 (464) | 550( 542) | 522 (528 ) | 491 ( 441) | 538 ( 526) |
| **Incongruent** | 633 ( 618) | 562 (545 ) | 627 (630 ) | 606 ( 617) | 550 (520) | 627 (617) |
| **Correlation** | 0.99 | | | | | |
| **RMSD** | 15 | | | | | |

It was observed that none of the other effects or interactions changed due to this variation, which indicates that auditory alerting may be quicker than visual alerting, but once the state of alertness has been achieved, the behaviour of the rest of the system remains the same and the orienting and executive efficiencies are similar. Even the interactions of the networks do not change. Therefore, irrespective of whether alerting is auditory or visual, the other network efficiencies and the interactions remain unchanged. This is also supported by the literature, where both the visual and auditory versions of the ANT were given to participants (Roberts, Summerfield & Hall, 2006). It was established that not only is there no significant difference in the magnitudes of alerting and visual alerting, but also the benefits gained from auditory alerting are no different from those of visual alerting (Roberts, et al., 2006). Consequently, introducing an alerting signal here just helps to measure the efficiency score explicitly. There is also evidence from the neuroscientific literature that the neural correlates of auditory and visual alertness may be supramodal (Thiel & Fink, 2007; Pardo, Fox & Raichele, 1991; Sturm & Willmes, 2001). Hence, these findings indicate that “alerting may be a general attentional resource which is unaffected by task modality” (Roberts et al., 2006, p. 490). Model-3’s efficiencies and interactions under reduced alerting effect results are shown in sections 6.1.4.4 and 6.1.4.5 respectively.

#### 6.1.4.3 Accuracy data

Table 6.5 compares the accuracy data for model-3 and the human study (Callejas et al., 2005). Looking at the accuracy data, a few observations can be made. In the case of congruent conditions, the error percentages are lower than those for the incongruent condition. There is no significant difference for accuracy between alerting and no-alerting states; so, unlike for the latency conditions, accuracy does not show any significant improvement due to alerting. Therefore, model-3 simulates the accuracy results of the human data well, as exemplified by the correlations and RMSD of 0.85 and 0.6, and there is no deviation from the human findings.

Table 6-5: Accuracy data produced by model-3 evaluated against human data (Callejas et al., 2005).

| | **No-alerting tone** | | | **Alerting tone** | | |
|---|---|---|---|---|---|---|
| | **No cue** | **Cued** | **Uncued** | **No cue** | **Cued** | **Uncued** |
| **Congruent** | 1.2(1) | 0.5(0.7) | 2(1.6) | 1.9(0.5) | 1.1(0.7) | 4.8(0.3) |
| **Incongruent** | 7.6(3.5) | 4.4(2.6) | 10.9(3.9) | 6.3(2.3) | 3.9(2.1) | 7.7(4.2) |
| **Correlation** | 0.85 | | | | | |
| **RMSD** | 0.6 | | | | | |

### 6.1.4.4 Efficiencies of attentional networks

Using equations 6.1-6.3, network efficiencies were calculated as illustrated in Figure 6.6. As mentioned earlier in section 6.1.4.2, model-3 was adjusted to simulate the reduced alerting effect. Model-3 variation1 is the initial simulation of Callejas et al.,'s (2005) study, while model-3 variation2 is the variation altering the model by quickening the alerting efficiency. As a result, reducing the firing time of no-alertness production from 40ms to 20ms produced the effect of making the efficiency of alerting faster, but the efficiencies of the orienting and executive control remained the same; even the interactions remained the same (as seen in section 6.1.4.5).

The correlation and RMSD for the human data with model-3 variation1 is 0.98 and 11, whereas for model-3 variation2 they are 0.96 and 10. In sum, there was not much difference in the correlations and RMSDs of these two data sets.

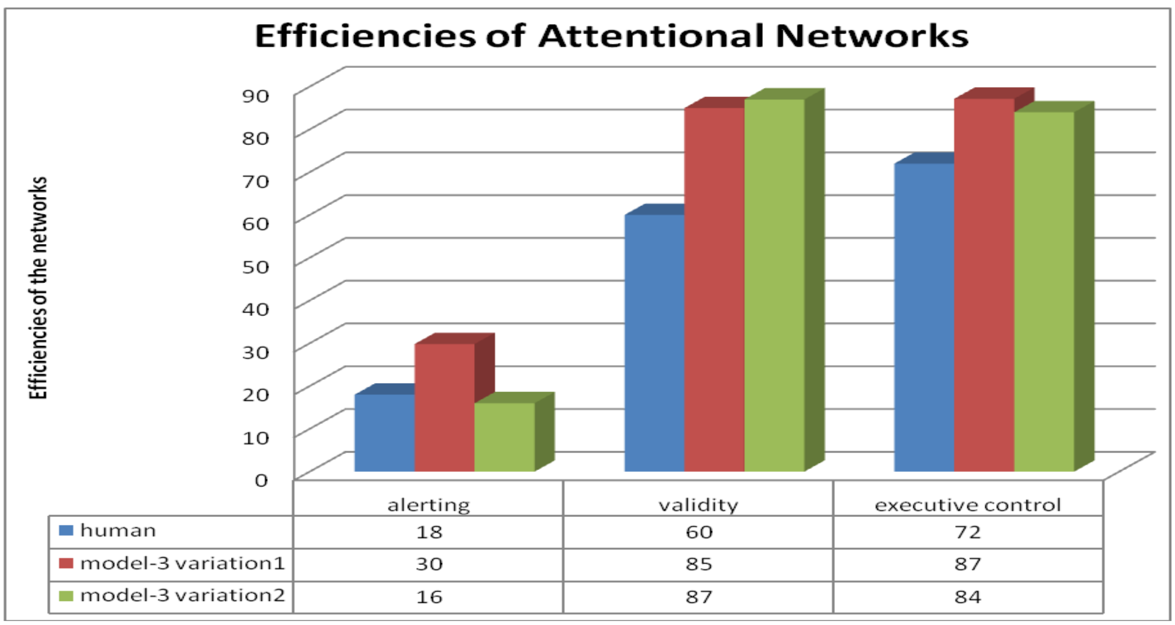



Figure 6-6: Efficiencies of attentional networks compared with the human study (Callejas et al., 2005). Model-3 variation1 denotes the simulation with unaltered alerting network efficiencies, whereas model-3 variation2 denotes the no-alertness fired at 20ms.

### 6.1.4.5 Interactions between attentional networks

Based on the operational definitions calculated in section 6.1.3, the behavioural interactions of the networks are reported. Model-3 simulated the human data (Callejas et al., 2005), showing that the alerting network had an inhibitory influence on the congruency effect, the orienting network had a positive influence on the control network, and the alerting network showed acceleration in orienting.

Model-3 handled both the alerting by congruency and cueing by congruency effects through manipulating the range of values that are available for selection. It was also observed while data fitting that if the negative effect of alerting on congruency was reduced, then the validity effect on congruency increased, showing the benefit of cueing. The graph in Figure 6.7 illustrates the interactions between the networks of alerting, orienting and executive control from the human study (Callejas et al., 2005) and model-3 as explained below.

#### 6.1.4.5.1 Alerting by congruency

It is evident from the graph in Figure 6.7 that when there is alerting, the congruency effect is higher as opposed to the condition when there is no-alerting effect, hence giving a negative net effect of alerting on the flanker effect. Thus, in order to enhance fast responses to sensory inputs, the attention system may be slowed down from focusing on the stimulus, which may ultimately affect the conflict resolution process.

#### 6.1.4.5.2. Cueing by congruency

If a spatial cue is given before the appearance of the target, then this has a positive effect on the flanker effect. The positive net effect showed that when the location of the target was cued, the congruency effect was smaller compared to the condition in which the location of the target was cued in the opposite location, as illustrated in Figure 6.7.

#### 6.1.4.5.3. Alerting by cueing

The graph in Figure 6.7 indicates that when there is an alerting signal, the cueing effect is faster than the condition when there is no-alerting signal; this is referred to as the ‘speeding up effect’ of alerting on orienting in the Callejas et al., (2005) study.

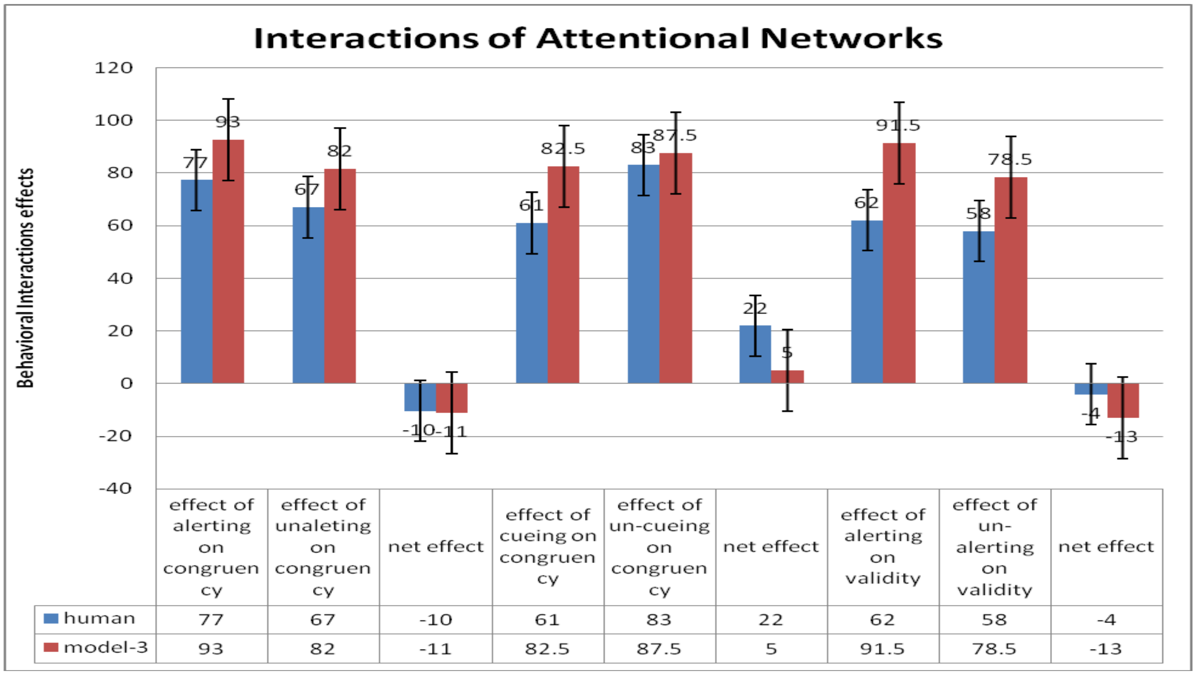



Figure 6-7: Interactions between the networks, model-3 simulates human study (Callejas et al., 2005). Error bars indicate standard errors.

### 6.1.5 Summary of the results and model validation

Based on the statistics of the correlations, RMSDs (and also F-values for interactions) on all measures of latency, accuracy and efficiencies, model-3 is shown to be a valid simulation of the human study (Callejas et al., 2004; 2005). The correlations and RMSDs for the latency data, accuracy data and efficiencies of the three networks of alerting, orienting and control are summarised in Table 6.6. Model-3 variation1 is the initial simulation of the human study (Callejas et al., 2004; 2005), while model-3 variation2 is the alerting efficiency fitted further to the human alerting efficiency level (by reducing the firing time of the alerting production to 20ms).

Table 6-6: Summary of the correlations and root mean square deviations for the latency, accuracy and efficiency data of model-3 variations compared against the human data (Callejas et al., 2005).

| | Correlation ( r ) | Root Mean Square Deviation |
|---|---|---|
| **Human data/ model-3 Variation1** | | |
| Latency | 0.98 | 10 |
| Accuracy | 0.8 | 0.6 |
| Efficiencies of networks | 0.98 | 11 |
| **Human data/ model-3 Variation2** | | |
| Latency | 0.99 | 15 |
| Accuracy | 0.8 | 0.6 |
| Efficiencies of networks | 0.96 | 10 |

In addition to using correlations and RMSD, the latency data were also entered in a 2 X 3 X 2 repeated measures within subject ANOVA table. A statistically significant effect of alerting, cueing and the flanker effect was observed. Responses were faster in trials where there was an alerting signal ($F_{(1,46)} = 100.49$; $p < 0.0001$); cued trials ($F_{(2,92)} = 83.59$; $p < 0.0001$) and in congruent trials ($F_{(1,46)} = 310.43$; $p < 0.0001$). Behavioural interactions between networks were shown in the results, and the following statistically significant interactions were seen from the model results: alert by cue interaction was significant ($F_{(2,92)} = 4.8$; $p = 0.01$), as was the alert by flanker interaction ($F_{(1,46)} = 7.4$; $p = 0.009$). These significant effects were the same as found in the human study (Callejas et al., 2005). Hence, model-3 is shown to be a valid simulation of the human study.

## 6.2 Discussion and chapter summary

The purpose of this chapter was to explore the interactions of attentional networks through the modelling of a revised ANT study which shows various network interactions (Callejas et al., 2005). The results of model-3 on all measures of latency, accuracy, efficiencies and interactions validated the simulation. Model-3 shows the same interactions as the human study and does not predict anything more than what is known about the interactions or deviate from the human study. However, it does make some important contributions towards the understanding of interactions of the networks.

1. Based on the way human behaviour is simulated in model-3, it is suggested how and why the networks may be interacting. For example, the use of the varying spread of visual attention and the command set-visloc-default, which is described earlier in section 6.1.3.2, produces beneficial effects in both cued and congruent conditions, but no advantage in all other cue and flanker conditions. So, by increasing the spread of visual attention, alerting increases the congruency effect and cueing decreases the congruency effect. Therefore, if the range of focus is reduced, then the congruency effect will reduce and the cueing effect will increase. Furthermore, if the range of focus is increased, the alerting effect increases congruency but decreases the cueing effect, so a “double cause”

of cueing (as pointed out by Callejas et al., 2005, p. 35) has been shown by the working of the model.

2. Another important observation was regarding the impact of auditory alerting. The human study reported faster alerting efficiency if auditory cues were used. To see the change in this behaviour, in model-3 the alerting efficiency was reduced by altering the rule firing time of the production no-alertness (the rule firing time was reduced from 40ms to 20ms). The alerting time when reduced, though, gave a better fit to alerting efficiency value; no other data produced by the model changed, but the overall efficiencies and even the interactions were the same. This indicates that auditory alerting may be quicker, but once the alerting has been achieved, the interactions of the networks do not necessarily change, i.e. the effect on each other remains the same.

The next two chapters explore the behaviour and interactions of attentional networks in various pathologies and in children using the modelling work and the insights gained from modelling elucidated so far in this thesis.

# 7. Modelling Attention-Related Pathologies

In Chapter 5 of this thesis, model-1 and model-2 established the working of valid models of performance on healthy adults on the original ANT (Fan et al., 2002) and the ANT extended with an invalid cueing. In Chapter 6, model-3 explored attentional network interactions by simulating the human study (Callejas et al., 2004; 2005). In this chapter, model-1 and model-2, along with insights gained from how the modulation effect is simulated in model-3, are modified to simulate human studies that assess the performance of Alzheimer’s disease and mild traumatic brain injury (mTBI) patients on the ANT (Fernandez-Duque & Black, 2006; Halterman et al., 2006).

The objective here, again through cognitive modelling, is to gain understanding about the behaviour and efficiencies of attention networks in various attention-related pathologies. The reason for choosing these two pathologies in addition to the advantage that human data were available for these studies is as follows: The Alzheimer’s disease simulation is a sort of static model that captures behaviour in a particular point in time for AD patients, whereas the mTBI model(s) simulates behaviour over a trajectory of time, that is over a recovery period of thirty days.

Two main subsections cover this area of study: section 7.1 explicates the simulation of AD patients’ performance on the ANT. This is referred to as ‘model-2-AD’ because model-2 is applied/modified to simulate the AD patients’ performance. Section 7.2 explicates the simulation of the performance of mTBI patients on the ANT. This is referred to as ‘model1-mTBI’ and ‘model2-mTBI’ (here, both model-1 and model-2 are modified and applied). The results produced by the models are validated against human studies and further based on the model results and the data fitting process, informed mostly by the literature, observations/predictions are made about the efficiencies and interaction of the attention networks in both pathologies.

## 7.1 Model-2-AD – Simulation of performance on ANT of Alzheimer's disease patients

### 7.1.1 About Alzheimer's disease

Alzheimer's disease (AD) is a progressive and fatal brain disorder. The condition gradually destroys brain cells, causing problems with memory, thinking and behaviour, and affecting work and/or social life. The brain has 100 billion nerve cells (neurons), each of which communicates with many others to form networks. These nerve cell networks have special jobs that involve thinking, learning, remembering and sensory capabilities. In Alzheimer's disease, parts of the cell's factory stop functioning causing these cells to lose their ability to do their jobs well, which can have serious effects (http://www.alz.org/alzheimers_disease_what_is_alzheimers.asp).

Evidence in the literature supports the view that breakdowns in attention may be an indication that a patient is suffering with early symptoms of Alzheimer's-related dementia (Levinoff, Saumier & Chertkow, 2005). Although AD is mainly a condition of the elderly, it has been established that age may be of less importance than the brain network affected. A survey of the neuropsychology literature shows that processing speed, also referred to as 'mental slowing' or 'performance variability' (Gorus, de Raedt, Lambert, Lemper & Mets, 2008; Warkentin, Erikson & Janciauskiene, 2008; Nestor, Parasuraman & Haxby, 1991), executive control network efficiency (Perry & Hodges, 1999; Wylie, Ridderinkhof, Eckerle & Manning, 2007) and orienting network efficiency (Parasuraman, Greenwood, Haxby & Grady, 1992; Parasurman & Haxby, 1993) deteriorate with Alzheimer's.

### 7.1.2 Design and functionality of model-2-AD

Model-2-AD simulates the performance of Alzheimer's disease patients on a revised ANT design (Fernandez-Duque & Black, 2006). This study reported the performance of young adults (average age 19 years), older healthy adults (average age 73 years) and AD patients, average age 75 years. Recall that this study was modelled in section 5.2 as 'model-2', using only the data of healthy subjects. Therefore, model-2's design and settings are the baseline, and modifications are made to fit the AD patients' data. The flowchart for model-2 is given in Figure 5.10. The basic design and the functionality of the model remain unchanged. The efficiency of the networks is measured using Equations 2.1, 2.3 and 5.2, and the network interactions calculated using Equations 7.1-7.4 (the use of these operational definitions has been explained in section 6.1.3 in the context of network interactions).

$$effect\ of\ alerting\ on\ congruency = (RTalert_{incong} - RTalert_{cong}) \quad \text{Equation 7.1}$$
$$effect\ of\ noalerting\ on\ congruency = (RTnocue_{incong} - RTnocue_{cong}) \quad \text{Equation 7.2}$$
$$effect\ of\ cueing\ on\ congruency = (RTcued_{incong} - RTcued_{cong}) \quad \text{Equation 7.3}$$
$$effect\ of\ uncueing\ on\ congruency = (RTuncued_{incong} - RTuncued_{cong}) \quad \text{Equation 7.4}$$

### 7.1.3 Justification and data fitting

According to the human study (Fernandez-Duque & Black, 2006), the AD patients were reported to have overall higher latency and error rates. The errors arose more due to the incongruency condition that is errors of commission. The human study also reported that alerting and orienting network efficiency remained unaffected, but the executive control network was impaired. Reporting on the interactions of the networks, it was observed that alerting had an inhibiting effect on congruency, while validity showed no beneficial effect on congruency.

To reflect the changes in attention network functionality observed in this study, logical changes were made to model-2, after which the results were recorded. Modifications were made by altering the parameter/production settings by changing the rule firing time, utility values handling executive control networks, and so on. Two sets of modifications (out of the many tried) that produced good statistical fits and were informed by AD literature are reported here, and based on these findings an analysis is undertaken and observations made. The process of data fitting involved first determining what parameter/production settings needed to be altered, and then systematically altering one setting at a time until a good fit was found based on the latency, accuracy and efficiencies of the three networks. The changes to model-2 along with a justification for the changes are explained below.

#### 7.1.3.1 Increased latency

Overall, slow reaction times can correspond to the overall slowdown in the processing of each step of the task. This can be simulated by altering the overall firing time of each production in model-2. The firing time used for the healthy adult model (model-2) was 40ms and thus much higher values were tried until a fit to the human data was found. The range of values tried was from 40-150ms. Two sets of values produced results that were taken to be good fits – the first was with a rule firing time of around 62ms and the second at 80ms (obviously, close value ranges also worked, but for the purpose of reporting exact reaction times in the thesis, the best specific values are given). The slowing down of the rule firing time corresponds to the mental slowing/cognitive slowing or performance variability in AD patients, as found in the literature (Gorus, et al., 2008; Warkentin, et al., 2008; Nestor, Parasurman & Haxby, 1991, Nebes, Brady, Reynolds, 1992). For example, Nestor and colleagues (1991) administered variations of choice-RT tests on a group of AD patients along with controls. It was observed that AD patients showed slow down in information processing. The authors suggested that this slowing could be related to complexity and attentional demands. Also, Nebes and colleagues (1992) using an enumeration task showed that response time slowing on psychological tasks is found both in Alzheimer's disease and depression. Data was recorded for four subject groups (Alzheimer patients, depressed geriatric patients, healthy old controls, and healthy young controls) and it was observed that response time increased linearly with array size. The slope of this linear function was significantly greater in the Alzheimer patients, suggesting the presence of a cognitive slowing in Alzheimer's disease.

#### 7.1.3.2 Decreased accuracy

Based on previous work in the literature on inducing errors of commission in AD patients (Serna, et al., 2007), utility values of the error productions were altered and the best fit to the data was achieved with values 5, 10 and 20 for two sets of productions error-left and error-right [P37, P38]; random-left and random-right [P33, P34]; decide-left and decide-right [P31, P32] (these error-related productions are described in detail earlier in section 5.1.3.3.4). Consequently, a utility value of 5 was set for [P37] and [P38], 10 for [P33] and [P34], and 20 for [P31] and [P32]. Compared with the healthy human model setting, this reflects an increase in probability of the participant giving an erroneous response in the case of incongruency rather than just a random response, i.e. the utility values for productions [P37] and [P38] are set higher.

#### 7.1.3.3 Impaired executive control network

Based on how the executive control network is implemented and mapped onto the dual-process model (see section 5.1.3.1.3), there could be two reasons why the executive control network was impaired. The deficit in this network could mean either (1) a higher chance of using the strategy of refocusing every time a distracter is encountered or (2) taking longer to refocus after distraction. These correspond to (1) altering the utility values of the productions harvest-target-directly-if-incongruent [P29] and refocus-again-if-incongruent [P30] or (2) increasing the rule firing time of the production [P30], which is responsible for refocusing in order to handle distraction (the workings of each of these incongruency handling productions are described in detail in section 5.1.3.1.3). There is evidence in the literature that in AD and other pathologies the response inhibition of the executive function is impaired, and therefore this is the justification for changing utility values in simulating the behaviour of patients with AD (this corresponds to condition option (1)); response inhibition helps to resolve conflict (Perry & Hodges, 1999, Wylie et al., 2007). Perry and Hodges (1999) observed in their study that the attentional tasks particularly affected in AD patients were those involving response inhibition, target selection or switching. Based on this, they suggested that it was not the facilitatory functions of attention, such as detecting targets that were hampered; rather it was the coping with the interference that was particularly impaired. Wylie and colleagues (2007) administered the flanker test (Eriksen & Eriksen, 1974) to participants diagnosed with mild cognitive impairment (MCI, a condition which warrants a diagnosis of AD). They observed that these patients exhibit greater difficulty resolving conflict which appears to arise more from an inefficient response inhibition function.

#### 7.1.3.4 Stable alerting and orienting network

Since the alerting and orienting networks were reported to be stable in the human study, model-2-AD simulated this effect by keeping the rule firing times of the productions responsible for simulating the alerting and orienting effect at 40ms (the setting used for healthy models). Recall that the production responsible for inducing a surprise state in the case of no-alerting is the production [P4], not-cue-so-switch-state, and to induce a delay effect due to disengagement required after an invalid cue is processed is [P41], disengage-production.

#### 7.1.3.5 Summary of model-2-AD's settings

As mentioned earlier, multiple ways of data fitting were explored; the results from the two best fits are reported and analysed in the results section and the modifications summarised in Table 7.1. There are six columns in this table, the first of which denotes the group, that is settings used for simulation of performance on ANT of AD patients and healthy adults (variation1 and variation2 are two different sets of parameter settings for model-2-AD). Settings for the healthy model are also given for reference purposes. The second column gives values for the overall rule firing time for each group. The third column gives the value of the firing time used for production [P4], which is responsible for inducing the alerting effect in the models. The fourth column gives the value used for production [P41], which simulates the effect of disengaging from an invalidly cued location, while the fifth column denotes the utility values for error inducing productions [P31-P34] and [P37-38]. Finally, the last column describes the settings of the utility values of productions [P29] and [P30], which deal with conflict resolution. Also, the firing time of production [P30] is slowed down, which simulates the slower refocusing capacity of AD patients. All these productions are explained in Table 5.3 and 5.13.

Table 7-1: Summary of modifications to model-2 to create model-2-AD that simulates AD patients' performance on the ANT.

| **Group** | **Overall Rule firing** | **Firing time for P4 (Alerting)** | **Firing time for P41 (Disengage Effect)** | **Utility values for productions P31-P34,P37-38** | **Utility values for conflict handling productions P29 and P30** |
|---|---|---|---|---|---|
| Variation1 for model-2-AD | 62 | 40 | 40 | 5,10,20 | 5, 20, refocusing production P30 fired at 120 ms |
| Variation2 for model-2-AD | 80 | 40 | 40 | 5, 10, 20 | 5, 20, refocusing production P30 fired at 120 ms |
| Healthy model settings | 40 | 40 | 40 | 5,8,20 | 7, 15, refocusing production fired at 40 ms |

### 7.1.4 Results

The Fernandez-Duque and Black (2006) study involved thirteen participants and the design of the experiment was two locations, two directions, four cues and two flanker conditions, representing a block of thirty-two trials. There were total of five blocks, so a total of 160 trials for each subject. The same design was replicated in the model and mean reaction times, and error percentages and network efficiencies were recorded for model-2-AD. Further statistical evaluations and a comparison of the results were undertaken to determine the goodness-of-fit of model-2-AD (two variations are used based on data fitting settings summarised in Table 7.1).

#### 7.1.4.1 Latency data

Latency data from model-2-AD closely simulate the findings of the human study (Fernandez-Duque & Black, 2006). First of all, the overall reaction times were slower in the AD model than the healthy subject model, and both groups responded slower to the incongruent conditions compared to the congruent conditions, showing the effect of greater difficulty in resolving conflict. Reaction times were faster when the target appeared at the cued location or when an alerting signal was given before the appearance of the target. Table 7.2 shows three sets of latency data: (1) the mean reaction times for each cue and flanker condition for healthy young adults, (2) results produced by variation-1 of model-2-AD and (3) results produced by variation-2 of model-2-AD. Correlations and RMSDs are shown for each set of data. Both variations of the model fitted the data well with high correlations, but the second variation produced better (that is lower) RMSDs.

Table 7-2: Latency data from the human study (Fernandez-Duque & Black Study, 2006) and simulation results from the two model-2-AD variations.

| Latency Data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Alert | | No Cue | | Valid | | Invalid | |
| Group | Cong | Incong | Cong | Incong | Cong | Incong | Cong | Incong |
| Healthy Subject | 455 | 566 | 493 | 574 | 429 | 538 | 495 | 600 |
| Healthy Model | 469 | 570 | 523 | 603 | 443 | 514 | 526 | 617 |
| Correlation | 0.96 | | | | | | | |
| RMSD | 22 | | | | | | | |
| AD Subject | 761 | 948 | 851 | 947 | 729 | 889 | 817 | 982 |
| Variation1 model-2-AD | 564 | 720 | 622 | 745 | 525 | 651 | 628 | 768 |
| Correlation | 0.98 | | | | | | | |
| RMSD | 213 | | | | | | | |
| AD Subject | 761 | 948 | 851 | 947 | 729 | 889 | 817 | 982 |
| Variation2 model-2-AD | 642 | 815 | 706 | 842 | 587 | 725 | 713 | 870 |
| Correlation | 0.97 | | | | | | | |
| RMSD | 130 | | | | | | | |

#### 7.1.4.2 Accuracy data

As reported in the human study (Fernandez-Duque & Black, 2006), in addition to overall slower reaction times, the AD subjects were also less accurate. Table 7.3 records the percentage of errors for both healthy and AD subjects, as generated by the human study (Fernandez-Duque & Black, 2006) and ACT-R models. The correlations and RMSDs of the data show a good fit of the model to the data. Here again, three sets of data are given, which show the healthy human model performance along with two variations of model-2-AD. Both variations of model-2-AD produced equally good fits (more so because both variations simulated errors in the same way).

Table 7-3: Accuracy Data from the human study (Fernandez-Duque & Black, 2006) and simulation results from the two model-2-AD variations.

| Accuracy data | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Alert | | No Cue | | Valid | | Invalid | |
| Group | Cong | Incong | Cong | Incong | Cong | Incong | Cong | Incong |
| Healthy Subject | 1.9 | 8.1 | 1.2 | 5.5 | 0.4 | 7.6 | 1.5 | 6.2 |
| Healthy Model | 0.8 | 5 | 3.8 | 6.3 | 2.5 | 6.30 | 1.7 | 8.8 |
| Correlation | 0.76 | | | | | | | |
| RMSD | 1.6 | | | | | | | |
| AD Subject | 3.6 | 9.3 | 2.8 | 7.2 | 2.2 | 8.3 | 2.8 | 8.5 |
| Variation1 model-2-AD | 1.8 | 9.2 | 4.2 | 9.2 | 2.7 | 9.6 | 2.7 | 10 |
| Correlation | 0.95 | | | | | | | |
| RMSD | 1.29 | | | | | | | |
| AD Subject | 3.6 | 9.3 | 2.8 | 7.2 | 2.2 | 8.3 | 2.8 | 8.5 |
| Variation2 model-2-AD | 3.5 | 8.5 | 1.9 | 10.4 | 3.8 | 7.7 | 2.3 | 11.2 |
| Correlation | 0.9 | | | | | | | |
| RMSD | 1.6 | | | | | | | |

7.1.4.3 Efficiencies of attentional networks

The efficiencies of the networks using the latency data are calculated using Equations 2.1, 2.3 and 5.2. Table 7.4 shows efficiencies of the three networks for the healthy model, as well as from the two model-2-AD variations. Correlations and RMSDs for each comparison are also given. Looking at the effeiciency data, it was observed that both variations of the model showed that alerting network efficiency remained stable, whereas the conflict resolution ability was impaired for AD patients. The data fitting process suggests that the reason for impairment in the executive control network could be impaired response inhibition functions and/or AD patients taking longer to refocus if distracted. This is also suggested by the literature on impairment in the executive control network in AD patients (Perry & Hodges, 1999; Wylie, et al., 2007).

However, the interesting observation here was that both variations of model-2-AD show a deficit in the orienting network. In fact, the second variation, which actually has a better statistical fit from the point of view of low RMSD, shows more impairment than the first variation. Although the human study carried out by Fernandez-Duque and Black (2006), which is simulated here, did not report any impairment in the network of orienting, there is evidence in the neuropsychology literature (Buck, Black, Behrmann, Caldwell, Bronskill, 1997; Parasuraman et al., 1992) that patients may have difficulty orienting to target locations. There is further evidence in the literature that the ability to disengage is impaired in AD patients, but not the engage or move components of orienting (Parasuraman et al, 1992; Parasurman & Haxby, 1993; Perry and Hodges, 1999). This is discussed further in section 7.1.6.

Table 7-4: Efficiencies of the attentional networks shown for the human study (Fernandez-Duque & Black, 2006) and both variations of model-2-AD.

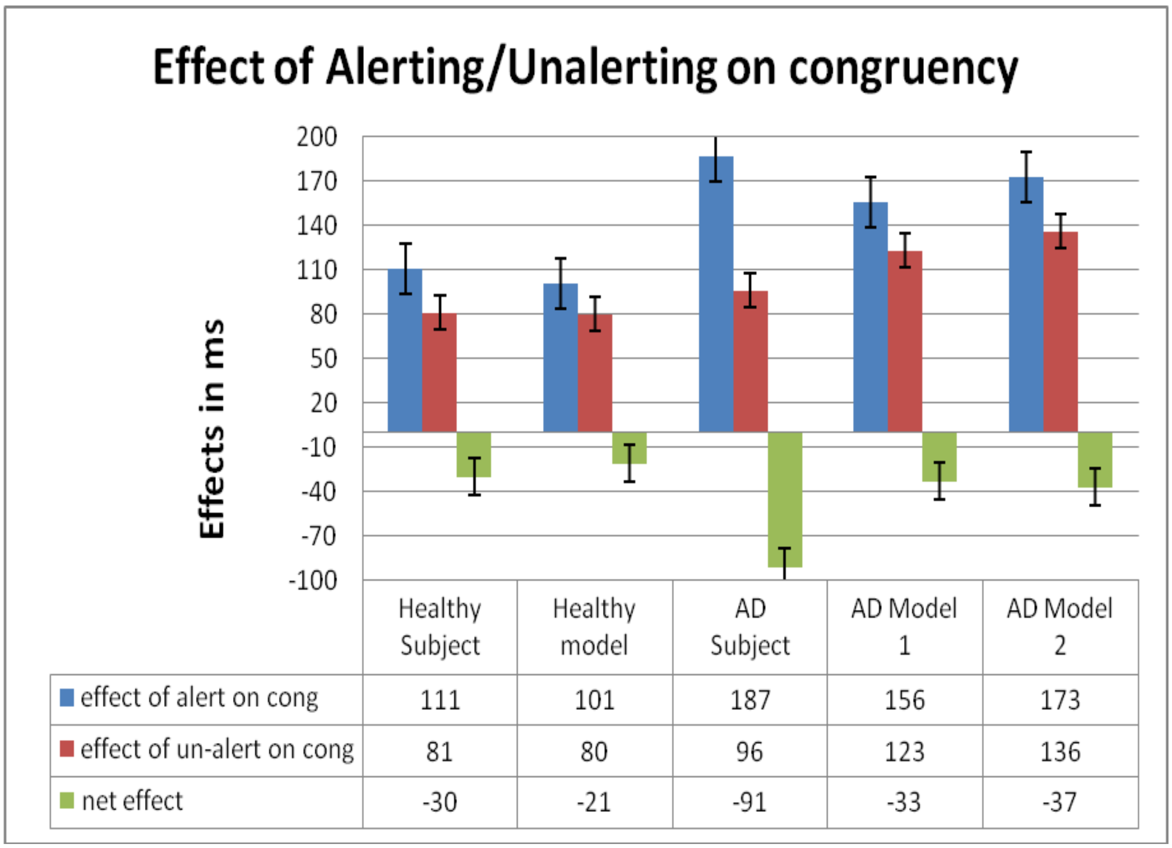
| Efficiencies of Attentional Networks | | | |
|---|---|---|---|
| | Alerting | Validity | Executive Control |
| Healthy subject | 23 | 64 | 102 |
| Healthy model | 43.5 | 93 | 86 |
| Correlations | 0.81 | | |
| RMSD | 22 | | |
| AD subject | 44.5 | 90.5 | 152 |
| Variation 1 model-2-AD | 42 | 109 | 136 |
| Correlations | 0.95 | | |
| RMSD | 14 | | |
| AD subject | 44.5 | 90.5 | 152 |
| Variation 2 model-2-AD | 45 | 135 | 151 |
| Correlations | 0.9 | | |
| RMSD | 25 | | |

7.1.4.4 Interactions between attentional networks

Network effects are calculated using Equations 7.1-7.4. Based on the model results, the AD patients showed similar interactions as found earlier in healthy subjects in Callejas et al.'s (2004, 2005) study and simulated in Chapter 6. Consequently, alerting had an inhibiting effect on the congruency effect. Regarding the effect of validity on congruency, the Fernandez-Duque and Black (2006) experiment (in disagreement with other findings (Callejas et al., 2004; 2005)) indicates that validity may not necessarily help in resolving conflict for the healthy subject, but does have a positive effect for AD patients. The results from model-2 and model-2-AD do not agree with these findings

(Fernandez-Duque & Black, 2006); rather, they are in agreement with other studies (Callejas 2004; 2005; Fan et al., 2009) indicating that validity of the cue has a facilitatory effect on congruency.

The negative net effect of alerting on congruency and the positive net effect of cueing on congruency are illustrated in Figures 7.1 and 7.2 respectively. Healthy human data and AD patient data are taken from the Fernandez-Duque and Black (2006) study, whereas the healthy model's data are the results of model-2, and the AD model's data are the results produced by model-2-AD.




| | Healthy Subject | Healthy model | AD Subject | AD Model 1 | AD Model 2 |
|---|---|---|---|---|---|
| effect of alert on cong | 111 | 101 | 187 | 156 | 173 |
| effect of un-alert on cong | 81 | 80 | 96 | 123 | 136 |
| net effect | -30 | -21 | -91 | -33 | -37 |

Figure 7-1: Interactions of the networks showing the effects of alerting/un-alerting on the congruency networks for healthy adults and AD patients (human and model). Bars indicate standard errors. AD model 1 is variation 1 and AD model 2 is variation 2.

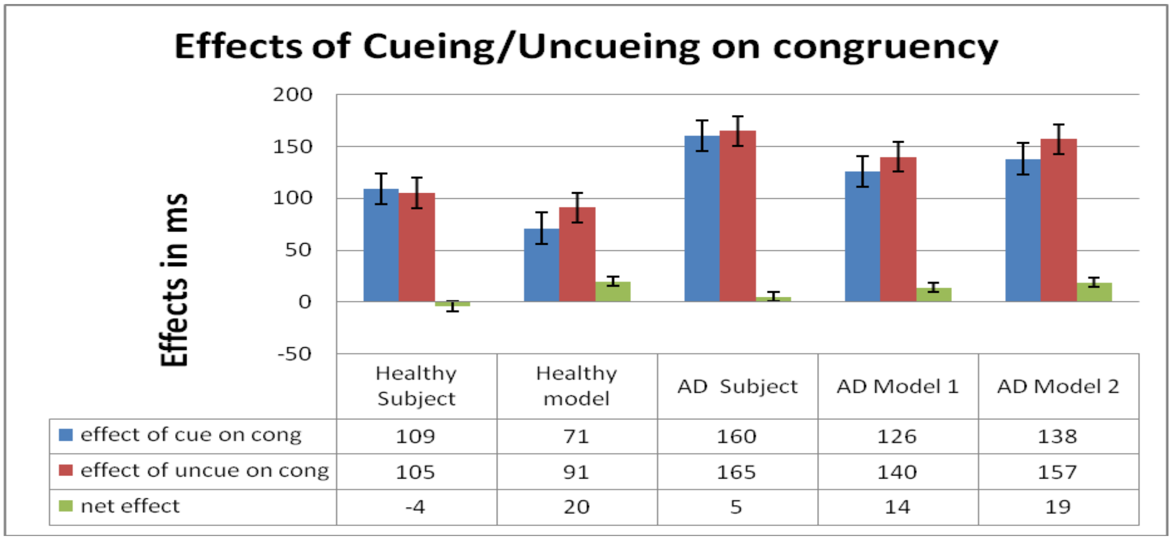



Figure 7-2: Interactions of the networks showing the effects of cueing and uncueing on the congruency networks (human and model). Bars indicate standard errors. AD model 1 is variation 1 and AD model 2 is variation 2.

### 7.1.5 Summary of results and model validation

Section 7.1.4 provided detailed tabulated results for both variations of model-2-AD, simulating the performance of AD patients on the ANT along with healthy human/model data on all measures of latency, accuracy, efficiencies of networks and behavioural interactions. The correlations and RMSDs of all these measures are summarised in Table 7.5 for overview and discussion. Looking at the efficiencies of the networks, variation1 has a slightly better fit to the human data when looking at the efficiencies, and variation2 has a better fit based on the latency data. Nevertheless, the overall correlations and RMSDs show that these are both decent fits to the human data.

Table 7-5: Summary of the correlations and root mean square deviations for the latency, accuracy and efficiency data of variations 1 and 2 of model-2-AD compared against human data (Fernandez-Duque & Black, 2006).

| | Correlation ( r ) | Root Mean Square Deviation (RMSD) |
|---|---|---|
| **Human Data / Model 2-AD Variation 1** | | |
| Latency | 0.98 | 213 |
| Accuracy | 0.95 | 1.29 |
| Efficiencies of networks | 0.95 | 14 |
| **Human Data / Model 2-AD Variation 2** | | |
| Latency | 0.97 | 130 |
| Accuracy | 0.9 | 1.6 |
| Efficiencies of networks | 0.9 | 25 |

### 7.1.6 Discussion

In section 7.1, model-2-AD was presented, which simulates the human study of performance on the ANT of Alzheimer's disease patients (Fernandez-Duque & Black, 2006). Based on the observed human behaviour and further insights gained from the neuropsychology literature, various modifications were made to model-2 (which is shown to be a valid representation of healthy human performance on the ANT) to produce model-2-AD. The two best fits were reported for analysis. Model validation was performed on all measures of the output, namely latency, accuracy and efficiencies of the networks. Correlations and RMSDs showed good fits on every measure. Simulating the human study (Fernandez-Duque & Black, 2006), model-2-AD replicated overall high reaction times, higher error rates and impairment of the executive control network. A few observations can now be made based on the model results and the data fitting process:

1. The data fits could not be achieved without altering the overall rule firing time of model-2. This slowdown in response time, simulated by modifying the rule firing time, provides support for the view that a major detrimental impact for the pathology is that AD patients slow down mentally and their overall processing speed may be significantly hampered. This corresponds to evidence in the literature that AD patients slow down and their performance variability is affected by the disease (Gorus, et al., 2008; Warkentin, et al., 2008; Nestor, Parasurman & Haxby, 1991).
2. The orienting network is reported to be stable in the human study, but the model results show an impaired orienting network. From the working of the model, it seems apparent that the deficit in orienting could be a result of the impairment of the ability to disengage from an invalidly cued location. This indication is also supported by evidence from the literature on Alzheimer's disease (Buck, et al., 1997; Parasuraman et al., 1992). Therefore, the model results are in tandem with the neuropsychology literature, but are in disagreement with this human study results (Fernandez-Duque & Black, 2006). This calls for replication of the human experiment and further testing through imaging studies.

3. Simulating impaired executive control network efficiency by modifying utility values to show the deficit in executive functions corresponds to a possible deficit in the response inhibition function for AD patients. Furthermore, a better fit was achieved by setting a longer firing time for production [P30], which was responsible for refocusing when a conflict situation arose (which corresponds to the deliberate route on the dual-process model explained in section 5.1.3.1.3). This suggests that, for AD patients, it is not only the response inhibition function which is impaired, but also it may generally take the AD patients longer to refocus attention in conflict situations.
4. In addition, looking at the behavioural interactions of the networks, it was observed that, in agreement with earlier studies examining the interaction of networks (Callejas et al., 2004; 2005; Fan et al., 2009), even for the AD subjects just like normal subjects, alerting has an inhibiting effect on congruency, whereas cueing has a facilitating effect.

As a result, model-2-AD not only simulates the AD patients' performances on the ANT, but also makes certain predictions and observations regarding the reason for an effect or localized impairment. These could be further validated through the replication of experiments or imaging studies.

The next section applies the same methodology of modifying model-1 and model-2, for simulating the recovery process (over thirty days) of patients affected with mild traumatic brain injury.

## 7.2 Model-1-mTBI - Simulation of ANT performance for patients with mild traumatic brain injury (mTBI)

### 7.2.1 About mild Traumatic Brain Injury (mTBI)

Concussion, or mild traumatic brain injury (mTBI), is referred to as a temporary neurological condition caused by a physical trauma or injury to the head (Giza & Hovda, 2001). It has been established that attentional and memory impairments are the commonly found neuropsychological deficits which take place after some sort of traumatic brain injury. Following a mild head injury it has been observed that, over the course of a few weeks, symptoms start to improve rapidly and attentional difficulties seem to resolve, but cases of moderate to severe injuries may take much longer (Ruff, Marshall, Crouch, Klauber, Levin, Barth, 1993; Tate, Lulham, Broe, Strettles & Pfaff, 1989; Van Zomeren & Brouwer, 1994).

In the mTBI-related studies, the efficiencies of attentional networks have been mostly assessed separately. For example, posterior attentional networks (orienting) have been assessed using cueing paradigms (Cremona-Meteyard & Geffen, 1994). Visual search tasks have also been used (Ponsford & Kinsella, 1991). Anterior attentional networks have been assessed (executive control) using control tasks such as the Stroop colour word test (Stroop, 1935). Alerting and vigilance have been assessed using tasks such as the Paced Auditory Serial Addition Test (PASAT) (Gronwall, 1977). However, in order to assess the efficiencies of the three networks in a single task, the Attentional Network Test (ANT) has been administered to mTBI patients to determine the deficits in the alerting, orienting or executive control networks (Halterman, et al., 2006). In this study, the rate and degree of recovery of the patients were recorded at intervals over a period of one month after the injury.

### 7.2.2 Design and functionality of model-1-mTBI

The administration of the ANT (Fan et al., 2002) to mTBI patients over different time intervals was simulated by running model-1, suitably modified for each time period to alter the behaviour of the efficiencies of the network (Halterman et al., 2006). To simulate the time course, there were two choices: either to run four loops simulating four different sessions (run the model four times) or to run multiple models in ACT-R. After evaluating the needs of the simulation, it was decided to run the model four times with different settings rather than running parallel sessions which would have made the code more complicated – without any benefit.

Initially, model-1(section 5.1), which simulated performance on the original ANT design, is modified to simulate the Halterman et al. (2006) study, and the results are reported along with their analyses. Later, in section 7.2, the same data fitting parameters are used to modify the invalid cueing model (model-2, section 5.2) in order to assess specifically how mTBI affects the ability to handle invalid cueing. The basic model-1 and model-2 designs remained unchanged. The efficiencies of the networks were calculated using Equations 2.1-2.3 and the network effects were calculated using Equations 7.5-7.8.

$$Effect\ of\ alerting\ on\ congruency = RT\ double_{incong} - RT\ double_{cong} \quad \text{Equation 7.5}$$

$$Effect\ of\ noalerting\ on\ congruency = RT\ nocue_{incong} - RT\ nocue_{cong} \quad \text{Equation 7.6}$$

$$Effect\ of\ cueing\ on\ congruency = RT\ cued_{incong} - RT\ cued_{cong} \quad \text{Equation 7.7}$$

$$Effect\ of\ cueing\ on\ congruency = RT\ center\_incong - RT\ center\_cong \quad \text{Equation 7.8}$$

To simulate performance changes in mTBI patients over the four time intervals (Halterman et al., 2006), the model was incrementally modified to simulate behaviour exhibited in the human study. Theoretical interpretation of the human study findings guided the modifications for model-1 and helped to explain the likely bases 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 were obtained through further minor adjustments of the modified parameters to find an appropriate fit.

### 7.2.3 Justification and data fitting

The human study (Halterman et al., 2006) shows that, compared to the controls, mTBI subjects take longer to respond to stimuli, gradually improving over the recovery period.

It was observed that alerting network efficiency is unimpaired, despite the injury. Orienting network efficiency is affected initially, but regains effectiveness within one week. However, there is no significant improvement in executive control efficiency, which remains impoverished compared to the controls over the observed period.

To reflect the human study results (Halterman et al., 2006), changes were made to the attention network functionalities in model-1. Modifications to model-1 involved altering the overall rule firing time for slow latency, a slower firing time for productions responsible for the orienting of attention, and changing utility values to further impair the conflict resolution ability. By modifying model-1, four new models were created and run to simulate the recovery process of mTBI patients at intervals of 2, 7, 14 and 30 days. All these changes are described below, along with the rationale for doing so.

#### 7.2.3.1 Increased latency

Adjusting the rule firing time was a logical choice for obtaining the increased reaction times for each test interval. The range of values tried for ‘dat’ (default action time) started with 80ms, finding the best fit for the first interval at 45ms. Slowing down the reaction time for an injury or impairment corresponds to what is referred to as ‘cognitive slowing’ in the literature (Nebes, Brady & Reynolds, 1992). This has been explained earlier in section 7.1.3.1.

It was observed that only by increasing the rule firing time for the first interval for model-1-mTBI and keeping the default value (40ms) for the simulation of the other three intervals provided a good fit to human data. This indicates that, for mTBI patients, the overall processing time/capacity returns to normal within a week and only the increased congruency effect due to impaired control network efficiency gives rise to higher reaction times for the next three intervals.

#### 7.2.3.2 Unaffected 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 that the within subject variability was similar. Furthermore, it was deduced from the human study that there was no interaction between the error rates and reaction times, which meant that neither the controls nor the subject adopted any strategy for focusing on accuracy at the expense of latency, or vice versa. To simulate this effect, nothing was changed within the model with respect to producing errors.

#### 7.2.3.3 Stable 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. It is believed that the reason for this was owed to the blanket increase in the rule firing rate, so that the extra production not-cue-so-switch-state [P4] responsible for giving the effect of surprise (in the no-cue condition) was also fired at the slower rate, as if alerting gain was increased. To keep the alerting effect stable, the firing time for the production [P4] was kept unchanged, at 40ms. Recall that this production is responsible for inducing a delay effect in the case of no alerting signal. Keeping the firing time of this action at healthy adults' levels is consistent with the view that the alerting network (and therefore alerting efficiency) is not impaired in mTBI.

#### 7.2.3.4 Impaired orienting network efficiency

It was observed in the human study that the orienting network was initially impaired. Based on the way orienting is implemented in model-1 (section 5.1.3.1.2), two possible ways of data fitting were explored:

1. Recall that orienting network efficiency is the difference in reaction times between the centre-cue and spatial-cue conditions. Therefore, if the ability to move attention from the centre-cued location, shift and re-engage attention back to the cued location is affected, then spatial orienting could be impaired, which could result in the indication that injury has affected the brain regions associated with the spatial orienting of attention. This was simulated in model-1-mTBI by slowing down the rule firing time for production [P17] notice-stimulus-with-centercue-and-shift in test interval 1, reverting to the default for each subsequent test interval.
2. Another possible reason for slower orienting efficiency could be associated with the selection of a location other than the target location, and then having the need to

refocus to target. This was simulated by altering the buffer stuffing properties used in the model (see section 5.1.3.1.2). Recall that the set-visloc-default command controlling the buffer stuffing mechanism is set to control the range of spatial attention 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. Anything outside that range will not be attended to.

Both data fitting options were explored in model-1-mTBI. It was observed from the model results that changing the rule firing for production [P17] notice-stimulus-with-centercue-and-shift 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 ability to shift and reengage attention probably has a major role to play in affecting patients' orienting network efficiency in the case of mTBI. Based on this indication, it was predicted that, specifically, the effect of disengaging from a wrongly cued location could also be a factor, and therefore this was further investigated in section 7.3.4 by applying the data fitting parameter of model-1-mTBI to model-2.

7.2.3.5 Impaired executive control network efficiency

It was observed in the human study that the executive control network was initially impaired. Based on the way executive control is implemented in model-1 (section 5.1.3.1.3), two possible ways of data fitting were explored:

1. Recall that the executive control network was implemented in model-1 using two competing productions (based on the dual-process model), and their selection depended upon the utility values of the production (see section 5.1.2.1.1.3). Similar to data fitting model-2-AD, the executive control network was impaired by changing the utility values of the two conflicting productions harvest-target-directly-if-incongruent [P29] and refocus-again-if-incongruent [P30] that handle incongruency.
2. Alternatively, only the value of the noise parameter was altered. It was shown in utility Equation 3.1 that the parameter 's' induces more randomness in the system. As a consequence, it was explored whether just increasing the value of the noise

parameter accounted for the overall impairment of the executive control network. In Equation 3.1, ‘s’ is set by the value of the parameter egs, which induces noise in the system and hence more non-deterministic behaviour. The value of the ‘egs’ parameter was increased (see exact values in Table 7.6).

Based on the model results, it was observed that just changing the noise or utility values was not fitting the data well, so both were used, inducing non-deterministic behaviour in conflict resolving ability. As a result, both approaches are used in the model. The value of the noise parameter varied between 3-5, utility values for [P29] from 3-7 and [P30] from 10-20. The final values giving the best fit are shown in Table 7.6.

7.2.3.6 Summary of model-1-mTBI’s settings

A summary of modifications made to model-1 to produce model-1-mTBI to simulate the performance of mTBI patients over a recovery period of one month (Halterman et al., 2006) is given here. For each time interval, the variations involved changing the overall rule firing time to simulate slower response times, keeping the alerting network efficiency constant by keeping the rule firing time of [P4] at a normal firing time (40ms), impairing orienting efficiency by increasing the rule firing time for production [P17], and simulating impaired executive control network efficiency by increasing noise and changing the utility values of [P29] and [P30]. A range of values were tried for each interval, with the best fitting examples reported in Table 7.6. The values for control are the settings used in model-1, which indicate healthy adult simulation.

Table 7-6: Parameter settings applied to model-1 to produce model-1-mTBI for simulating the recovery of the efficiencies of attentional networks in mTBI patients.

| **Time (days)** | **Overall rule firing time** | **Firing time of [P4] for impaired alerting network** | **Firing time for [P17] for impaired orienting network** | **Noise (egs)** | **Utility values for [P29] [P30]** |
|---|---|---|---|---|---|
| 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 |

### 7.2.4 Results

The model was run twenty times to simulate the behaviour of twenty subjects as part of the human study (Halterman et al., 2006). The design used four cues, two flankers, two directions and two locations, and each block was run twice, producing a total of sixty-four /trials for each model run. Model-1-mTBI was run four times, each time with a different setting as given in Table 7.6. The model was run for each interval to simulate the incremental change in performance over a period of one month, and the reaction time data were recorded on each run.[10]

In addition to increased reaction times, the results simulating the human study showed that the orienting and executive control networks were affected significantly by mTBI in the initial stages, but there was no impact on the alerting network. Replicating the human study, model-1-mTBI also showed an improvement in the orienting network over time, but no significant improvement was seen in the executive control network. Detailed results for latency, efficiencies of networks and behavioural interactions are given below.

7.2.4.1 Latency data

The model was run four times to simulate the change in performance over a period of one month, and the data were recorded on each run. Using reaction times for each run, a mean was calculated. Table 7.7 records the reaction time data for each cue and flanker condition, which is later used to make suggestions about the behaviour and interactions of the networks.[11]

Figure 7.3 plots and records the median reaction times over the four intervals for the controls (both human and model-1), human mTBI patients and simulated mTBI subjects. These show an overall improvement in latency over time. Note that, in both controls and the mTBI subjects, the reaction times drop as low as 440 and 475ms,

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[10] In the human study (Halterman et al., 2006) concerning accuracy, no significant change was reported; in addition, there was no human data available to compare the accuracy results of model-1-mTBI. Therefore, accuracy results are not discussed here.

[11] A breakdown of the human data (Halterman et al., 2006), i.e. the reaction times for each cue and flanker condition, was not available for use. Mean reaction times given in the form of a graph were used in the validation of model-1-mTBI.

whereas those for the models are comparatively higher. Even in the original ANT experiment (Fan et al., 2002) for healthy subjects, the mean reaction time is 511ms with a standard deviation of 44. Another unusual observation from the control data was that they seemed to reduce over the four time intervals; however, there is no logical explanation for this; the model was not made to fit these low reaction time outlier data. The correlations and root mean square deviations (RMSD) for the median reaction times were 0.88 and 41 for the controls and 0.98 and 15 for the mTBI subjects.

Table 7-7: Reaction times produced by model-1-mTBI for each cue and flanker condition.

| **Time Interval 1** | | | | |
|---|---|---|---|---|
| | Nocue | Cued | Center | Double |
| Neutral | 546 | 458 | 524 | 473 |
| Congruent | 545 | 460 | 511 | 487 |
| Incongruent | 625 | 548 | 600 | 592 |
| **Time Interval 2** | | | | |
| | Nocue | Cued | Center | Double |
| Neutral | 524 | 440 | 501 | 464 |
| Congruent | 524 | 446 | 480 | 469 |
| Incongruent | 594 | 517 | 564 | 542 |
| **Time Interval 3** | | | | |
| | Nocue | Cued | Center | Double |
| Neutral | 524 | 440 | 493 | 462 |
| Congruent | 524 | 441 | 484 | 463 |
| Incongruent | 588 | 525 | 555 | 546 |
| **Time Interval 4** | | | | |
| | Nocue | Cued | Center | Double |
| Neutral | 512 | 435 | 493 | 467 |
| Congruent | 520 | 442 | 475 | 472 |
| Incongruent | 582 | 515 | 545 | 538 |

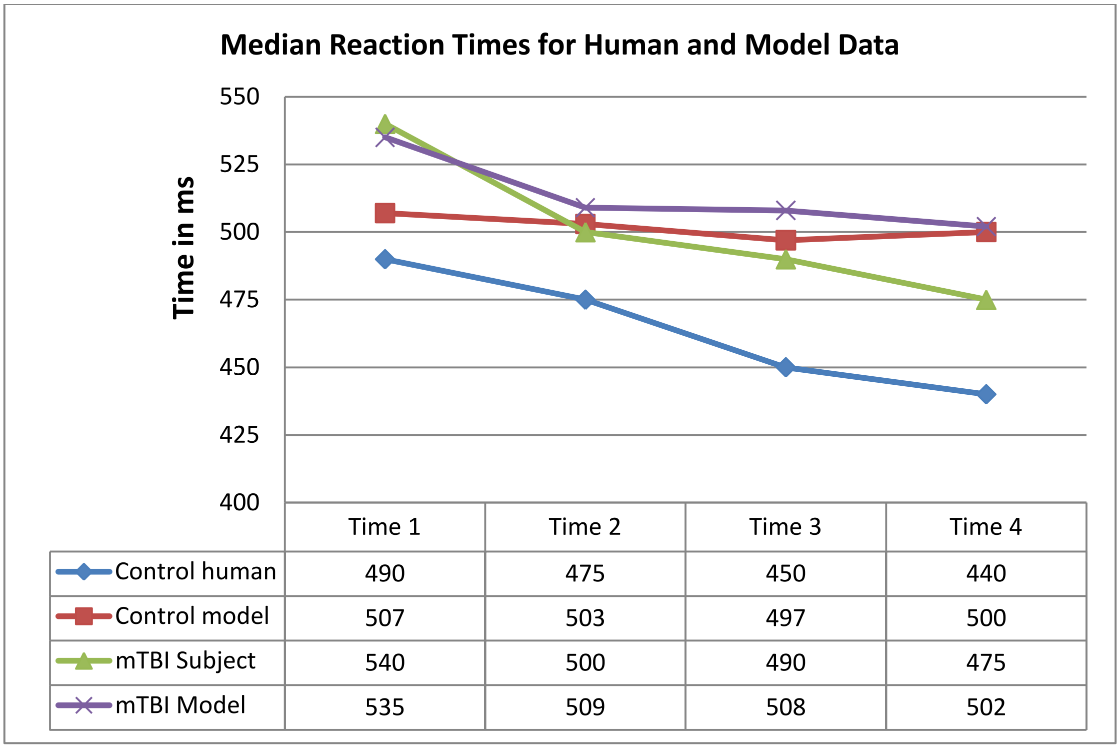
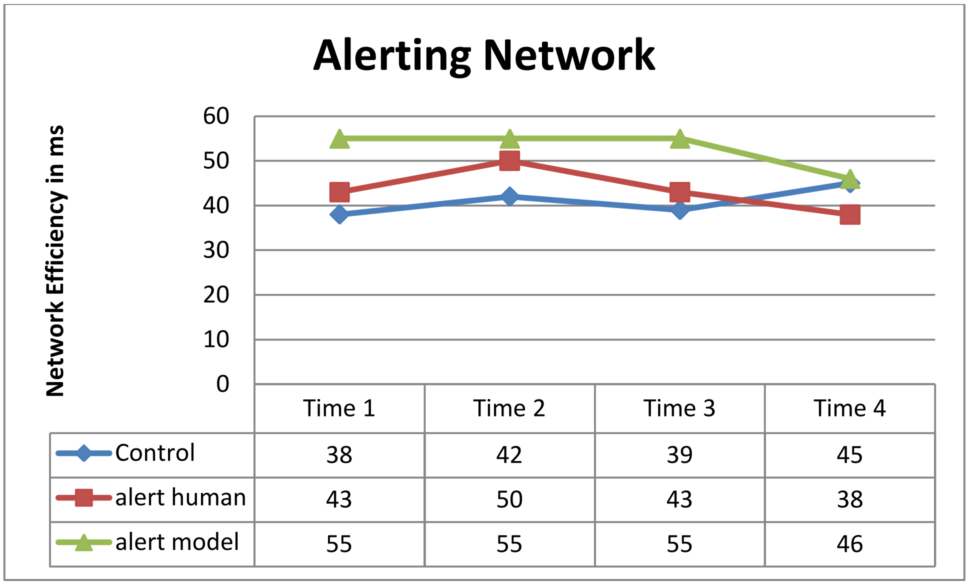



Figure 7-3: Graph plotting the median reaction times over four intervals for controls (both human and model-1), mTBI human data (Halterman et al., 2006) and model-1-mTBI.

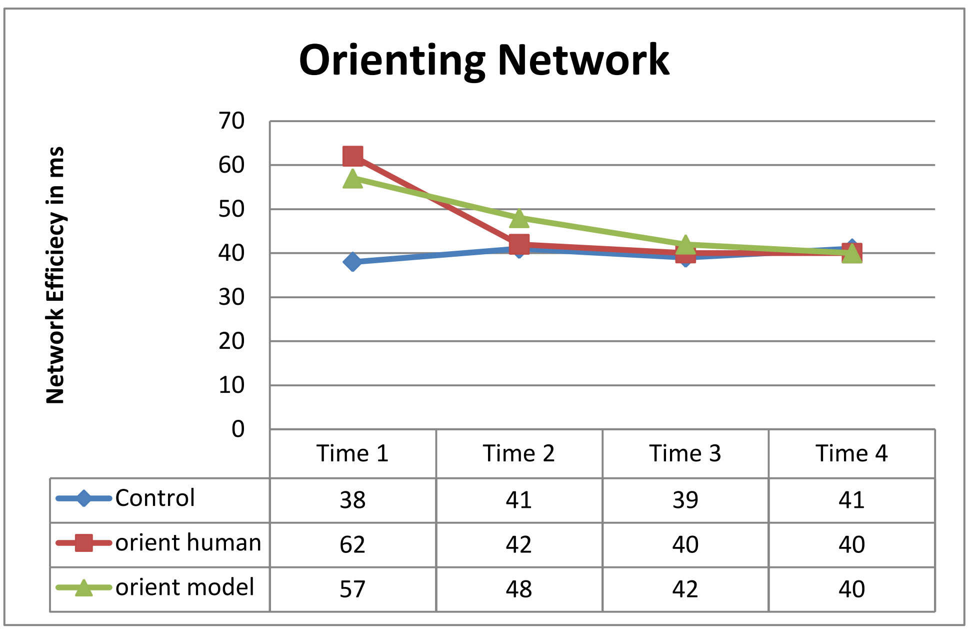
### 7.2.4.2 Efficiencies of attentional networks

The efficiency of each network was calculated using Equations 2.1-2.3. Due to the unavailability of the raw data, the data in this particular case were reproduced from the graphs given in the paper (Halterman et al., 2006). Figures 7.4, 7.5 and 7.6 illustrate the efficiencies of the alerting, orienting and executive control networks respectively. Control data are given for reference purposes. Model-1-mTBI simulates human behaviour well. The efficiency of the orienting network improves significantly over a one-month period, while executive control, although it reduces over time, is still not close to the control data, whereas the alerting network remains unaffected.




| | Time 1 | Time 2 | Time 3 | Time 4 |
|---|---|---|---|---|
| Control | 38 | 42 | 39 | 45 |
| alert human | 43 | 50 | 43 | 38 |
| alert model | 55 | 55 | 55 | 46 |

Figure 7-4: Alerting network efficiency of model1-mTBI compared with human data (Halterman et al., 2006).




| | Time 1 | Time 2 | Time 3 | Time 4 |
|---|---|---|---|---|
| Control | 38 | 41 | 39 | 41 |
| orient human | 62 | 42 | 40 | 40 |
| orient model | 57 | 48 | 42 | 40 |

Figure 7-5: Orienting network efficiency of model1-mTBI compared with human data (Halterman et al., 2006).

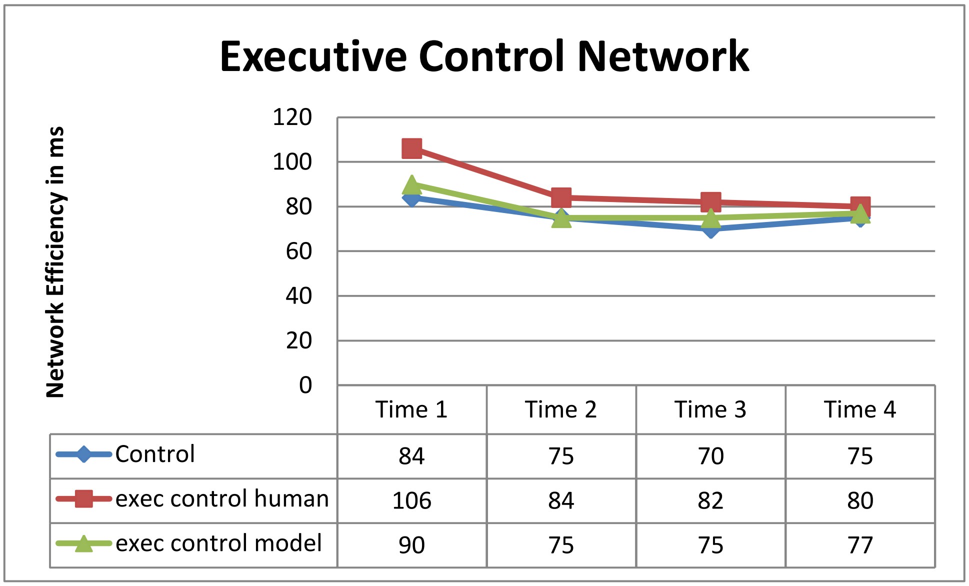



Figure 7-6: Executive control network efficiency of model1-mTBI compared with human data (Halterman et al., 2006).

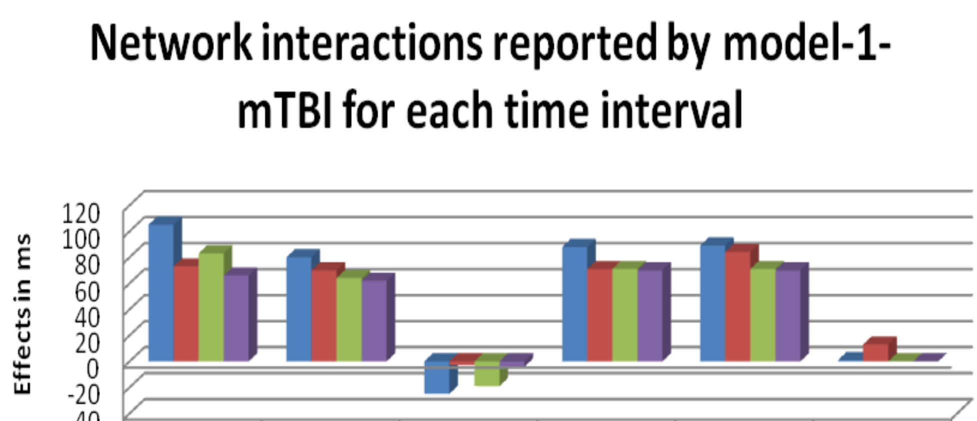
Table 7.8 gives a detailed breakdown of the efficiencies of all three networks for matched controls, mTBI patients (Halterman et al., 2006) and the data produced by model-1-mTBI. All correlations and RMSDs obtained show a good fit of the model. The correlations and RMSDs over all four intervals are 0.74 and 9.7 for alerting, 0.87 and 4.5 for orienting, and 0.97 and 9.94 for the executive control network.

Table 7-8: Efficiencies of the networks of alerting, orienting and executive control found in the human study (Halterman et al., 2006) simulated by model-1-mTBI.

| | **Human** | **Model** | **Human** | **Model** | **Human** | **Model** |
|---|---|---|---|---|---|---|
| | **Alerting** | | **Orienting** | | **Executive control** | |
| **Time1** | 43 | 55 | 62 | 57 | 106 | 90 |
| **Time2** | 50 | 55 | 42 | 48 | 84 | 75 |
| **Time3** | 43 | 55 | 40 | 42 | 82 | 75 |
| **Time4** | 38 | 46 | 44 | 40 | 80 | 77 |
| **Correlation** | 0.74 | | 0.87 | | 0.97 | |
| **RMSD** | 9.71 | | 4.50 | | 9.94 | |

### 7.2.4.3 Interactions between attentional networks

Although the human study does not talk about any network interactions, based on the simulation data available from all the models, using Equations 7.5-7.8, the net effects of the networks on each other were explored (similar to the work of Callejas et al.'s (2004, 2005) study and its simulation in Chapter 6). Based on the graph in Figure 7.7, it was observed that the alerting network has an inhibitory effect on congruency, whereas the orienting network has a facilitatory effect or no effect on congruency (later, section 7.2.6 further explores if cueing has a positive effect or no effect on congruency). Recall that similar effects were found also for healthy humans (Callejas et al., 2004; 2005).




| | Effect of alerting on congruency | Effect of un alerting on congruency | Net effect | Effect of cueing on congruency | Effect of uncueing on congruency | net effect |
|---|---|---|---|---|---|---|
| Time 1 | 105 | 80 | -25 | 88 | 89 | 1 |
| Time 2 | 73 | 70 | -3 | 71 | 84 | 13 |
| Time 3 | 83 | 64 | -19 | 71 | 71 | 0 |
| Time 4 | 66 | 62 | -4 | 70 | 70 | 0 |

Figure 7-7: Graph plotting the interactions of alerting and cueing on congruency.

### 7.2.5 Summary of results and model validation

Section 7.2.4 outlines detailed results of model-1-mTBI, simulating the recovery of mTBI patients on ANT performance, along with healthy human/model data on all measures of latency, efficiencies of networks and behavioural interactions. The correlations and RMSDs of every measure are summarised in Table 7.9. For the latency data, the correlations and root mean square deviations (RMSD) are 0.98 and 15, 0.74

and 10 for alerting, 0.87 and 5 for the orienting network, and 0.97 and 10 for the executive control network. All these statistics show a good fit to the human data.

Table 7-9: Summary of results of model-1-mTBI compared with human study on latency and efficiencies of networks. Correlations and RMSDs are given.

| | **Correlation ( r )** | **Root Mean Square Deviation (RMSD)** |
|---|---|---|
| Latency for model1-mTBI | 0.98 | 15 |
| Efficiencies of alerting network | 0.74 | 10 |
| Efficiencies of orienting network | 087 | 5 |
| Efficiencies of executive control | 0.97 | 10 |

Based on the interactions graph, it was observed that the alerting network has an inhibitory effect on congruency, whereas the orienting network has a facilitatory or no effect. The interesting observation is that these interactions remain quite stable over each test interval under study. This suggests that, although mTBI affects the efficiency of both the orienting and executive control networks, there may not be any impairment or variation in the interactions between networks. It is predicted that the effects of cueing on congruency will become clear in the invalid cueing model results explicated in section 7.3.

### 7.2.6 Discussion

In section 7.2, model-1-mTBI was described as simulating the recovery process of patients affected by mild traumatic brain injury over a period of one month using performance on the ANT as an indicator. Model-1-mTBI simulates the human study well, which is shown statistically by correlations and RMSDs.  Replicating the human study, the overall reaction times were higher in the first week, the alerting network efficiency remained stable irrespective of the injury, and the orienting network efficiency was impaired initially, whereas the executive control network showed no significant improvement over time. Based on the data fitting process, the following observations/predictions were made:

1. Altering the rule firing time only for the first interval and then resetting it to a healthy adult level suggests that, for mTBI patients, the processing speed is affected initially but returns to normal within a week. Although the overall reaction times are

still higher over the next two to three weeks, this effect does not arise out of an increased firing time (in other words, performance variability) rather due to the slower conflict resolution mechanism. Looking closely at the detailed data for each cue and flanker condition in Table 7.7, it becomes clear that after week one the main difference in the reaction time data was only for incongruent conditions, which also resulted in overall higher mean reaction times for the mTBI models compared to the controls. However, this could not be verified, as the detailed human data was not available.

2. The conflict resolution ability, as shown by the human study and simulated by the model, remained impaired throughout the recovery period. The model points out that this was mainly due to the impaired response inhibition function, which maps to impaired conflict resolution ability. Furthermore, the use of added noise to better fit the overall data suggests that it is possible that, due to the trauma to the brain, the patients may exhibit more non-deterministic behaviour for reasons unknown.
3. The behavioural interactions of the networks were not discussed in the human study, but based on the model results it was inferred that, despite brain dysfunction, the effects remained the same as in healthy humans (Callejas et al., 2004; 2005). In other words, there is an inhibiting effect of alerting on congruency, but cueing seems to have a positive or no effect on congruency. This is further tested in section 7.3.

In the next section, the effect of cueing on congruency is retested applying model-2 fitted with the same modifications for producing model-1-mTBI (as summarised in Table 7.6).

## 7.3 Model-2-mTBI: Effect of invalid cueing on ANT performance for mTBI patients

In section 7.2, model-1 was fitted to simulate the human study that simulated performance of the mTBI patients on the ANT over a recovery period of one month (Halterman et al., 2006). This study used the original ANT design (Fan et al., 2002) and did not explore whether the mTBI patients had any impact on their capacity to handle invalid cues (recall that the simulation of invalid cueing in an ANT is modelled and discussed in detail in section 5.2, and also applied in the simulation of the performance of AD patients on the ANT).

Based on the results from model-1-mTBI, it was predicted after calculating the interactions' effects that there would be a positive effect of cueing on congruency. Therefore, using model-2 here for simulation could help to study this interaction explicitly. This was also of interest because it was found in the literature that brain regions associated with performing the operations of disengage, shift or re-engage may be affected due to trauma to the brain (Nobre, Sebestyn, Gitelman, Mesulam, Frackowiak & Firth, 1997; Kim, Gitelman, Nobre, Parrish, Labar & Mesulam, 1999; Yantis et al., 2002).

### 7.3.1 Design and functionality of model-2-mTBI

To investigate the effect on invalid cueing for mTBI patients, model-2-mTBI was implemented by using the model-1-mTBI settings in model-2. Thus, settings in Table 7.6 were applied to model-2 instead of model-1. The only change in this table setting is column four, which indicates the firing time of production [P17] related to the orienting effect. Here, instead of [P17], the rule firing time of production [P41], which is responsible for disengaging attention in the case of invalid cueing, is set to a higher rule firing time. There is no change in the design of model-2, and it remains exactly the same as described in section 5.2. The purpose of doing this is to investigate or predict the behaviour of the mTBI patients if they were administered the ANT extended with an invalid cueing condition.

### 7.3.2 Results

Model-2-mTBI was run to simulate the same number of trials and subjects as model-1-mTBI. The measures of interest here were latency data, the validity effect and most importantly the effect of cueing on congruency.

#### 7.3.2.1 Latency

It was expected that the mean reaction times would be higher due to an additional disengage step in processing in the case of an invalid cue condition. This is illustrated in Figure 7.8, which shows the mean reaction times produced by model-2-mTBI over the four time intervals.

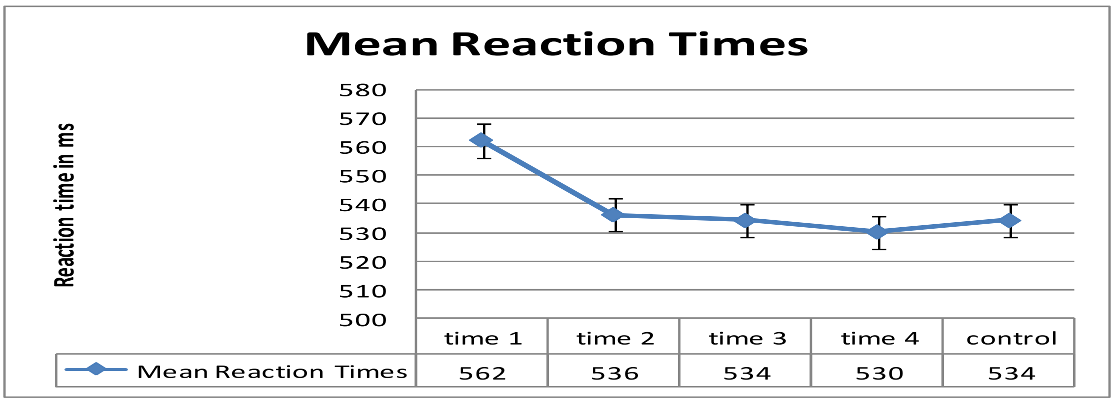



Figure 7-8: Graph plotting the median reaction times over four intervals for the control and model-2-mTBI.

#### 7.3.2.2 Validity effect

Recall that the validity effect as given in Equation 5.2 is the difference in reaction times between invalid and valid cue conditions. Based on the results of model-2-mTBI, and as illustrated in Figure 7.9, it was observed that the validity effect was higher initially, which seemed to stabilise by the second week of the study. Based on the data fitting of model-2-mTBI, it is posited that this increase could be attributed to the impaired ability of mTBI patients in disengaging attention when they encounter invalid cues.

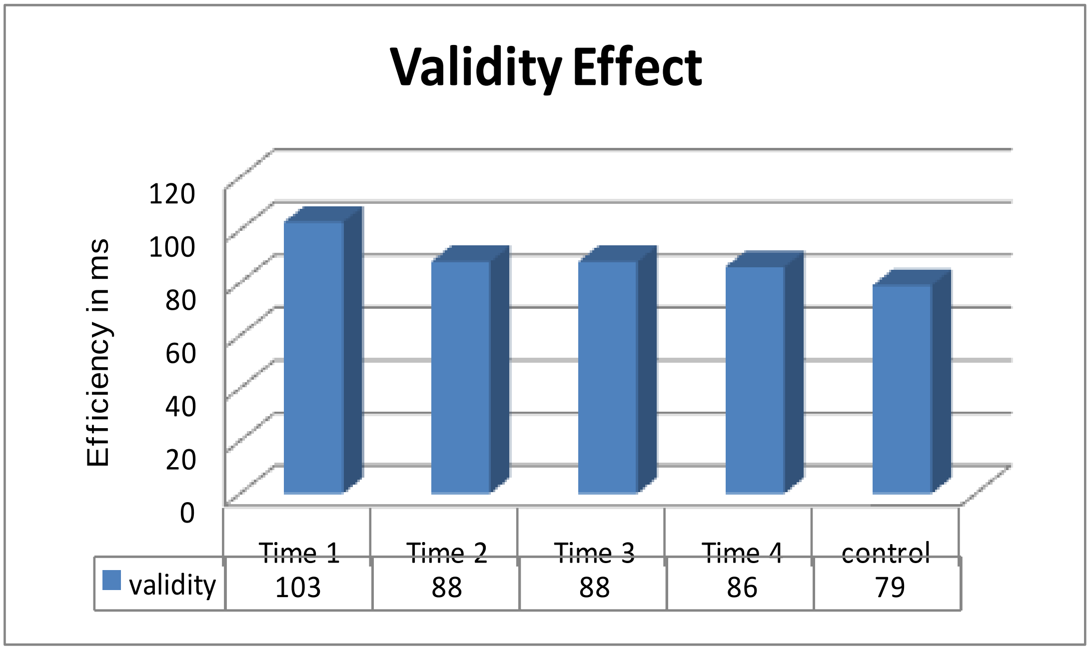



Figure 7-9: Graph plotting the validity effect over the four time intervals, based on the results of model-2-mTBI.

#### 7.3.2.3 Effect of cueing on congruency

Regarding the effect of cueing on congruency, which showed a positive or no effect in section 7.2.4.3, it is clear from Figure 7.10 that there is a positive net effect of cueing on congruency (using equation 7.3-7.4); hence, the ambiguity is removed through applying model-1-mTBI's settings to model-2 to produce model-2-mTBI.

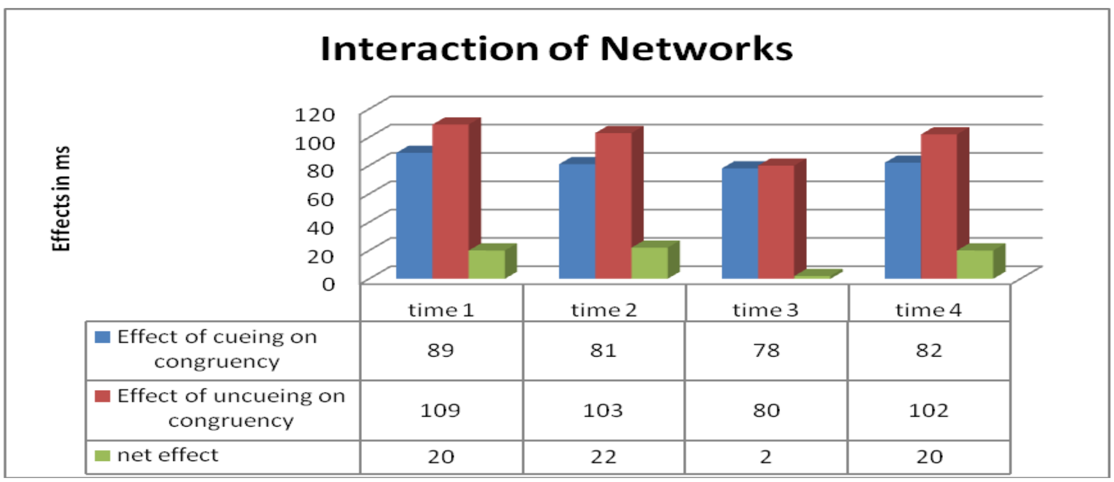



Figure 7-10: Graph plotting the interactions of the cueing/uncueing on congruency, based on the results of an invalid mTBI cueing model (model2-mTBI).

### 7.3.3 Discussion

In this section, modelling is used as a tool to predict the performance of mTBI patients when administered the revised ANT design, exploring the effect of invalid cueing. The motivation was to show how the performance would be affected and, most importantly, what would be the effect of cueing on congruency (since this effect was not very clear from the model-1-mTBI results).

The premise here was that, since model-1-mTBI was shown to be a valid simulation of the human study (Halterman et al., 2006), its data fitting parameters could be applied to model-2 to produce model-2-mTBI. After applying the same settings as in Table 7.6 at each interval, the model results made predictions about how the mTBI patients would perform if they were administered the ANT revised with an invalid cueing condition. It was suggested that the mean reaction times would be higher than the case when the subject has to deal with no invalid cue condition, because of the extra step of disengagement that is required if the subject needs to disengage attention from an invalid cue condition and refocus. This would also give rise to a slower efficiency of validity, and it was suggested that the validity effect was higher initially for the mTBI patients, which seemed to stabilise by the second week. Model-2-mTBI results also suggested that the effect of cueing on congruency (which was not very clear from the results of model-1-mTBI) will have a positive effect on congruency, hence the result is clarified.

## 7.4 Chapter summary

The work reported in this chapter uses model-1 and model-2 to explore the performance on the ANT of subjects suffering from attention-related deficit conditions such as Alzheimer's disease (AD) and mild traumatic brain injury (mTBI). The reason for choosing these two pathologies, in addition to the advantage that human data were available for these studies, is that both show different aspects of modelling. The AD model is a sort of static model that captures behaviour in a particular point in time, whereas the mTBI model(s) simulates behaviour over a trajectory of time, i.e. over a recovery period of thirty days. This modelling work has some useful implications to report about the behaviour of attentional networks in the case of pathologies like Alzheimer's disease and mild traumatic brain injury elucidated below:

### 7.4.1 The case of Alzheimer's disease

Model 2-AD is a simulation of the performance of AD patients on the ANT (Fernandez-Duque & Black, 2006). Based on this observed human behaviour, various modifications were made to model-2. The two best fits were reported in this chapter. Model validation was performed on all measures of the output, namely latency, accuracy and efficiencies of the networks, while correlations and RMSDs were used to show goodness-of-fit. Simulating the human study (Fernandez-Duque & Black, 2006), model-2-AD replicated overall high reaction times, higher error rates and impairment of the executive control network. Based on the modelling exercise, a few useful observations and implications can now be made as discussed below:

1. The slowdown in response time, simulated by modifying the rule firing time, for model-2-AD provides support for the view that a major detrimental impact for the pathology is that AD patients slow down mentally and their overall processing speed may be significantly hampered. This corresponds to evidence in the literature that AD patients slow down and their performance variability is affected by the disease (Gorus, et al., 2008; Warkentin, et al., 2008; Nestor, Parasurman & Haxby, 1991). For example, when Nestor and colleagues (1991) administered variations of choice-RT tests on a group of AD patients along with controls, it was observed that AD patients showed slow down in information

processing. The authors suggested that this slowing could be related to complexity and attentional demands. Also, Nebes and colleagues (1992) using an enumeration task showed that response time slowing on psychological tasks is found both in Alzheimer's disease and depression where it was observed that response time increased linearly with array size, an indication of presence of a cognitive slowing in Alzheimer's disease. So the model-2-AD results second both these theoretical claims.

2. The orienting network is reported to be stable in the simulated human study (Fernandez-Duque & Black, 2006), but the model results show an impaired orienting network. From the working of the model, it seems apparent that the deficit in orienting could be a result of the impairment of the ability to disengage from an invalidly cued location. This indication supports the claim in the neuropsychology literature on Alzheimer's disease (Buck, et al., 1997; Parasuraman et al., 1992) that patients may have difficulty orienting to target locations and also the ability to disengage is impaired in AD patients, but not the engage or move components of orienting (Parasurman & Haxby, 1993; Perry and Hodges, 1999). Therefore, the model results are in tandem with other neuropsychology literature, but are in disagreement with this human study result (Fernandez-Duque & Black, 2006) which is being simulated here. This calls for replication of the human experiment and further testing through imaging studies.

3. Simulating impaired executive control network efficiency by modifying utility values to show the deficit in executive functions corresponds to a possible deficit in the response inhibition function for AD patients. Going through the data fitting process, it was seen that a better fit was achieved by setting a longer firing time for production [P30], which was responsible for refocusing when a conflict situation arose (which corresponds to the deliberate route on the dual-process model explained in section 5.1.3.1.3). This suggests that, for AD patients, it is not only the response inhibition function which is impaired, but also it may generally take the AD patients longer to refocus attention in conflict situations. This is in support of theoretical claim in the literature (Perry & Hodges, 1999, Wylie et al., 2007). For example, Perry and Hodges (1999)

observed in their study that the attentional tasks particularly affected in AD patients were those involving response inhibition, target selection or switching. Based on this they suggested that the ability to cope with the incongruency effect was particularly impaired. Wylie and colleagues (2007) administered the flanker test (Eriksen & Eriksen, 1974) to subjects diagnosed with mild cognitive impairment (MCI, a condition which warrants a diagnosis of AD). They also observed that these patients exhibited greater difficulty resolving conflict which appeared to arise more from the inefficient response inhibition function.

4. In addition, looking at the behavioural interactions of the networks as produced by model-2-AD results, it was observed that, in agreement with earlier studies examining the interaction of networks (Callejas et al., 2004; 2005; Fan et al., 2009), even for the AD subjects just like normal subjects, alerting has an inhibiting effect on congruency, whereas cueing has a facilitating effect. So model results also suggest that the pathology does not alter the network interactions.

### 7.4.2 The case of mild traumatic brain injury

Model-1-mTBI and model-2-mTBI, explicated in sections 7.2 and 7.3, simulate the recovery process of patients affected by mTBI over a period of one month, by using their performance on the ANT as an indicator (Halterman et al., 2006). At first, model-1 was modified to simulate the performance of mTBI patients on ANT, then, once these models were established as valid fits to the human data, the same modifications were applied to model-2 to explore the effect of validity in mTBI patients. Based on the data fitting process of model-1-mTBI and model-2-mTBI, the following observations/predictions were made:

1. The need for alteration of the rule firing time only for simulation of first week performance and then resetting it to a healthy adult level suggests that, for mTBI patients, the processing speed is affected only for a short period of time which returns to normal within a week. Based on this, it is also implied that over the recovery period, slowdown in response time does not arise out of an increased firing

time (in other words, performance variability) rather due to the slower conflict resolution mechanism.

2. The conflict resolution ability, as shown by the human study (Halterman et al., 2006) and simulated by the model, remained affected throughout the recovery period of one month (which was under observation). The data fitting process indicated that an impaired response inhibition function could be a reason for impaired conflict resolution ability.

3. The behavioural interactions of the networks were not discussed in the human study, but based on the model results it was inferred that, despite brain dysfunction, the effects remained the same as those observed in healthy adults (Callejas et al., 2004; 2005). There was an inhibiting effect of alerting on congruency, but cueing seemed to have a positive or no effect (this positive effect of cueing on congruency was retested using model-2-mTBI, as this effect was not very clear in model1-mTBI).

All of these model-based observations and predictions call for replication of the human experiment and further testing through imaging studies.

# 8. Modelling the Cognitive Development of Attentional Networks

In the previous chapter, the behaviour of all three networks was explored by using ANT performance as an indicator for patients affected with Alzheimer's disease and mild traumatic brain injury. Both model-1 and model-2, representing valid simulations of healthy adult performance on the ANT, were fitted to human data. Based on the process of modelling and data fitting, it was investigated how attentional networks were affected as a result of the pathologies, and certain observations and predictions were made.

For the investigation in this chapter, the performance of children aged 6-10 on a child-friendly version of the ANT (ANT-C) (Rueda et al., 2004) is modelled. The modified version is referred to as 'model-1-child' (because model-1 is modified to simulate children's performance). Furthermore, model-2 is also modified using the data fitting parameters of model-1-child to study the effect of invalid cueing in children. This is referred to as 'model-2-child'. Model-1-child is validated against the human study (Rueda et al., 2004), but for model-2-child, there is no human data to validate against, so it is used only as a predictive tool.

## 8.1 Model-1-child: Simulation of the performance of children on the attentional network test adapted for children (ANT-C)

### 8.1.1 Task representation

ANT-C is the modified version of the original ANT (Fan et al., 2002), which is used to study the development of networks in children. ANT-C is adapted to be more child-friendly by replacing the target stimuli with five colourful fish.

As illustrated in Figure 8.1, each ANT-C trial begins with a central fixation cross followed by a cue (or a blank interval in the no-cue condition) informing children that a target will occur soon, and possibly where (spatial cue). There are four cue conditions, namely no-cue, centre-cue, double-cue and spatial-cue, and three congruency conditions, namely neutral, congruent and incongruent. The target always appears above or below the centre screen fixation point. 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 the opposite direction (incongruent). Based on the direction of the centre fish, the children press the corresponding left or right button on the mouse. The reaction time spans the stimulus presentation to the button press. The duration of each trial lasts between 25-30 minutes and children are given sufficient practice on the task before the data are formally collected. Other than the replacement of the arrows with fish and the colourful display, the rest of the experimental setup remains the same as the original ANT (Fan et al., 2002) experiment. The formulae used to calculate the efficiencies remain the same as given in Equations 2.1-2.3.

In this study (Rueda et al., 2004), a series of experiments were conducted with various age groups of children. The first experiment in this study studied four age groups of children ranging from 6 to 9 years. The second experiment studied and compared children aged 10 years with adults on both the ANT-C and the adult ANT in terms of the latency, accuracy and efficiencies of the networks.

The children’s performance (Rueda, et al., 2004) reported that latency and accuracy improved over age, up to adulthood. The efficiency of the alerting network was much higher in children up to 9 years, with no significant change across ages. By age 10, alerting efficiency significantly improved. The orienting network seemed to be relatively stable (close to adult's orienting efficiency values) throughout the age groups under study. The efficiency of executive control network seemed to reduce significantly from ages 6 to 7, but after that seemed to stabilise up to adulthood, with no significant changes.

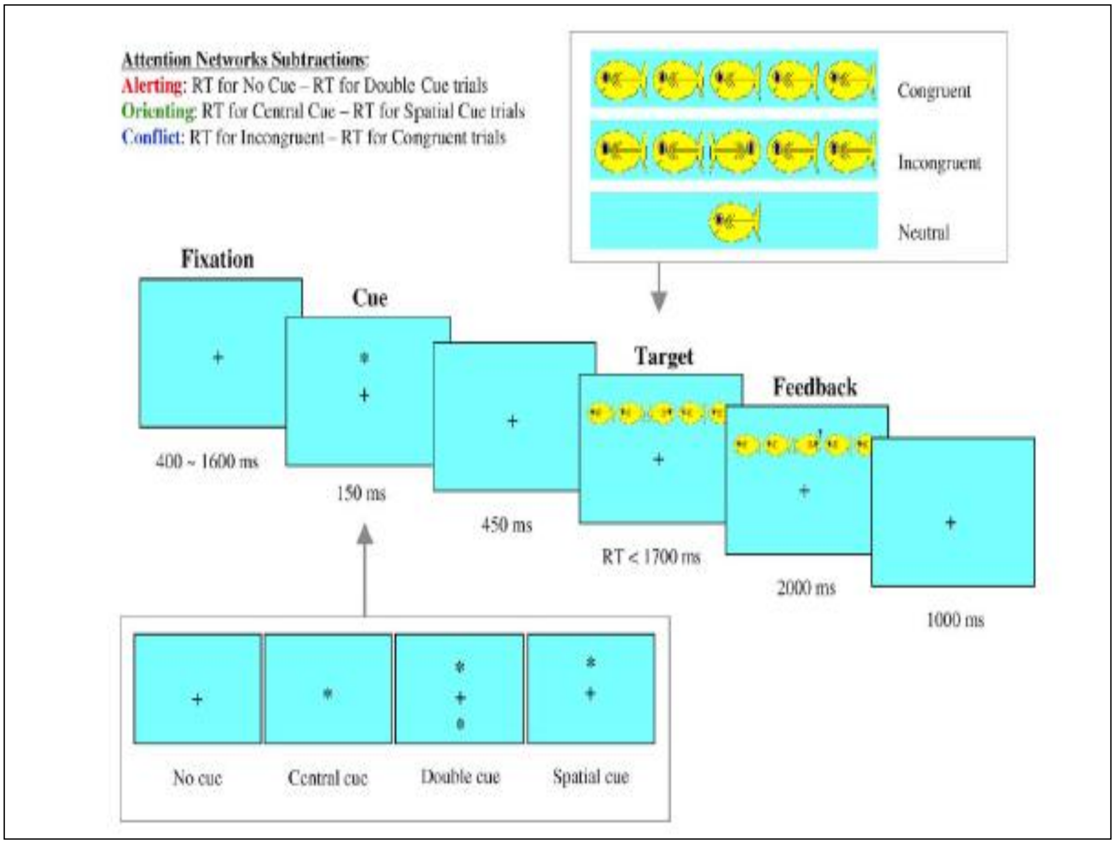



Figure 8-1: A sketch of the design of the child version of the attentional network test, ANT-C (Rueda et al., 2004, p. 1031).

### 8.1.2 Design and functionality of model-1-child

Model-1 (section 5.1) was modified to simulate the attentional network test for children (ANT-C) (Rueda et al., 2004). The display for ANT-C was different from the ANT replacing colourful fish with arrows on a blue background. Model-1 could have been modified to simulate this change; however, from the point of view of the functionality and behaviour of the simulation, it makes no difference whether the target is an arrow or a fish. The important element to be captured here is the behaviour in terms of the cueing and congruity information content of the display, and not the colour, shape and other visual aspects of the stimuli. In addition, the basic functionality of model-1 remains the same.

Similar to model-1-mTBI, to simulate the time course, there were two choices: either to run four loops simulating four different age groups (run the model code four times) or run multiple models in ACT-R. After evaluating the needs of the simulation, it was simpler to run the code a number of times rather than running parallel sessions, which would have made the code more complicated, without any benefit.

### 8.1.3 Justification and data fitting

It has been suggested that, generally, there are two ways of going about modelling cognitive development: (1) either model adult behaviour, and then modify behaviour to fit child behaviour, or (2) first model the child behaviour (lower performance level) and progressively change this to fit the adult behaviour (higher performance level) (Jones, 1999; Jones, Ritter & Wood, 2000). This chapter uses the former approach. Researchers have also shown that model behaviour 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, 1998; 2000; Serna, et al., 2007; van Rijn, et al., 2003).

Model-1 is the starting point for the simulation of children's performance on the ANT, which was subsequently modified incrementally to simulate attentional network development in various age groups. The approach used was to find a fit for the first model in the series to simulate age group 6 – the youngest age group under study here – and then models for ages 7-10 were obtained subsequently through further minor adjustments to the modified parameters to find an appropriate fit. Theoretical interpretation of the human study findings suggested the basis for developmental differences in the various networks and their implementation, described further below. More than one way of simulating the development is shown analyzing both, showing the results from each behaviour simulation along with their strengths and weaknesses. The data fitting process for each measure using two variations is described below and summarised in Tables 8.1 and 8.2.

8.1.3.1 Increased latency

It was reported in the human study that the overall reaction times were considerably higher in children (Rueda et al., 2004). This increased latency was simulated by starting with an overall higher rule firing time, and then gradually decreasing it with each age group. Adjusting the rule firing time seems a natural choice to obtain uniformly increased latencies across the whole model. The rationale for doing this was based on the literature on cognitive development and theories of development where processing speed is compared with the clock of a computer. The cognitive development literature shows that processing speed rises during maturation from childhood into adulthood, but then decreases as senescence is approached (Kail & Salthouse, 1994; Kail, 1991; 1993). Here Kail and colleagues basically argued that processing speed meets the requirement necessary to qualify as a mental resource and has an effect on a broad range of cognitive processes. This is in line with the processing speed theory of development as opposed to other famous theories of cognitive development (Piaget, 1950; Vygotsky, 1978).

8.1.3.1.1 Data fitting variation 1

One way of simulating increased latency was to start with an overall high firing rate and incrementally decreasing it while keeping the alerting and control network effects higher than the modified overall firing times. The rule firing time (dat parameter) was varied from 40ms (the value used in the healthy adult model) to 65 ms in model-1-child for age group 6, which was then reduced gradually for each age group simulation approaching the adult rule firing time. The range of values attempted for the rule firing started from 80ms, and good fits were achieved with the values given in Table 8.1.

8.1.3.1.2 Data fitting variation 2

Another approach was to start with an overall high firing rate and incrementally decrease it, still keeping the firing time for productions for alerting and congruency greater than the adult model setting (which was 40ms), but no higher than the adjusted overall firing time. In this way of fitting the data, the rule firing time (:dat parameter) was increased from 40ms (the value used in the healthy adult model) to 110ms in model-1-child of age group 6, which was then reduced until age 10, approaching the adult rule firing time. The range of values tried for the rule firing started from 140ms, and good fits were achieved with the values given in Table 8.2.

8.1.3.2 Decreased accuracy

It was also reported in the human study that accuracy was lower in children than it was for adults (Rueda et al., 2004). In model-1-child, this was adjusted by changing the overall noise and utility values of the error production (see section 5.1.3.3.4). The justification for doing this is based on other work in the literature where errors were induced in the system either through changing and increasing the utility values of the error productions (Serna, et al., 2007) or through inducing more noise in the system (Jones & Ritter, 2000).

8.1.3.2.1 Data fitting variation 1

To model accuracy, the noise parameter in ACT-R (egs) was varied. Researchers have, in the past, changed the value of noise to simulate errors, demonstrating that increasing noise will increase the number of errors (Lovett, et al., 1997; Rehling, et al., 2004; Ritter, Schoelles, Klein & Kase, 2007). The values attempted were in the range 3 to 6, and the values which gave the best fits are shown in Table 8.1. The default value of egs is 0, and mostly found in the literature, it is set to 3 to simulate any non-deterministic behaviour of the models.

8.1.3.1.2 Data fitting variation 2

Based on other similar work in the literature, using conflicting productions for inducing error is akin to simulating poor choices among different strategies (Jongman & Taatgen, 1999; Serna et al., 2007). In section 5.1.3.3.4, the use of error productions is explained. For each age group of children, the utility values were systematically changed by observing which values produced the best fit to the model, hence making it more error prone and likely to closely simulate children's performance on the ANT-C. It has been reported in the child development literature (Mezzacappa, 2004) that commission errors occur mainly due to confusion or distraction which arise in the cases of incongruency conditions. This was simulated in model-1 and model-2 by productions error-left [P37] and error-right, [P38]. (Recall that [P37] and [P38] compete with the other decision making productions [P31]–[P34] only in the case of incongruency). Model-1 had earlier fitted the data well for the values 5 for random-left and random-right, 8 for error-left and error-right, and 20 for decide-left and decide-right. The logic used here was to change the utility values of erroneous answers ([P37] and [P38]) incrementally, as well as the randomness productions ([P33] and [P34]), keeping the utility for the decision-making productions ([P31] and [P32]) constant (as given in table 8.2).

8.1.3.3 Slower alerting network efficiency

It was observed from the human study results that alerting efficiency was slower up to age 9 (almost double), which reduced around age 10 and further for adults. This was modelled by modifying the rule firing time for the production notice-something-but-not-a-cue [P4], making it higher than the adult value (which was 40ms) for age group 6, and then gradually reducing it. This was done because this is the main production responsible for giving rise to the effect of surprise when a stimulus appears without an alerting signal.

8.1.3.3.1 Data fitting variation 1

Based on the value of default activation time (dat), the firing time for the production notice-something-but-not-a-cue [P4] was changed to 68 ms from 40ms. The fact that the alerting network had to be slowed down more than in the model-1 showed that there was significantly slower alerting efficiency in the younger age group. The values varied from 80ms to 50ms, and the best values that fitted the data are given in Table 8.1.

8.1.3.3.2 Data fitting variation 2

The overall rule firing time was set much slower for all productions, but not as slow for the production responsible for the alerting effect, which was still fired at a slower time than the healthy adult model. The fact that it was still slower than the adult model values (40 ms) points to the same interpretation that in younger age groups the alerting network is not as developed. The values varied from 80ms to 50ms, and the best values that fit the data are given in Table 8.2.

#### 8.1.3.4 Stable orienting network efficiency

Since the orienting network was reported to be unaffected by age, the production that gives the effect of a delay in the case of a centre cue condition notice-stimulus-with-centercue-and-shift [P17] was fired at a normal adult setting. No other change was made to any parameter or settings related to the orienting network in the model.

#### 8.1.3.5 Slower executive control network efficiency

There is a vast amount of literature in cognitive development suggesting that older children perform better than younger children in tasks that require response inhibition (Enns, 1990; Huizinga, et al., 2006). Specifically, it has also been posited that these improvements are due to age-related changes in S-R translations (Ridderinkhof & van der Molen, 1995; Ridderinkhof, van der Molen, Band & Bashore, 1997). Ridderinkhof and colleagues (1995; 1997) observed younger children are relatively more sensitive to adverse effects of response competition. Recall that in model-1 (and also model-2) the executive control network was simulated based on the dual-process model that handles interference (see section 5.1.3.1.3).

##### 8.1.3.5.1 Data fitting variation 1

Using the adult model as a benchmark, one approach initially used to achieve the desired effect was to change the relative utility values of the two conflicting productions that handle incongruency: (1) harvest-target-directly-if-incongruent [P29] and (2) refocus-again-if-incongruent [P30]. However, this did not produce the results fitting the experimental data, especially for age 6. This led to the belief that, at age 6, conflict resolution ability is so primitive that every time a conflict arises, refocusing might be required exclusively. With this in mind, the alternative approach of using production (2) in isolation was adopted. However, with age group 7 onwards, both conflicting productions were retained, reflecting the view that, by this age, children develop the ability to resolve conflict. Furthermore, but only for the 6-year-olds model, the rule firing time for production [P30] had to be increased to 100ms, reflecting a slightly slower capacity to refocus than the other productions. The values 7 and 15 for productions [P29] and [P30] were the tried and tested values for the healthy adult model for simulating the executive control network effect, and were used for all age groups except for age 6. Therefore, if this is thought of in terms of the dual-process model, based on which the executive control network is implemented, this indicates the use of the deliberate focused route (dual-process model explained in section 5.1.3.1.3).

#### 8.1.3.5.2 Data fitting variation 2

In this variation, the overall firing time (processing speed) was significantly higher, which seems to account for most of the executive control slow down effect. Here, both conflicting productions [P29] and [P30] were retained, indicating a primitive presence of conflict resolution ability. Nevertheless, the firing time of [P30] for the 6-year-olds was still fired at an action time higher than set in the adult model. This simulated a slowed down effect and indicated that children took longer in having to refocus most of the times when the flanker effect was encountered, but returned to 40ms by age 7. Therefore, if this is thought of in terms of the dual-process model, based on which the executive control network is implemented, this indicates the use of both the direct and the deliberate focused routes (also operating at a slower speed), but the main difference from variation 1 is that the overall firing times used in variation 2 were very high. Later, the relation between overall high processing speed and inhibitory control is discussed, reviewing evidence from the cognitive development literature.

### 8.1.3.6 Summary of modifications

Table 8.1 summarises one approach used for the data fitting process. The first column is the age group modelled, which is 6-10 years and adults. The second column shows how the overall reaction times increase by varying the rule firing time of the model. The third column indicates that higher error rates are produced by increasing the noise parameter. The effect of increased alerting network efficiency is modelled through increasing the firing time of production [P4] not-cue-so-switch-state, which simulates the element of surprise when no alerting signal is given. Finally, the last column shows that, for age group 6, for handling distraction only production [P30] is used (that too is slowed down to fire at 100ms), so production [P29] is not used, but for the later age 7 and beyond the utility values of 7 and 15 are used for both productions responsible for handling distraction (recall that 7 and 15 are the values shown to be the best fit for model-1).

Table 8-1: Summary of modifications (according to variation 1) to parameter/production settings to model-1 to produce model-1-child.

| **Age in years** | **Latency (overall rule firing time) in ms** | **Noise parameter 's'** | **Alerting effect in ms** | **Executive control effect utility values for [P29] and [P30] and the firing time for [P30]** |
|---|---|---|---|---|
| 6 | 65 | 4.5 | 68 | Only [P30] used and fired at 100 ms |
| 7 | 62 | 4 | 65 | 7, 15; 40ms |
| 8 | 58 | 3.5 | 60 | 7, 15; 40ms |
| 9 | 50 | 3.2 | 55 | 7, 15; 40ms |
| 10 | 40 | 3.1 | 45 | 7, 15; 40ms |
| Adult | 40 | 3 | 40 | 7, 15; 40ms |

Table 8.2 summarises another approach used for data fitting. The first column indicates the age group modelled – age 6-10 years and adults. The second column shows how the overall reaction times were increased by varying the rule firing time of the model. The third column indicates that higher error rates were induced by increasing the probabilities of firing error productions. The effect of increased alerting network efficiency was modelled through increasing the firing time of production [P4]. Finally, the last column shows that, for age group 6, production [P30], which makes the model refocus (refocus-again-if-incongruent) every time a distracter is selected for processing, is slowed down, but for age 7 and up, it returns to the settings of model-1.

Table 8-2: Summary of modifications (according to variation 2) to parameter/production settings to model-1 to produce model-1-child.

| **Age in years** | **Latency (Rule firing time) in ms** | **Utility values for productions [P31-32], [P33-34] and [P37-38] for error** | **Alerting effect[2], firing time for [P4]** | **Executive Control Effect, utility values and firing time of [P30]** |
|---|---|---|---|---|
| 6 | 110 ms | 8, 13, 20 | 55 ms | 7, 15; 60 ms |
| 7 | 90 ms | 6, 12, 20 | 55 ms | 7, 15; 40 ms |
| 8 | 75 ms | 6, 11, 20 | 55 ms | 7, 15; 40 ms |
| 9 | 55 ms | 6, 10, 20 | 55 ms | 7, 15; 40 ms |
| 10 | 45 ms | 6, 9, 20 | 40 ms | 7, 15; 40 ms |
| Adult[4] | 40 | 5, 8, 20 | 40 | 7, 15; 40 ms |

After giving the results in the next section (produced from both variations), a detailed discussion and comparison of the two variations shall be undertaken, making inferences based on these findings; it is interesting to find such correlations in the cognitive development literature as well.

### 8.1.4 Results

The results from experiment 1 of the Rueda et al. (2004) study, which reports the performance of children of age groups 6-9 on the ANT-C, are compared with the model-1-child data. The data for 10-year-olds is taken from experiment 2 of the study, and adult data from experiment 3 (Rueda et al., 2004). The reaction times, error rates, network efficiencies and their interactions as produced by both approaches used for data fitting are given in detail below. Adult human data (Fan et al., 2002) and results from model-1 (from Table 5.1) are also reported for baseline values.

#### 8.1.4.1 Latency data

As observed from the human study, the response times produced by model-1-child also incrementally improved for each age group. Tables 8.3 and 8.4 give the mean reaction times for the human study (Rueda et al., 2004), along with the simulated results from model-1-child for each age group. The statistics of correlation and RMSD for both approaches is given in Table 8.7, which shows a good fit to the human data. Figure 8.1 shows the decrement in reaction times as age progresses, as indicated by the human study (Rueda et al., 2004) and simulated by model-1-child. Standard deviations (SD) are given in brackets (SDs from human data could not be obtained).

Table 8-3: Latency data from the human study (Rueda et al., 2004) simulated by model-1-child using variation 1.

| **Flanker type** | **Age years** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **No cue** | | **Center** | | **Double** | | **Spatial** | |
| | | Human | Model | Human | Model | Human | Model | Human | Model |
| **Neutral** | 6 | 991 | 668(10) | 890 | 599(9) | 906 | 569(12) | 835 | 530(6) |
| | 7 | 846 | 650(5) | 819 | 585(6) | 741 | 558(12) | 748 | 521(9) |
| | 8 | 834 | 625(5) | 790 | 565(6) | 765 | 540(12) | 691 | 507(9) |
| | 9 | 765 | 585(5) | 675 | 526(7) | 678 | 503(12) | 669 | 475(9) |
| | 10 | 673 | 528(5) | 619 | 482(6) | 577 | 463(12) | 584 | 441(8) |
| | Adult | 476 | 520(5) | 467 | 482(6) | 438 | 464(7) | 429 | 441(6) |
| | | | | | | | | | |
| **Congruent** | 6 | 968 | 663(6) | 905 | 598(7) | 847 | 560(9) | 859 | 531(7) |
| | 7 | 905 | 649(8) | 833 | 583(8) | 794 | 549(7) | 762 | 517(5) |
| | 8 | 854 | 626(8) | 807 | 568(8) | 758 | 531(7) | 767 | 508(5) |
| | 9 | 783 | 583(8) | 752 | 528(8) | 677 | 497(7) | 702 | 478(5) |
| | 10 | 655 | 526(7) | 656 | 478(7) | 618 | 460(7) | 591 | 443(5) |
| | Adult | 505 | 521(4) | 477 | 483(4) | 469 | 459(7) | 453 | 441(5) |
| | | | | | | | | | |
| **Incongruent** | 6 | 1041 | 787(21) | 1006 | 716(28) | 954 | 691(30) | 959 | 656(28) |
| | 7 | 959 | 747(29) | 887 | 681(26) | 899 | 651(25) | 827 | 622(20) |
| | 8 | 922 | 705(29) | 864 | 651(26) | 825 | 624(25) | 854 | 603(19) |
| | 9 | 857 | 666(29) | 781 | 619(26) | 791 | 589(25) | 755 | 559(19) |
| | 10 | 719 | 602(28) | 723 | 563(25) | 677 | 545(24) | 674 | 517(18) |
| | Adult | 546 | 592(19) | 548 | 557(18) | 525 | 531(16) | 527 | 527(21) |

Table 8-4: Latency data from the human study (Rueda et al., 2004) simulated by model-1-child using variation 2.

| Flanker type | Age years | Warning type | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No cue | | Center | | Double | | Spatial | |
| | | Human | Model | Human | Model | Human | Model | Human | Model |
| **Neutral** | 6 | 991 | 887(16) | 890 | 765(14) | 906 | 774(19) | 835 | 726(8) |
| | 7 | 846 | 780(11) | 819 | 666(14) | 741 | 668(15) | 748 | 625(10) |
| | 8 | 834 | 673(8) | 790 | 592(7) | 765 | 589(2) | 691 | 552(8) |
| | 9 | 765 | 609(8) | 675 | 538(7) | 678 | 523(8) | 669 | 496(7) |
| | 10 | 673 | 547(5) | 619 | 501(6) | 577 | 481(7) | 584 | 460(6) |
| | Adult | 476 | 520(5) | 467 | 482(6) | 438 | 464(7) | 429 | 441(6) |
| | | | | | | | | | |
| **Congruent** | 6 | 968 | 884(11) | 905 | 761(14) | 847 | 797(8) | 859 | 722(21) |
| | 7 | 905 | 775(7) | 833 | 675(17) | 794 | 698(11) | 762 | 626(7) |
| | 8 | 854 | 673(7) | 807 | 594(9) | 758 | 599(12) | 767 | 552(7) |
| | 9 | 783 | 603(6) | 752 | 536(7) | 677 | 535(8) | 702 | 499(6) |
| | 10 | 655 | 543(5) | 656 | 498(5) | 618 | 491(5) | 591 | 461(6) |
| | Adult | 505 | 521(4) | 477 | 483(4) | 469 | 459(7) | 453 | 441(5) |
| | | | | | | | | | |
| **Incongruent** | 6 | 1041 | 993(34) | 1006 | 854(35) | 954 | 937(24) | 959 | 830(22) |
| | 7 | 959 | 869(19) | 887 | 749(27) | 899 | 792(15) | 827 | 707(32) |
| | 8 | 922 | 757(26) | 864 | 664(18) | 825 | 699(21) | 854 | 631(17) |
| | 9 | 857 | 690(13) | 781 | 606(19) | 791 | 627(20) | 755 | 582(20) |
| | 10 | 719 | 622(22) | 723 | 588(18) | 677 | 589(13) | 674 | 539(27) |
| | Adult | 546 | 592(19) | 548 | 557(18) | 525 | 531(16) | 527 | 527(21) |

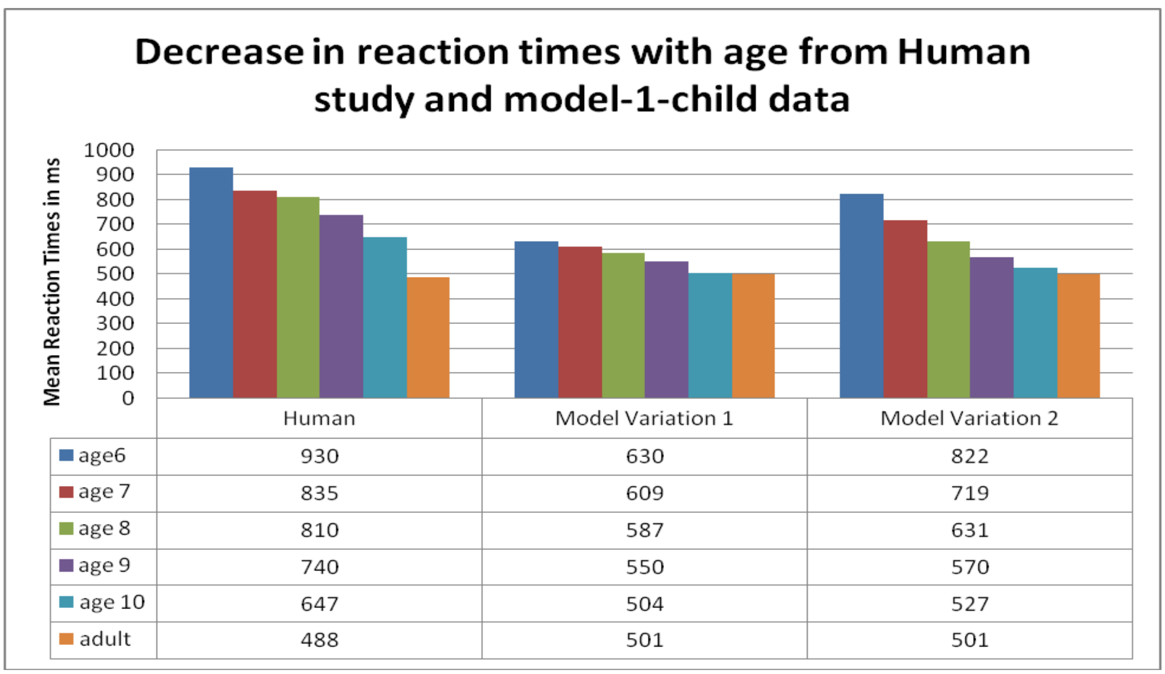



Figure 8-2: From Tables 8.3 and 8.4, we see a decrease in mean reaction times with age from the human data and two variations of model-1-child illustrating similar trends in magnitude.

#### 8.1.4.2 Accuracy data

As observed from the human study, the model-1-child error rates also 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 condition than the incongruent conditions (Rueda et al., 2004); nevertheless, Rueda and colleagues did not comment on this. The accuracy results produced by model-1-child for ages 7 and 8 were therefore correlated negatively with the human study data. Although the model-1-child results could have been fitted to simulate this anomaly, it did not seem, however, logical to do so. The data from other studies showed consistency in accuracy scores in relation to target stimulus and across age groups (Ahktar & Enns, 1989).

As a result, model-1-child for all age groups incrementally showed improvement in accuracy and increased the chance of error in the case of the incongruent condition when compared to neutral or congruent conditions. Consequently, age groups 6, 9 and 10 showed better correlations but age groups 7 and 8 showed negative correlations. For further validation, the data for age 7 and 8 from model-1-child were compared with accuracy data from experiment 3 (in which the average age is 7.5); these showed better correlations as given in section 8.1.5.

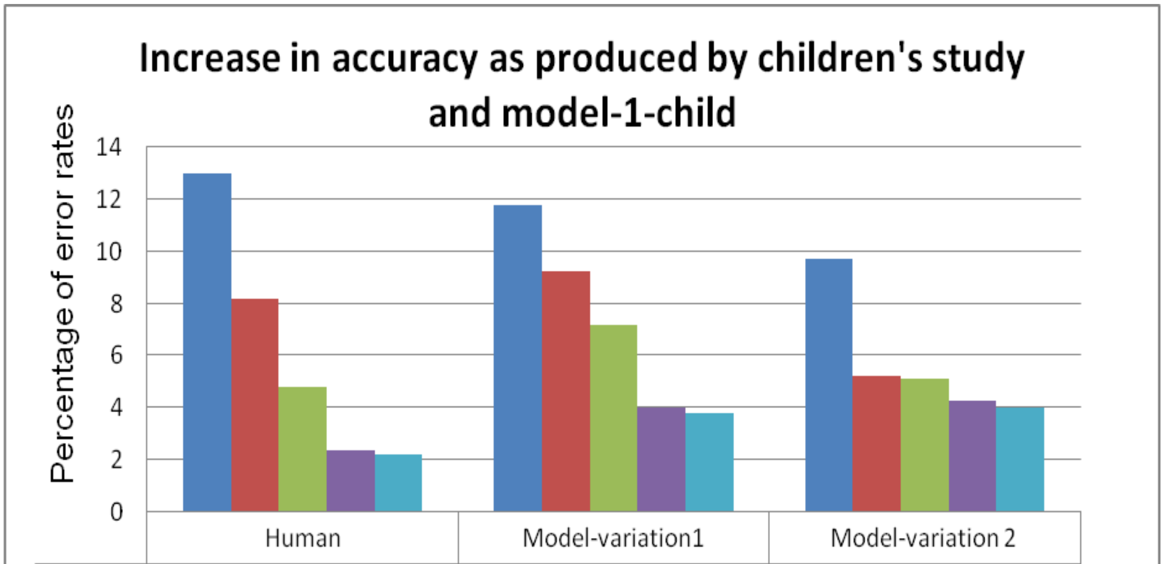
As mentioned earlier, two error modelling approaches were explored. Table 8.5 shows accuracy data produced and fitted to human data by varying the noise parameter, while Table 8.6 shows the results of the same process, but instead modifies the utility values of the error productions.

Table 8-5: Error rates from the children's study (Rueda et al., 2004) and model-1-child using variation1.

| **Flanker type** | **Age** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No cue | | Center | | Double | | Spatial | |
| | | Human | Model | Human | Model | Human | Model | Human | Model |
| **Neutral** | 6 | 5.6 | 12 | 9.7 | 6 | 8.3 | 10 | 6.3 | 4 |
| | 7 | 7.6 | 4 | 6.3 | 6 | 8.3 | 12 | 6.3 | 4 |
| | 8 | 6.9 | 6 | 5.6 | 8 | 3.5 | 4 | 3.5 | 6 |
| | 9 | 2.1 | 0 | 2.1 | 0 | 2.1 | 4 | 0.7 | 2 |
| | 10 | 2.1 | 0 | 2.1 | 0 | 2.1 | 4 | 1 | 2 |
| | Adult | 2.1 | 1.3 | 0 | 1.9 | 4.2 | 3.4 | 0 | 0.9 |
| | | | | | | | | | |
| **Congruent** | 6 | 11.8 | 4 | 5.6 | 8 | 7.6 | 12 | 6.9 | 4 |
| | 7 | 4.2 | 4 | 4.9 | 4 | 4.9 | 2 | 7.6 | 12 |
| | 8 | 3.5 | 6 | 6.3 | 0 | 4.9 | 4 | 4.9 | 2 |
| | 9 | 2.8 | 2 | 2.1 | 4 | 0.7 | 0 | 2.1 | 2 |
| | 10 | 2.1 | 2 | 1 | 4 | 1 | 0 | 1 | 2 |
| | Adult | 0 | 1.6 | 3.1 | 4.7 | 1 | 0.3 | 1 | 2.8 |
| | | | | | | | | | |
| **Incongruent** | 6 | 25 | 15 | 24 | 17 | 21.5 | 25 | 23.6 | 25 |
| | 7 | 6.9 | 19 | 4.2 | 15 | 2.1 | 19 | 10.4 | 10 |
| | 8 | 4.2 | 17 | 4.9 | 10 | 4.2 | 8 | 5.6 | 15 |
| | 9 | 4.9 | 10 | 3.5 | 10 | 4.2 | 10 | 1.4 | 4 |
| | 10 | 4.2 | 10 | 3.1 | 10 | 5.2 | 8 | 1 | 4 |
| | Adult | 8.3 | 4.7 | 0 | 0.9 | 0 | 0.9 | 2.1 | 3.4 |

Table 8-6: Error rates from the children's study (Rueda et al., 2004) and model-1-child using variation2.

| **Flanker type** | **Age** | **Warning type** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | No cue | | Center | | Double | | Spatial | |
| | | Human | Model | Human | Model | Human | Model | Human | Model |
| **Neutral** | 6 | 5.6 | 4.7 | 9.7 | 3.1 | 8.3 | 5.7 | 6.3 | 4.7 |
| | 7 | 7.2 | 2.1 | 6.8 | 2.1 | 12.9 | 1.6 | 6.3 | 2.1 |
| | 8 | 6.9 | 2.6 | 5.6 | 1.6 | 3.5 | 3.1 | 3.5 | 3.1 |
| | 9 | 2.1 | 3.6 | 2.1 | 1.6 | 2.1 | 4.7 | 0.7 | 2.7 |
| | 10 | 2.1 | 1.6 | 2.1 | 2.6 | 2.1 | 5.2 | 1 | 4.2 |
| | Adult | 2.1 | 1.3 | 0 | 1.9 | 4.2 | 3.4 | 0 | 0.9 |
| | | | | | | | | | |
| **Congruent** | 6 | 11.8 | 6.3 | 5.6 | 8.3 | 7.6 | 4.2 | 6.9 | 7.3 |
| | 7 | 4.4 | 0.5 | 12.5 | 5.2 | 5.1 | 4.7 | 5.5 | 3.6 |
| | 8 | 3.5 | 1.6 | 6.3 | 2.6 | 4.9 | 5.7 | 4.9 | 0.5 |
| | 9 | 2.8 | 1.6 | 2.1 | 1.7 | 0.7 | 2.6 | 2.1 | 3.1 |
| | 10 | 2.1 | 2.1 | 1 | 7.8 | 1 | 3.6 | 1 | 3.1 |
| | Adult | 0 | 1.6 | 3.1 | 4.7 | 1 | 0.3 | 1 | 2.8 |
| | | | | | | | | | |
| **Incongruent** | 6 | 25 | 19.8 | 24 | 15.6 | 21.5 | 16.7 | 23.6 | 19.8 |
| | 7 | 12.5 | 8.3 | 5.7 | 12 | 6.1 | 9.9 | 13.5 | 10.9 |
| | 8 | 4.2 | 14.1 | 4.9 | 9.9 | 4.2 | 7.8 | 5.6 | 9 |
| | 9 | 4.9 | 7.8 | 3.5 | 6.3 | 4.2 | 8.9 | 1.4 | 8 |
| | 10 | 4.2 | 7.8 | 3.1 | 2.1 | 5.2 | 3.1 | 1 | 5.2 |
| | Adult | 8.3 | 4.7 | 0 | 0.9 | 0 | 0.9 | 2.1 | 3.4 |




| | Human | Model-variation1 | Model-variation 2 |
|---|---|---|---|
| age6 | 13 | 11.8 | 9.7 |
| age 7 | 8.2 | 9.25 | 5.24 |
| age 8 | 4.8 | 7.2 | 5.1 |
| age 9 | 2.4 | 4 | 4.3 |
| age 10 | 2.2 | 3.8 | 4 |

Figure 8-3: From Tables 8.5 and 8.6, the mean error rates across all age groups for the human data and two variations of model-1-child showing a decrease in the mean error rates.

#### 8.1.4.3 Efficiencies of attentional networks

The efficiencies of each network for ages 6-10 were calculated using Equations 2.1-2.3. Table 8.7 reports the efficiencies of the alerting, orienting and control networks across each age group for both variations of model-1-child. The efficiency data further validate the fit of the model. As reported in the human study, alerting is much higher in age groups 6-9; orienting scores do not show any significant difference across various age groups, whereas executive control shows a high value for age 6, improving as age progresses.

Table 8-7: Network efficiencies from the ANT-C (Rueda et al., 2004) and model-1-child (from variation1 and variation2).

| Network Efficiency | Age years | Human | Model-1-child Variation 1 | Model-1-child Variation 2 |
|---|---|---|---|---|
| **Alerting** | 6 | 79 | 99 | 87 |
| | 7 | 100 | 99 | 88 |
| | 8 | 73 | 67 | 72 |
| | 9 | 79 | 81 | 72 |
| | 10 | 41 | 62 | 50 |
| | Adult | 30 | 46 | 46 |
| **Orienting** | 6 | 58 | 65 | 35 |
| | 7 | 62 | 63 | 44 |
| | 8 | 63 | 55 | 38 |
| | 9 | 42 | 53 | 34 |
| | 10 | 46 | 40 | 42 |
| | Adult | 32 | 38 | 38 |
| **Executive Control** | 6 | 115 | 124 | 114 |
| | 7 | 63 | 98 | 86 |
| | 8 | 71 | 87 | 83 |
| | 9 | 67 | 86 | 83 |
| | 10 | 69 | 80 | 86 |
| | Adult | 61 | 86 | 86 |

8.1.4.4 Interaction of attentional networks

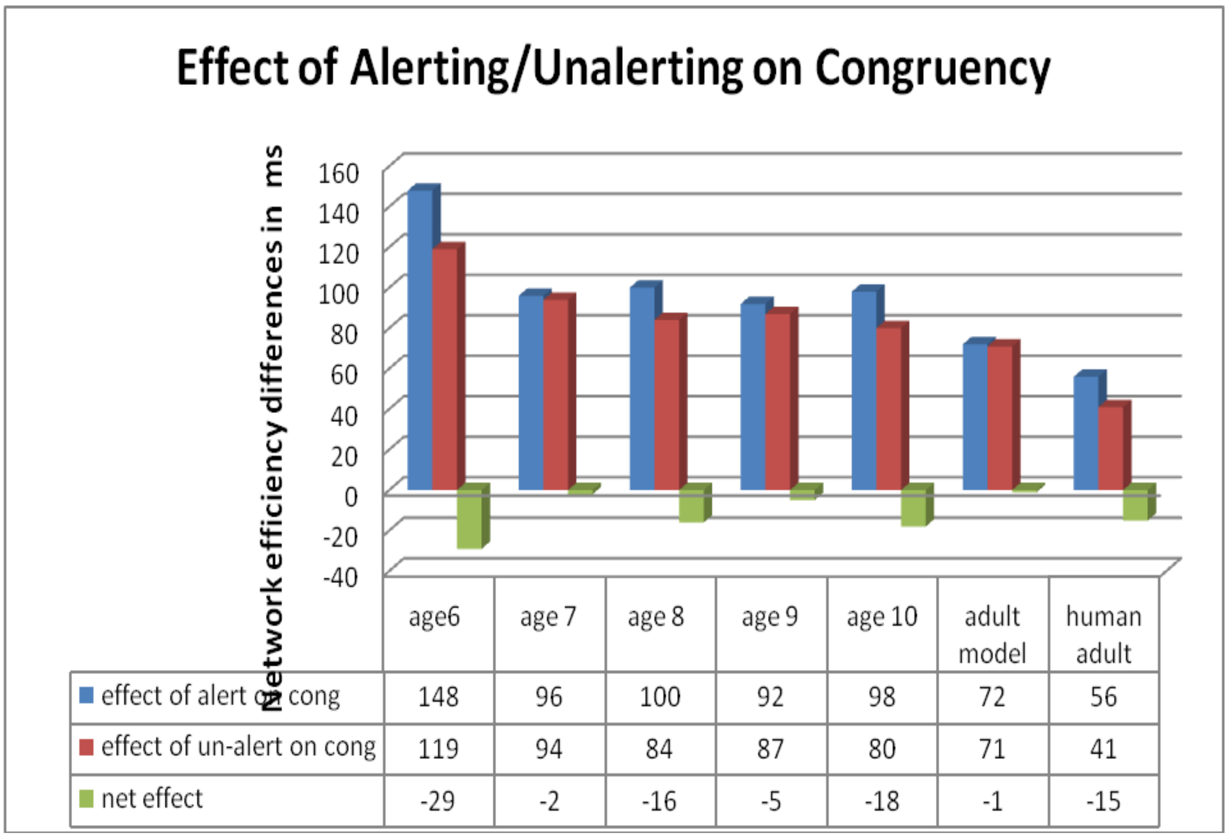
Based on the above results, once model-1-child for all age groups demonstrated veridical simulations of the children's data, the behavioural interactions of the networks on each other were explored the way it was done in Chapter 6 for healthy adults and in Chapter 7 for AD and mTBI patients. The children's study (Rueda et al., 2004) based on lack of correlations on the network efficiencies suggests independence, however the authors do show concern that, "it would not be reasonable to consider the networks as totally independent since the brain areas involved clearly communicate with each other" (Rueda et al., 2004, p. 1037).

Using the data produced by model-1-child, the effects were calculated as suggested in Chapter 6, based on other studies exploring the interactions of networks (Callejas et al., 2004; 2005). Therefore, applying the formulae in Equations 8.1-8.2, the effects of alerting on congruency were calculated from the model-1-child data (alerting and control were the two most affected networks, so the effects of these were mainly of interest).

$$Effect\ of\ alerting\ on\ congruency = RT\ double_{incong} - RT\ double_{cong} \quad \text{Equation 8.1}$$

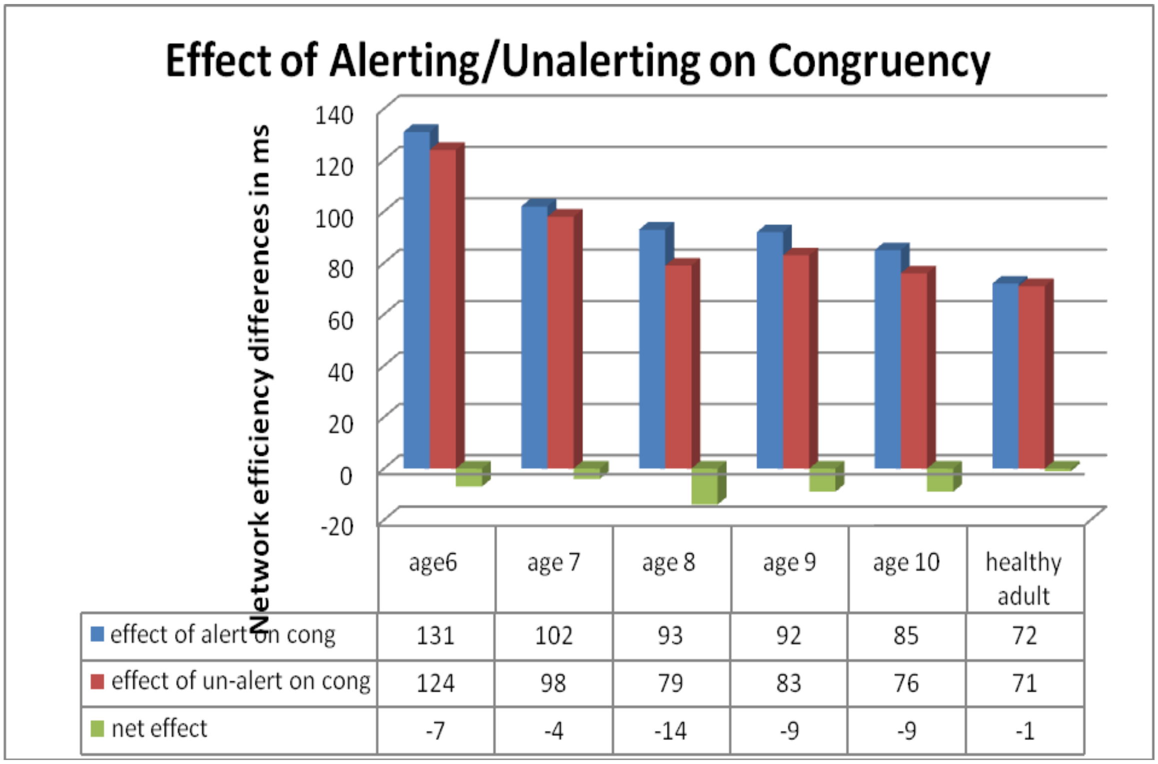
$$Effect\ of\ noalerting\ on\ congruency = RT\ nocue_{incong} - RT\ nocue_{cong} \quad \text{Equation 8.2}$$

Both approaches to data fitting produced an inhibiting effect of alerting on congruency throughout the age groups 6-10 and into adulthood (as seen for adults, and as discussed in Chapter 6). This may suggest that, although the networks of alerting and congruency have slower efficiencies, the interactions are similar to those produced in adult human studies. Figures 8.4 and 8.5 show consistent results.




| | age6 | age 7 | age 8 | age 9 | age 10 | adult model | human adult |
|---|---|---|---|---|---|---|---|
| effect of alert on cong | 148 | 96 | 100 | 92 | 98 | 72 | 56 |
| effect of un-alert on cong | 119 | 94 | 84 | 87 | 80 | 71 | 41 |
| net effect | -29 | -2 | -16 | -5 | -18 | -1 | -15 |

Figure 8-4: Effect of alerting on congruency for all age groups 6-10 and for healthy young adults using variation 1 of data fitting for model-1-child.




| | age6 | age 7 | age 8 | age 9 | age 10 | healthy adult |
|---|---|---|---|---|---|---|
| effect of alert on cong | 131 | 102 | 93 | 92 | 85 | 72 |
| effect of un-alert on cong | 124 | 98 | 79 | 83 | 76 | 71 |
| net effect | -7 | -4 | -14 | -9 | -9 | -1 |

Figure 8-5: Effect of alerting on congruency for all age groups 6-10 and for healthy young adults using variation 2 of data fitting for model-1-child.

### 8.1.5 Summary of results and model validation

Model-1-child simulated human results whereby the overall reaction times and error rates were higher, alerting was affected up to age 9, conflict resolution capability was highly affected at age 6 and orienting remained unaffected.

The results produced by the two approaches to fitting data explored in section 8.1.2 are given. The correlations and RMSD for each data set compared with the human data for both latency and accuracy data is given in Table 8.8, while those of the efficiencies of the three networks are shown in Table 8.9. Good fits on all measures of latency, accuracy and efficiencies indicate the validity of the models. Furthermore, based on the model results, it is interesting to note that, although the alerting and congruency networks were affected, the inhibiting effect of alerting on congruency, which is seen in adults, was preserved even at younger age groups.

Table 8-8: Model-1-child (variation1 and 2) correlations and RMSD with children's data (Rueda et al., 2004) for latency data from Tables 8.3 and 8.4, accuracy data from Tables 8.5 and 8.6.[12]

| | **Latency Data** | | | | **Accuracy Data** | | | |
|---|---|---|---|---|---|---|---|---|
| **Age** | **Correlations Variations** | | **RMSD Variations** | | **Correlations Variations** | | **RMSD Variations** | |
| | **1** | **2** | **1** | **2** | **1** | **2** | **1** | **2** |
| **6** | 0.97 | 0.79 | 86 | 34 | 0.77 | 0.93 | 1.5 | 1.28 |
| **7** | 0.94 | 0.92 | 65 | 34 | 0.73 | 0.86 | 1.2 | 1.02 |
| **8** | 0.94 | 0.88 | 64 | 52 | 0.86 | 0.85 | 1.6 | 1.24 |
| **9** | 0.93 | 0.93 | 49 | 38 | 0.81 | 0.58 | 0.8 | 1.15 |
| **10** | 0.93 | 0.93 | 41 | 35 | 0.72 | 0.72 | 0.9 | 0.68 |
| **adult** | 0.93 | 0.93 | 6 | 6 | 0.73 | 0.73 | 0.60 | 0.60 |

Table 8-9: Model-1-child (variation1 and variation2) data from Table 8.8 for the three networks over age groups 6-10 compared with children's data (Rueda et al., 2004).

| | **Network Efficiencies** | | | |
|---|---|---|---|---|
| **Age** | **Correlations Variations** | | **RMSD Variations** | |
| | **1** | **2** | **1** | **2** |
| **6** | 0.97 | 0.95 | 7.67 | 8.12 |
| **7** | 0.54 | 0.55 | 11.68 | 10.35 |
| **8** | 0.65 | 0.91 | 6.29 | 9.25 |
| **9** | 0.89 | 0.86 | 7.35 | 6.4 |
| **10** | 0.73 | 0.94 | 8.15 | 6.55 |
| **Adult** | 0.95 | 0.95 | 4.71 | 6.71 |

### 8.1.6 Discussion

In section 8.1, the performance of children on the attentional network test adapted for children (ANT-C) is simulated, exploring more than one way of simulating the effects. Model-1-child fits the human data well, as shown by the statistics of correlations and root mean square deviations on all the measures of latency, accuracy and efficiencies of the three networks. Here, by using modelling as a tool, the rate and form of development of the networks are simulated so that a comparison can be made with adult behaviour.

Various methods of simulating children's performance were explored, and two variations with valid and interesting, interpretations were reported. The different ways of simulating behaviour helped in guiding possibly why children's behaviour is different, and then related these with evidence from the literature. Variation1 produced good correlations, but RMSDs were high because, for the children's data, a very high

[12] Accuracy data for age groups 7 and 8 of model-1-child are correlated with data from experiment 3 of Ruedal et al., (2004) study. As discussed in section 8.1.4.2, experiment 1 data showed negative correlations.

RT was seen compared to what the model simulated. Variation2 gave a slightly better fit showing low RMSD. Based on the process of model fitting, the following can be suggested about the cognitive development of attentional networks:

1. When the rule firing time is set at very slow (variation2), then the control network is shown to be affected minimally, but when a relatively faster rule firing time is set, although still slower than adult simulation settings, (variation1), then the control network has to be shown to be very immature to the extent that the ability to resolve conflict for children is very primitive. This indicates a possible relationship between processing speed and the mechanism of inhibitory control. Further, by using different firing times for certain productions attributed to different processes, it is shown that there is not always a "global clock" which controls processing speed in children, and different processes may be running with different processing times. These findings were confirmed from a review of the literature where the argument was that age-related changes in processing speed do not pertain to all cognitive processes with the same degree. The literature also emphasised the role of inhibitory control in cognitive development, establishing a relationship between inhibitory control and age-related variations in processing speed (Ridderenkhof & van der Molen, 1997; Ridderenkhof, et al., 1997).
2. The children's study (Rueda et al., 2004) showed that the alerting network was affected up to age 9 in children. In all the approaches attempted for data fitting, irrespective of the overall increased rule firing time, the production not-cue-so-switch-state, [P4], which induces the effect of delay in the case of no alerting, was set to fire at a higher rate than the overall rule firing time. This shows that, no matter how the data were fitted, the alerting networks showed slowing down, thus leading to further validation of the idea that it takes children longer to respond to stimuli in the absence of alerting than healthy adults.
3. In relation to the executive control network, variations of model fitting led to the determination that the incongruency effect may be higher in children mainly due to the fact that the conflict resolution mechanism is not so developed at early ages. The model fitting also suggests that children tend to choose only the deliberately controlled pathway (see the discussion of two pathways in a dual-process model in

section 5.1.3.1.3), which may also have a slower processing time than that for adults (indicated by a slower firing time of rule [P30]). This reflects the slowed executive control network effect due to an affected refocusing capacity. Ridderinkhof and colleagues (1995; 1997) observed younger children are relatively more sensitive to adverse effects of response competition.

4. The study (Rueda et al., 2004) also showed that children made more errors than adults. However, at age 7 and 8, the study results deviated from this result. There is evidence in the cognitive development literature which points out that accuracy is generally lower in children, and the model also predicts the same for all age groups under study (Akhtar & Enns, 1989). So, it is possible that the children's experiment needs to be replicated to explore this discrepancy in human and model data.
5. Regarding the interactions of the networks, the model predicts that, although alerting and congruency networks are affected, the inhibiting effect of alerting which is seen in adults, is preserved even in younger age groups. This may imply that, although alerting and congruency networks may not be fully developed, the neural circuitry involved is established to the extent that they start interacting with each other. Therefore, although the networks may still be in the developmental stages, they are developed enough or strong enough to be able to interact with one another. This may be further validated through imaging studies.

In the next section, model-2 (section 5.2) is used with the data fitting settings of model-1-child to investigate the effect of validity and interaction of cueing and congruency in children.

## 8.2 Model-2–Child: Effect of invalid cueing on performance of children ANT-C

The Rueda et al. study (2004) of children’s performance on the ANT did not use an invalid cue; hence, the effect of invalidity and disengaging from a location could not be assessed in children through this study. However, this is of significant importance to researchers (Mezzacappa, 2004), and there is evidence that children have a slowed down ability to disengage from an invalidly cued location and engage a target location (Akhtar and Enns, 1989; Trick & Enns, 1998, Enns & Brodeur, 1989). For example, Enns and Brodeur (1989) administered a classification task designed to measure the covert shifts of visual attention and observed that children processed uncued (invalidly cued) locations more slowly than adults.

In section 8.1, model-1-child, simulating children’s performance on the ANT, was validated against children’s data (Rueda et al., 2004). Furthermore, in section 5.2, an ANT model extended with invalid cue conditions (model-2) was explicated and validated against human data (Fernandez-Duque & Black, 2006; Fan et al., 2009). So, modifications summarised in Table 8.1 were applied to model-2 and results were recorded. The basic design of model-2 remained unchanged. This revised model is referred to as ‘model-2-child.’

As a consequence, there were two objectives for doing this: (1) To investigate whether the validity effect for children was higher than adults. If yes, then what was the rate of improvement and when did it become stable and match adult data (Fernandez-Duque & Black, 2006)? (2) In addition, with explicit cued and uncued conditions it would be easier to assess the effect of cueing/uncueing on congruency.

### 8.2.1 Results

To assess the efficiency of invalid cueing and the effect of disengaging from wrongly cued locations, model-2 was run with the parameter/production settings that worked for model-1-child for various age groups in children (results with variation 1 described in Table 8.1 are shown). Based on the latency data recorded, the validity effect (Equation 5.2) and the effects of cueing on congruency were explored as follows:

#### 8.2.1.1 Validity effect

It was observed from the results of model-2-child, as illustrated in Figure 8.6 for ages 6-10, that the validity efficiency was slower starting with ages 6 up to 9 years. This points to a slowdown in the disengagement effect, which may not be so mature in children up to age 10; this needs to be tested further by conducting another study with children administered on an ANT design revised with an invalid cue condition.

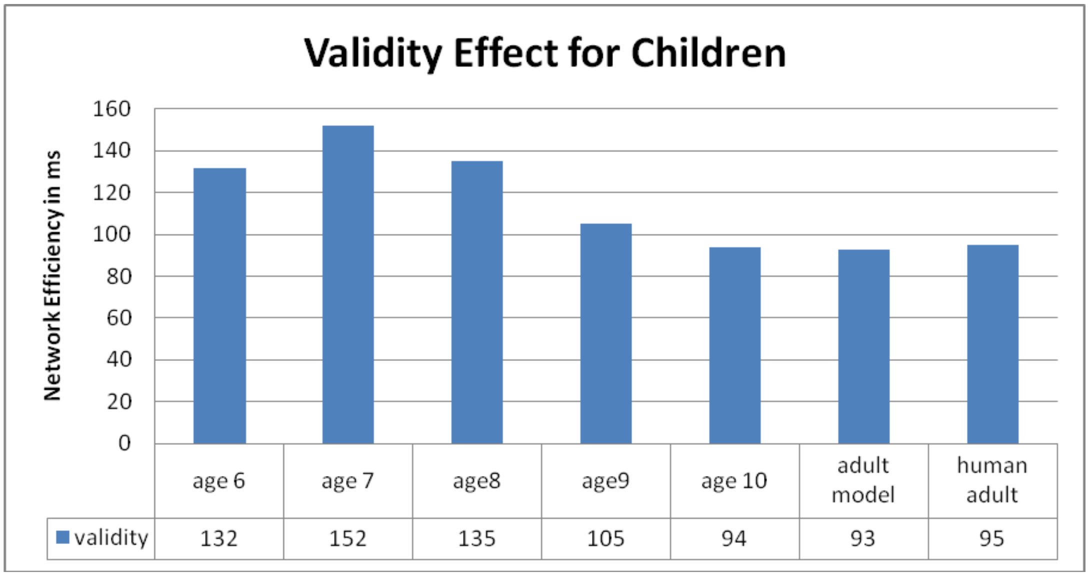


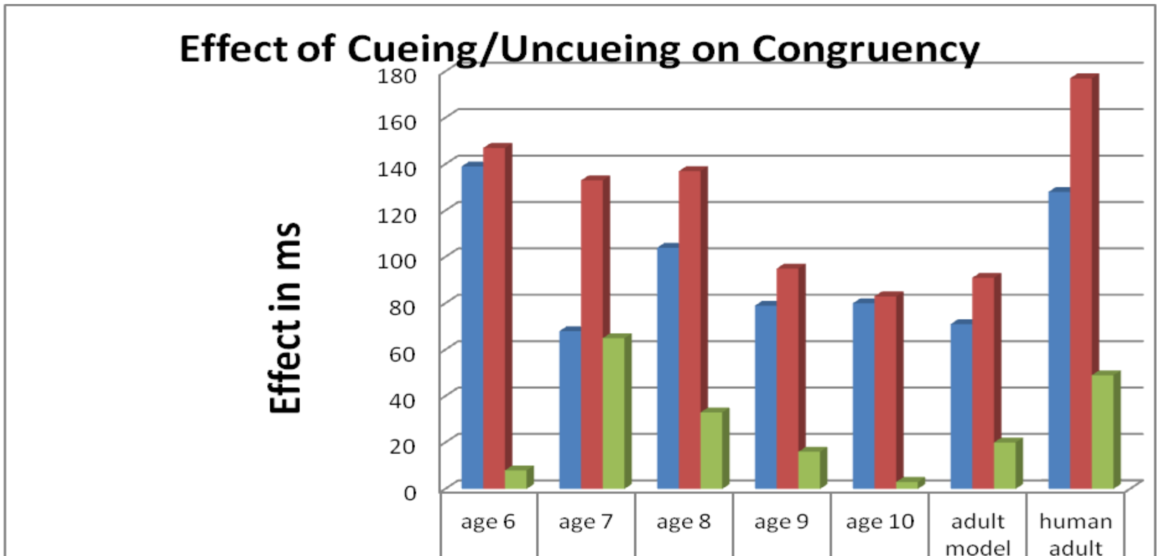

Figure 8-6: Validity efficiency for children, predicted using model-2-child.

#### 8.2.1.2 Effect of cueing on congruency

In addition, using the formulae in Equations 8.3 and 8.4, the effects of cueing on congruency were explored for children. A positive effect of cueing on congruency, as illustrated in Figure 8.7, was suggested across all age groups.

$$\text{Effect of cueing on congruency} = \text{RT cued}_{\text{incong}} - \text{RT cued}_{\text{cong}} \qquad \text{Equation 8.3}$$

$$\text{Effect of uncueing on congruency} = \text{RT uncued}_{\text{incong}} - \text{RT uncued}_{\text{cong}} \qquad \text{Equation 8.4}$$




| | age 6 | age 7 | age 8 | age 9 | age 10 | adult model | human adult |
|---|---|---|---|---|---|---|---|
| effect of cueing on congruency | 139 | 68 | 104 | 79 | 80 | 71 | 128 |
| effect of uncueing on congruency | 147 | 133 | 137 | 95 | 83 | 91 | 177 |
| net effect | 8 | 65 | 33 | 16 | 3 | 20 | 49 |

Figure 8-7: Effect of cueing on congruency for age groups 6-10 and for healthy young adults suggested by model-2-child.

### 8.2.2 Discussion

The children's study (Rueda et al., 2004) did not take into account the effect of invalid cueing (because no invalid condition was used in the ANT-C design). Therefore, the model settings used in model-1-child were applied to the invalid cueing model (model-2, section 5.2) to predict children's behaviour. It was no surprise that the simulated child model took longer to respond in the cue condition where a cue appeared in an incorrect location prior to the appearance of the stimulus. It was predicted that in children the validity efficiency would be slower up to age 10, which could be due to slow disengaging capacity from an uncued location. Also, model-2-child indicated that akin to adults, cueing has a positive effect on congruency. These call for further validation through another study, with children tested on a revised ANT design incorporated with an invalid cue condition.

### 8.3 Chapter summary

In this chapter, the performance of children on the attentional network test adapted for children (ANT-C) was simulated, exploring more than one way of simulating the effects. The models fitted the human data well, as shown by the statistics of correlations and root mean square deviations on all the measures of latency, accuracy and efficiencies of the three networks. Here, by using modelling as a tool, the rate and form of development of networks were simulated so that comparisons could be made with adult behaviour. The process of model fitting suggested possible reasons for why the effects were found in children (detailed in section 8.1.6 and 8.2.2), interesting observations are reiterated here.

1. Based on how the overall high latency was fitted, it was concluded that there has to be some relationship between processing speed and mechanism of inhibitory control. Moreover, by using different firing times for certain productions attributed to different processes, it was demonstrated that there is not always a "global clock" which controls processing speed in children, and different processes may be running with different processing times. These findings were confirmed by a review of the literature (Ridderenkhof & van der Molen, 1997; Ridderenkhof, et al., 1997), where the argument is that age-related changes in processing speed do not pertain to every cognitive process with the same degree. This literature also emphasised the role of inhibitory control in cognitive development, establishing a relationship between inhibitory control and age-related variations in processing speed.

2. In relation to the executive control network, it was suggested that in children the conflict resolution mechanism is not very developed at the early ages, and most of the time children tend to choose only the deliberately controlled pathway (see a discussion of the two pathways in a dual-process model in section 5.1.2.1), which may also have a slower processing time than adults. It was also suggested that the slowed executive control network effect is due to an affected refocusing capacity in children.

3. The human study showed that children made more errors than adults. However, at age 7 and 8, the study (Rueda et al., 2004) results deviated from this line. There is evidence in the cognitive development literature which points out that accuracy is generally lower in children, a finding also predicted by model-1-child for all age groups under study. In this case, it may be that the children's experiment needs to be replicated to explore this discrepancy in human and model data.

4. Regarding the interactions of the networks, the model results imply that, although the alerting and congruency networks may not be fully developed, the neural circuitry involved is established to the extent that they start interacting with each other. So, although the networks may still be in the developmental stages, they show the same interactions as found in human adults (Callejas et al., 2004; 2005), that is an inhibitory effect of alerting on congruency whereas a facilitatory effect of cueing on congruency.

5. Using invalid cueing in model-2-child, it was predicted that in children the validity effect is higher up to age 10, which could be due to slow disengaging capacity from an uncued location. This supports the study in the literature where it was reported that children have a slowed down ability to disengage from an invalidly cued location and engage at a target location (Akhtar and Enns, 1989; Trick & Enns, 1998, Enns & Brodeur, 1989). For example, Enns and Brodeur (1989) administered a classification task designed to measure the covert shifts of visual attention and observed that children processed uncued (invalidly cued) locations more slowly than adults.

Hence, by simulating the effects using different approaches, model analysis has provided pointers on what could be the possible reasons for slower efficiencies and overall effects. Similar to simulating the performance of children, ageing studies can be modelled to simulate the performance of older subjects on such attention-related tasks.

# 9. Conclusions

The goal of this thesis is to explore the theory of attentional networks with the help of newly designed computational models simulating the attentional network task in its original form and its variants. In this concluding chapter, it is re-examined how computational modelling has helped understand the human attentional networks describing not only the modelling work carried out in this thesis but more importantly what are the lesson learned from this modelling exercise. In the light of this, it is further explained how the modelling work carried out for different domains makes contributions to the respective domain. Finally, a few limitations of this work are outlined, giving directions for further research in this area, and then ending with some closing remarks.

## 9.1 How this thesis helps examine the human attentional networks

The modelling work carried out in this thesis spans across different domains and thus based on the modelling and analytical work a few claims and predictions can be made about these domains. In the light of all the work carried out in this thesis, contributions are made in the domain of psychology in general (in the context of explaining the behaviour and interactions of attentional networks in healthy human adults), in neuropsychology (in the form of impact on attention networks in pathologies and impairments such as Alzheimer's disease and mild traumatic brain injury) and in cognitive development (in terms of development of attentional networks in children).

As outlined in the aims and objectives of this thesis, in section 1.2, this section sets out to show how computational modelling has helped examine the human attentional networks in the light of performance on the attentional network test. This is a two-step process – first to model human performance on the ANT and variants of ANT for healthy human subjects, attention compromised subjects and children. Then, once veridical simulations have been completed, identify and explore the lessons learned from the modelling exercise. The examination of the theory of attentional networks encompasses exploring (1) the behaviour and efficiencies of attentional networks, (2) interactions of the attentional networks, (3) how attentional networks are affected by attention-related pathologies, and (4) development of the three networks in children.

Hence, to gain insight into each of these areas, human study simulations were produced based on the Attentional Networks Test (ANT) (Fan et al., 2002) and its variants (Fernandez-Duque & Black, 2006; Halterman et al., 2006; Rueda et al., 2004). Model validation was performed on all output measures, namely the latency, accuracy and efficiencies of the networks. Based on the model results and the data fitting process, suggestions about the behaviour of networks were made, discrepancies in model-human data were explained and, wherever possible, predictions were presented. All the modelling contributions are summarised in section 9.1.1 and the implications of this modelling work are given in section 9.1.2 below.

### 9.1.1 Modelling contributions

9.1.1.1 Simulations of the efficiencies and behaviour of networks

Model-1 produced a computational representation of the theory of attentional networks explicitly modelling the three networks of alerting, orienting and executive control simulating the ANT. The model design was informed by the attention literature wherever possible. The ACT-R 5.0 model of the ANT (Wang et al., 2004) was migrated to ACT-R 6.0 and validated against human data (Fan et al., 2002) and the ACT-R 5.0 model data (Wang et al., 2004). Computationally, the three networks were shown to be anatomically separate by emphasising in the model how each network was implemented through a distinctly different set of productions and parameter settings based on evidence from the attention literature. Through modelling, the behaviour of the three networks are demonstrated and explained. In all the new models introduced in this thesis, the implementation of the alerting network is the same as in Wang et al's model, but that relating to the three components of orienting – and specifically the theoretical basis of the executive control network – is a significant contribution, as described below:

**Alerting**: Alerting is a state that helps in the preparation for perceiving a stimulus. There is evidence in the literature that an increase in alertness improves the speed of processing events (Posner, 1994; Posner and Raichele, 1990), so no alertness would mean a slow down in response time. This slower reaction time is induced in the model through an extra production, which accounts for a state of surprise. The element of surprise leads to the firing of an extra production to compensate for the effect of no alertness.

**Orienting:** The bottom up/top down properties of visual orienting was simulated in the models using various features of the ACT-R architecture. Another property of attention focusing applied here in the model was that if the cue type is spatially cued, then it is assumed that the focus of attention is already at that location; however, in the case of other cue types, the focus of attention has to be moved to the target location. This was simulated in the model through productions that have to shift the focus of attention in the case of non-spatial cueing. Furthermore, the orienting network was simulated in model-2 to comprise the three subcomponents of disengage, move and engage, which were distinctly shown to be modelled through separate productions.

**Executive Control**: In the form of conflict resolution ability, every model simulates what is referred to as the ‘function of response inhibition’, an important component of the executive function (EF). There is evidence in the literature that, to explain this response inhibition function, many researchers have invoked a dual-processing model that deals with two neural routes or pathways, referred to as (1) the ‘direct response activation route’ and (2) the ‘deliberate response decision process’, both converging at the selective inhibition of activation. These two routes were modelled in the present study as conflicting productions in the model, and the utility function that resolves the conflict overlapped the function of the response inhibition function of this dual-process model (Ridderinkhof et al., 1995; 2000; de Jong et al., 1994) (explained in section 5.1.3.13). This dual process architecture utilised for understanding the flanker effect on target processing is the theoretical basis for implementing and explaining the executive control network of all the models in this thesis.

Although, model-1 did not have any significantly different findings from the earlier model (Wang et al., 2004) or the human study (Fan et al., 2002), it had applications whereby this model was extended and used in studying various pathologies and cognitive development. The functionality of model-1 was extended to simulate the behaviour of humans when an invalid cueing condition was added to the task, in order to explore how the three step process of orienting, namely disengage, move and engage (Posner et al., 1984; 1987) can be modelled. This disengagement effect has a significant impact in the case of deficits of attention, and hence seemed like an important effect to model. Model-1 was extended by incorporating an additional cue condition, and based on this the validity effect was obtained explicitly by taking the difference of reaction times between invalid cueing and valid cueing conditions. This was referred to as ‘model-2’, which is a more explicit representation of these subcomponents of visual orienting. Based on the simulation results, it was suggested that the disengagement effect gives rise to an overall slower reaction time in the case of invalid cueing. From the Alzheimer's disease study (Fernandez-Duque & Black, 2006), the data for healthy subjects were used for model evaluation. The model fitted well to these data. Both model-1 and model-2 were modified and applied in a simulation of the performance of Alzheimer's disease patients, mTBI patients and children.

9.1.1.2 Simulations of interactions of the attentional networks

Using the basic design constructs from model-1 and model- 2, model-3 was implemented by simulating the study that explored the modulation effects of attentional networks (Callejas et al., 2004; 2005), explicitly using an auditory alerting signal. Model-3 simulating the human study showed the same effects as the human study. The way these effects were modelled was of significant interest. By increasing the spread of visual attention, alerting increased the congruency effect, which was in turn decreased with cueing. In other words, if the range of objects focused increases, the alerting effect increases congruency, but with a decreased cueing effect, so a "double cause" of cueing (as pointed out by Callejas et al., 2005, p. 35) was shown by the working of the model. Hence, if the negative effect of alerting on congruency was reduced, then the validity effect on congruency was increased, showing more benefit to using cueing. There is evidence from the attention literature on how the narrowing of the attention of a zoom-lens or spotlight width reduces the effect of distraction and increases the cueing effect (van der Lubbe et al., 2001; Laberge, et al., 1991).

As described through the working of model-3, behavioural effects of the networks on each other were also determined for AD and mTBI patients as well as in children.

9.1.1.3 Simulations of attentional networks in pathologies

Having established model-1 and model-2 to be statistically and (wherever possible) theoretically valid representations of healthy, adult human behaviour, they were modified (based on reasoning informed by the literature wherever possible) to simulate the impairments of networks in attention-related pathologies. Two conditions chosen in this thesis for investigation were Alzheimer's disease (AD) and mild traumatic brain injury (mTBI).

Model-2-AD simulated the performance on the ANT of patients with Alzheimer's disease, and was validated against human data (Fernandez-Duque & Black, 2006). The statistics showed the models to be a good fit to the human data. Model-2-AD simulated the behaviour of the patient in relation to slower reaction times, a higher congruency effect and higher error rates, which were simulated by impairing and slowing down certain productions and modifying parameter settings.

The overall slowdown in response time simulated by modifying the rule firing time indicated that the Alzheimer's disease patients, due to a pathological slow down mentally or their overall processing speed may be hampered. The orienting network was reported to be stable in the human study, but the model results indicated an impaired orienting network. From the working of the model, it seems apparent that the deficit in orienting could be a result of the impairment of the ability to disengage from an invalidly cued location. This prediction is also supported by evidence from AD literature, which calls for replication of the human experiment and further testing through imaging studies. Modifying utility values to show the deficit in executive functions reflects the deficit in the response inhibition function of the Alzheimer's disease patients. Model-1-mTBI simulates the performance on the ANT of patients with mild Traumatic Brain Injury (mTBI), as well as the recovery process from the injury, validated against the human study (Halterman et al., 2006). This was in itself a series of four models modified and based on findings from the human study. Over the course of time, factors such as overall slow reaction times and impairment in the orienting and executive control networks were simulated. Halterman et al.'s (2006) study did not incorporate the effect of invalid cueing, but it was posited that exploring this effect could be beneficial because some studies have shown a deficit in disengagement in mTBI patients. Therefore, model-2 was modified and run over different time courses for mTBI simulation. Settings for model-1-mTBI over all time periods were used, which were validated to simulate the performance statistically well. This was referred to as 'model-2-mTBI'. It was observed that the mean reaction times were slightly higher in the case where an invalid cue condition was also incorporated. The implications related to these pathologies are explained in detail in the section 9.1.2.

9.1.1.4 Simulations of attentional networks in children

Model-1 is the starting point for the simulation of children's performance on the ANT, which was subsequently modified incrementally to simulate attentional network development in various age groups. This was done by first finding a fit for the first model in the series to simulate age group 6 – the youngest age group under study here – and then models for ages 7-10 were obtained subsequently through further minor adjustments to the model to find an appropriate fit. The rate and form of development of networks was simulated, and a comparison was made with attentional networks in adults. Theoretical interpretation of the human study findings suggested the basis for developmental differences in the various networks and their implementation. Different ways of data fitting were explored and analyzed. The modelling process indicated that slower reaction times are not merely attributed to slower processing time; rather, there is a possible relationship between processing speed and the mechanism of inhibitory control in children. In addition, by using different firing times for certain productions attributed to different processes, it was demonstrated that there is not always a "global clock" controlling processing speed in children, and different processes may be running with different processing times. Variations of model fitting led to the idea that the incongruency effect may be higher in children, mainly due to the fact that the conflict resolution mechanism is not so well-developed at an early age and most of the time children tend to choose only the deliberately controlled pathway (see discussion of handling interference through two pathways in a dual-process model in section 5.1.3.1.3), which may also lead to a slower processing time than adults.

The modifications/settings of model-1-child, which were shown to be a good fit to the human data, were applied to model-2 to explore the effect of disengaging in children. This was of significant importance, as there is evidence in the cognitive development literature that children may have a slowed down ability to disengage from an invalidly cued location or engage at the target location (Mezzacappa, 2004). Model-2 was run with parameter/productions settings that worked for various child age groups in model-1-child. Based on the results of model-2-child, it was predicted that in children the validity efficiency may not stabilise up to age 9-10; this calls for further validation through another study with children tested on a revised ANT design incorporated with an invalid cue condition. These implications related to behaviour of the networks in children are discussed in detail in section 9.1.2.3.

### 9.1.2 Implications of the modelling work

The more significant contribution of this thesis is the analytical work and implications of the models of human performance which primarily span (1) significant findings about the modulation effects of attentional networks in healthy humans, attention compromised conditions and in children, (2) significant findings and predictions about the behaviour of attentional networks in attention deficit patients and (3) significant findings and predictions about the behaviour of attentional networks in children.

#### 9.1.2.1 Significant findings about the interactions of attentional networks in healthy humans, attention-compromised patients and children

This thesis simulated the Callejas (2004; 2005) study to explore interactions of the networks with each other. All of the main effects of healthy human performance were simulated by model-3, which fitted the data well and resulted in the same interactions. Based on how the effects were calculated for model-3, these were applied in every other model, i.e. to models of performance on the ANT of children, AD and mTBI patients. The important findings in each case are described in the following subsections.

##### 9.1.2.1.1 Attentional network effects in AD patients

In agreement with the human data (Fernandez-Duque & Black, 2006), the model results, which were also in agreement with earlier studies of the interaction of networks for healthy subjects (Callejas et al., 2004; 2005), showed that alerting has an inhibiting effect on congruency, whereas cueing has a facilitating effect.

##### 9.1.2.1.2 Attentional network effects in mTBI patients

The behavioural interactions of the networks were not discussed in the human study (Halterman et al., 2006), but based on the model results it was inferred that, despite brain dysfunction, the effects remained the same as those for healthy humans (Callejas et al., 2004; 2005). In other words, there was an inhibiting effect of alerting on congruency, but cueing seemed to have a positive effect (this positive effect of cueing on congruency was retested using model-2-mTBI, as the effect was not overly clear in model-1-mTBI). Furthermore, another interesting observation was that the effects remained unchanged throughout the 30-day recovery period simulated here.

##### 9.1.2.1.3 Attentional network effects in children

The experiment with children (Rueda et al., 2004) did not report any significant network interactions. However, based on the subtractions used to calculate the behavioural effects of networks, the model predicted that, although the alerting and congruency networks were not fully developed in children in early ages, the inhibiting effect of alerting and a facilitating effect of cueing on congruency (as observed in adults) were preserved even for younger age groups. This may imply that, although the alerting and congruency networks may not be fully developed, the neural circuitry involved is established to the extent that they start interacting with each other. This may be further validated through imaging studies.

##### 9.1.2.1.4 Effect of auditory vs. visual alerting on the interactions of networks

Past human studies have also reported quicker alerting efficiency if auditory cues are used. To explore this effect, the alerting efficiency in the model was made quicker by altering certain rule firing times. The alerting time when reduced, though, gave a better fit to the alerting efficiency value, but the overall efficiencies and even the interactions remained the same. This may indicate that auditory alerting may be quicker than visual alerting, but once the state of alertness is achieved, the efficiencies of orienting or executive control networks and their effects on each other do not change. This is in line with evidence in the psychology and neuroscience literature that the magnitudes of auditory and visual alerting effects are not significantly different, and the neural correlates of auditory and visual alertness may be supramodal (Thiel & Fink, 2007; Sturm & Willmes, 2001; Roberts et al., 2006) (explained in detail in section 6.1.4.2).

#### 9.1.2.2 Significant findings about efficiencies of attentional networks in attention deficit patients

In this thesis, the two attention deficit-related pathologies chosen for investigation were Alzheimer’s disease and mild traumatic brain injury. The reason for choosing these two particular pathologies, in addition to the advantage that human data were available, is that both explore different aspects of modelling. The AD model was a type of static model that captured behaviour in a particular point in time, whereas the mTBI model(s) simulated behaviour over a trajectory of time, in other words over a recovery period of 30 days. Other pathologies can also be modelled on similar lines. A few observations and predictions were made from the model data and from insights gained through the process of data fitting, as follows.

9.1.2.2.1 The case of Alzheimer's disease

The human study (Fernandez-Duque & Black, 2006) of performance on the ANT of Alzheimer's disease patients was simulated in model-2-AD, and multiple variations of data fitting were explored, inspired by the psychological literature. Based on the model results, a few interesting observations about the overall performance and behaviour of networks are discussed here.

It was observed that the data fits could not be achieved without altering the rule firing time of the models. This slow down in response time, simulated by modifying the rule firing time, may suggest that a major detrimental impact of the pathology is that Alzheimer's disease patients slow down mentally and their overall processing speed may be significantly hampered. This corresponds to evidence in the literature that AD patients slow down and their performance variability is affected by the disease (Gorus, et al., 2008; Warkentin, et al., 2008; Nestor, Parasuraman & Haxby, 1991).

The orienting network was reported to be stable in the human study, but the model results indicated an impaired orienting network. From the working of the model, it seems apparent that the deficit in orienting could be a result of the impairment of the ability to disengage from an invalidly cued location. This prediction is also supported by evidence from the literature on Alzheimer's disease (Buck, et al. 1997; Parasuraman et al., 1992; Parasurman & Haxby, 1993; Perry & Hodges, 1999). Consequently, the model results are in tandem with other neuropsychology literature, but in disagreement with the human study results being modelled (Fernandez-Duque & Black, 2006). This therefore calls for replication of the human experiment and further testing through imaging studies.

Simulating the impaired executive control network by modifying utility values, in order to highlight deficits in executive functions, corresponds to the possible deficit in the response inhibition function for AD patients. In addition, it is suggested that for AD patients it is not only the response inhibition function that is impaired, but also it may generally take the AD patient longer to refocus attention in conflicting situations (recall the response inhibition function is explained in detail in section 5.1.3.1.3).

##### 9.1.2.2.2 The case of mild traumatic brain injury

The recovery process of patients affected by mild traumatic brain injury (Halterman et al., 2006) over a period of one month was simulated using a series of models adjusted incrementally to show the recovery process. Based on the data fitting process, it was indicated that for patients the processing speed is affected only in the first week after trauma, which then returns to normal in the following weeks. Although the overall reaction times are still higher over the next two to three weeks, this effect does not arise out of increased firing time (in other words, performance variability) but is due instead to the slower conflict resolution mechanism. The model also suggests that the reason for the conflict resolution ability to be impaired throughout the recovery period may possibly be due to the impaired response inhibition function, which maps to an impaired conflict resolution ability.

#### 9.1.2.3 Significant findings about the development of attentional networks in children

By using modelling as a tool, a comparison was made between adult and child performance on the ANT-C, informing about the rate and form of development of attention networks. Various methods of simulating children’s performance guided the study in explaining the variation in children’s behaviour, drawing relations with evidence from the literature.

It was observed that, when a rule firing time is set significantly higher for the model corresponding to a slower processing speed in children, the control network seems to be affected minimally; however, when a significantly higher rule firing time is not used, the control network is found to be very immature, to the extent that the ability to resolve conflict for children is very primitive. This shows a possible relationship between processing speed and the mechanism of inhibitory control in children. Moreover, by using different firing times for certain productions attributed to different processes, it was evidenced that there is not always a “global clock” controlling processing speed in children, and different processes may be running with different processing times. The above findings were confirmed by a review of the literature (Ridderenkhof & van der Molen, 1997; Ridderenkhof et al., 1997), where the argument is that age-related changes in processing speed do not pertain to all cognitive processes with the same degree, and a possible relationship between inhibitory control and age-related variations in processing speed.

In relation to how children may handle invalid cueing, the model predicted that children may take longer to respond in the cue condition where a cue appears in an incorrect location prior to the appearance of the stimulus. This is in line with a number of other studies where the effect of invalid cueing was studied in children in the context of visual-orienting theory (Trick & Enns, 1998; Akhtar & Enns, 1989). The model suggests that this delay in response time could be attributed to an immature ability to disengage attention. Furthermore, it is also suggested that for children the validity efficiency may stabilise up to age 9-10. This calls for further validation through another study with children tested on a revised ANT design incorporated with an invalid cue condition.

In relation to the development of the executive control network in children, the model suggested that it may be affected in children mainly due to the fact that the conflict resolution mechanism is not completely developed at an early age and most of the time children tend to choose only the deliberately controlled pathway which may also have a slower processing time than adults. This reflects the slower executive control network effect due to an undeveloped refocusing capacity.

## 9.2 Limitations of this thesis

The scope of the work given in this thesis is limited to designing and implementing cognitive models of attention and performing analytical work, making predictions based on the simulation results and model fitting process. Limitations related to the underlying theory, the behavioural task itself and some modelling limitations related to the software/architecture used are given in the following subsections.

### 9.2.1 Theoretical limitations

Although general attention theories were discussed and analysed in the literature review, as well as in some analytical discussion based on modelling work, this thesis mainly is based on the theory of attentional networks, which was simulated in every model in the realm of the attentional networks test.

In the context of cognitive development theory, it was mainly the work of Kail (1991; 1993) in the context of processing speed theory of development that was addressed, so other cognitive development theories such as those posited by Piaget (1950), Vgotsky (1978), etc. were not explored in line with various approaches in the simulation of children's performance on the ANT. Additionally, there has been some critique on working backwards from adult behaviour (Klahr, 1984), but after working with the adult model first, it was more simple and logical to adapt it to fit children's behaviour.

### 9.2.2 Behavioural task limitations

Every study simulated to examine the attentional network theory was performed on the attentional network task or its variants. Therefore, alerting was assessed mainly by alerting cues (visual or auditory); orienting mainly through the visual orienting task (cueing task using variations of cues, including invalid cues); and the control network is mainly assessed through the flanker task. This thesis cannot predict how the findings would change if, for example, the flanker task was replaced in the ANT by a Stroop task and so on.

### 9.2.3 System software and platform limitations

A few general comments about the use of the ACT-R architecture and the version of Lisp used in this thesis will now be made. All of the models designed in this thesis were

ACT-R 6.0 models, and, hence, if any other architecture needs to be used to carry this work further, the models will have to be migrated to that cognitive architecture; however, the data and control flow diagrams can be used because they are architecture independent. Since this thesis used ACT-R 6.0 for all modelling work, the models made use of and confirmed to the underlying theories of attention embedded in the architecture. However, it is noteworthy that ACT-R architecture is designed with strict psychology theories and principles in mind so that ad hoc modelling becomes difficult and at times impossible; this may not necessarily be a limitation, but a useful constraint. The Lisp used in this thesis was Allegro Common Lisp 8.1 for Windows, and if another platform is used, then the models will not run directly and minor changes will have to be made, for example for Mac Lisp or some other Lisp version. Any of these changes, nonetheless, will only require some minor migration efforts and should not have any impact on the overall results and findings produced by this thesis.

### 9.2.4 Experimentation/data limitations

The work presented here is limited to modelling and uses experimental data already available from previous psychology experiments. With this in mind, there was therefore no need to conduct experiments for data collection. Furthermore, although it has been suggested previously to use model data in tandem with fMRI data, no imaging studies have been conducted as part of this thesis. In addition, despite efforts to contact the authors, a breakdown of the experimental data from the children's study and the mTBI study could not be obtained, so only the summary data available in papers were used.

## 9.3 Guidelines for future work

In section 9.3, in the context of the limitations of this thesis, areas that could be explored for further research are suggested. In addition, a few other general recommendations are also made, all of which are outlined briefly here.

The model predictions that call for further investigation in relation to carrying out more psychophysical experimental work and imaging studies can be further validated. For example, a further study could administer the invalid cueing version of the ANT to children and mTBI patients to assess the validity of the observation based on the model results. Extending the modelling work further to simulate behaviour in other attention deficit conditions such as autism, ADHD, schizophrenia, and so on would help to make further predictions with regard to these pathologies**.** Similar to simulating the performance of children, the performance of older subjects on such tasks (Fernandez & Black, 2006) can also be modelled in this fashion.

## 9.4 Summary

This thesis presents a computational modelling approach to explore the theory of attentional networks through developing cognitive models for the attentional network test (ANT) and its variants. The use of computational modelling as a research tool is based on the premise that, by closely examining the models, we can increase our understanding of the cognitive phenomenon being modelled.

Based on the results produced by veridical simulations of human studies, and the insights gained from the modelling processes, this thesis presents explanations for discrepancies in the results and makes novel predictions which may be validated through further testing and imaging studies. Hence, these biologically, or more so psychologically, inspired computational models act as a good platform for simulating, predicting and explaining human behaviours, which is a step forward in an effort towards quantification in psychology.

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# Appendices

## Appendix A: User Manual

This section describes how to load ACT-R 6.0 and then how to load and run the models described in this thesis.

### A.1. Loading ACT-R 6.0

For Windows XP, go to start, program, then, start the lisp application (here Allegro Common Lisp 8.1 trial version is used). Then from file menu, locate the folder which contains ACT-R 6.0 files and then open file load-act-r-6.lisp. The following screen should appear in the listener window showing that ACT-R 6.0 was loaded successfully:

```
##################################
ACT-R Version Information:
Framework : 1.2 [r505]
BUFFER-TRACE : 1.0 A module that provides a buffer based tracing mechanism.
NAMING-MODULE : 1.2 Provides safe and repeatable new name generation for models.
DEVICE : 1.1 The device interface for a model
BUFFER-PARAMS : 1.0 Module to hold and control the buffer parameters
ENVIRONMENT : 2.0 A module to handle the environment connection if opened
PRINTING-MODULE : 1.0 Coordinates output of the model.
RANDOM-MODULE : 1.0 Provide a good and consistent source of pseudorandom numbers for all systems
DECLARATIVE : 1.1 The declarative memory module stores chunks from the buffers for retrieval
CENTRAL-PARAMETERS : 1.0 a module that maintains parameters used by other modules
VISION : 2.4 A module to provide a model with a visual attention system
BOLD : 1.1 A module to produce BOLD response predictions from buffer request activity.
SPEECH : 2.2 A module to provide a model with the ability to speak
GOAL : 1.1 The goal module creates new goals for the goal buffer
AUDIO : 2.3 A module which gives the model an auditory attentional system
UTILITY : 2.0 A module that computes production utilities
PRODUCTION-COMPILATION: 1.1 A module that assists the primary procedural module with compiling productions
IMAGINAL : 1.1 The imaginal module provides a goal style buffer with a delay and an action buffer for manipulating the imaginal chunk
PROCEDURAL : 1.3 The procedural module handles production definition and execution
MOTOR : 2.3 Module to provide a model with virtual hands
######### Loading of ACT-R 6 is complete #########
```

Then to start the GUI supported by ACT-R, load the environment by typing (Start-environment) at the Lisp prompt; following control panel given in Figure A.1 is loaded which is also a useful tool for debugging.


Figure A.1: A screen shot showing the GUI for ACT-R 6.

All model file could either be compiled or loaded from the menu in ACL or through the control panel. Once the model is loaded, the name appears in the control panel and the model could be run.

## A.2 A Sample Run of the model

A sample trace of the model run is briefly discussed and given here. Each line of the trace represents an event at a given time, in seconds. It shows everything that happened in detail (for this output, the trace is set to full details). The first line shows that the chunk goal is placed in the goal buffer by the goal module and this is automatic. At the same time, the vision module starts to place an item in the visual location buffer and the first production notice-fixation gets fired. Based on the item in the visual buffers and contents of the goal buffer, productions get fired and incase of any conflict utility values are consulted. After one trial is finished, clock is reset and the next trial starts till the time the whole experiment finishes or the execution time runs out and that is when all calculations are performed for means and standard deviations. Note each rule firing time is 40 ms, move-attention takes 85 ms and a key-press takes 210 ms. All buffers except for the goal buffer are cleared automatically because of the new strict harvesting mechanism of ACT-R 6. The time from which the stimulus appears till the time response is typed is recorded as the response time. All response times are added and in the end a mean reaction time is calculated. The key press ‘f’ represents left arrow key and the key press ‘j’ represents the right arrow key.

The trace shown below is the condition when the cue condition is double, stimulus-type is right, stimulus-position is top and flanker condition is incongruent. The reactions time is 620 (1520 -900). Here the trial time starts at 0 ms when the fixation appears which is noticed and fixated, as a result of which 2 rules are fired. At 400 ms a cue appears (any of the cue conditions randomly appear) which is processed. In this trial, the condition was top cue, so when a cue at the bottom was also found, it was understood by the model that this is a double cue and as a result four productions are fired. At time 900 ms, the goal buffer is modified again, this time around to recognize the target and respond; this is the official start time for the final latency. At this stage, since attention was randomized, the arrow on the right side of the target is picked up. This requires the model to bring attention to the center arrow. Since this trial presents an incongruent condition, based on the internal utility values, the model chooses to do a costly refocusing and then finally encodes the center arrow location. The production which checks for the direction of the arrow is fired which gives a correct response (the erroneous or random decision productions are not chosen due to lower probabilities in this trial). Finally at time 1310 ms the key '"j" is pressed as a result the motor module completes the action at time 1520 ms. The reactions time is 620 (1520 -900). In this time period:

- nine productions are fired (9 x 40=360)
- two visual encodings take place (85 x 2 = 170, 170 – 80 = 90, subtraction of 80 ms for parallel time for two productions)
- one motor movement is executed ( 1 x 210 = 210, 210 – 40 = 170, subtraction of 40 ms for parallel time for one production )

So, total of 620 ms elapses (360 + 90 + 170). After this the model prepares and cleans up for the next trial.

```
0.000   GOAL            SET-BUFFER-CHUNK GOAL GOAL REQUESTED NIL
0.000   VISION          SET-BUFFER-CHUNK VISUAL-LOCATION LOC0 REQUESTED NIL
0.000   VISION          SET-BUFFER-CHUNK VISUAL-LOCATION LOC1 REQUESTED NIL
0.000   PROCEDURAL        CONFLICT-RESOLUTION
0.040   PROCEDURAL        PRODUCTION-FIRED NOTICE-FIXATION
0.040   PROCEDURAL        CLEAR-BUFFER VISUAL-LOCATION
0.040   PROCEDURAL        CLEAR-BUFFER VISUAL
0.040   PROCEDURAL        CONFLICT-RESOLUTION
0.125   VISION          Encoding-complete LOC1-0 NIL
0.125   VISION          SET-BUFFER-CHUNK VISUAL TEXT27
0.125   PROCEDURAL        CONFLICT-RESOLUTION
0.165   PROCEDURAL        PRODUCTION-FIRED ENCODE-FIXATION-AND-WAITING
0.165   PROCEDURAL        CLEAR-BUFFER VISUAL-LOCATION
0.165   PROCEDURAL        CLEAR-BUFFER VISUAL
0.165   PROCEDURAL        CLEAR-BUFFER GOAL
0.165   GOAL            SET-BUFFER-CHUNK GOAL DO-ANT0
0.165   PROCEDURAL        CONFLICT-RESOLUTION
0.400   VISION          SET-BUFFER-CHUNK VISUAL-LOCATION LOC3 REQUESTED NIL
0.400   PROCEDURAL        CONFLICT-RESOLUTION
0.440   PROCEDURAL        PRODUCTION-FIRED NOTICE-A-TOP-CUE
0.440   PROCEDURAL        CLEAR-BUFFER VISUAL-LOCATION
0.440   PROCEDURAL        CONFLICT-RESOLUTION
0.480   PROCEDURAL        PRODUCTION-FIRED GIVEN-A-TOP-CUE-FIND-A-BOTTOM-CUE
```

0.480 PROCEDURAL CLEAR-BUFFER VISUAL-LOCATION
0.480 VISION Find-location
0.480 VISION SET-BUFFER-CHUNK VISUAL-LOCATION LOC4
0.480 PROCEDURAL CONFLICT-RESOLUTION
0.520 PROCEDURAL PRODUCTION-FIRED FIND-MORE-CUE-SO-DOUBLECUE
0.520 PROCEDURAL CLEAR-BUFFER VISUAL-LOCATION
0.520 PROCEDURAL CONFLICT-RESOLUTION
0.560 PROCEDURAL PRODUCTION-FIRED ANTICIPATING-THE-STIMULUS
0.560 PROCEDURAL CONFLICT-RESOLUTION
0.900 GOAL GOAL-MODIFICATION
0.900 VISION SET-BUFFER-CHUNK VISUAL-LOCATION LOC5 REQUESTED NIL
0.900 PROCEDURAL CONFLICT-RESOLUTION
0.940 PROCEDURAL PRODUCTION-FIRED NOTICE-STIMULUS-WITH-DOUBLECUE-AND-SHIFT
0.940 PROCEDURAL CLEAR-BUFFER VISUAL-LOCATION
0.940 VISION Find-location
0.940 VISION SET-BUFFER-CHUNK VISUAL-LOCATION LOC6
0.940 PROCEDURAL CONFLICT-RESOLUTION
0.980 PROCEDURAL PRODUCTION-FIRED ATTEND-TO-AT-LARGE-TARGET
0.980 PROCEDURAL CLEAR-BUFFER VISUAL
0.980 PROCEDURAL CONFLICT-RESOLUTION
1.020 PROCEDURAL PRODUCTION-FIRED ATTENTED-ITEM-IS-RIGHT-TO-THE-TARGET
1.020 PROCEDURAL CLEAR-BUFFER VISUAL-LOCATION
1.020 VISION Find-location
1.020 VISION SET-BUFFER-CHUNK VISUAL-LOCATION LOC7
1.020 PROCEDURAL CONFLICT-RESOLUTION
1.065 VISION Encoding-complete LOC6-0 NIL
1.065 VISION SET-BUFFER-CHUNK VISUAL TEXT117
1.065 PROCEDURAL CONFLICT-RESOLUTION
1.105 PROCEDURAL PRODUCTION-FIRED REFOCUS-AGAIN-IF-INCONGRUENT
1.105 PROCEDURAL CLEAR-BUFFER VISUAL
1.105 PROCEDURAL CLEAR-BUFFER VISUAL-LOCATION
1.105 VISION Find-location
1.105 VISION SET-BUFFER-CHUNK VISUAL-LOCATION LOC9
1.105 PROCEDURAL CONFLICT-RESOLUTION
1.145 PROCEDURAL PRODUCTION-FIRED HARVEST-TARGET
1.145 PROCEDURAL CLEAR-BUFFER VISUAL
1.145 PROCEDURAL CONFLICT-RESOLUTION
1.185 PROCEDURAL PRODUCTION-FIRED GOAHEAD-RESPONDING-IF-IT-IS-THE-TARGET
1.185 PROCEDURAL CLEAR-BUFFER VISUAL-LOCATION
1.185 PROCEDURAL CONFLICT-RESOLUTION

| | | |
|---|---|---|
| 1.230 | VISION | Encoding-complete LOC9-0 NIL |
| 1.230 | VISION | SET-BUFFER-CHUNK VISUAL TEXT115 |
| 1.230 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.270 | PROCEDURAL | PRODUCTION-FIRED DECIDE-RIGHT |
| 1.270 | PROCEDURAL | CLEAR-BUFFER VISUAL |
| 1.270 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.310 | PROCEDURAL | PRODUCTION-FIRED RESPOND |
| 1.310 | PROCEDURAL | CLEAR-BUFFER MANUAL |
| 1.310 | PROCEDURAL | CLEAR-BUFFER VISUAL-LOCATION |
| 1.310 | MOTOR | PRESS-KEY j |
| 1.310 | VISION | Find-location |
| 1.310 | VISION | SET-BUFFER-CHUNK VISUAL-LOCATION LOC12 |
| 1.310 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.350 | PROCEDURAL | PRODUCTION-FIRED REFIXATING-AND-WAIT-FOR-NEXT-TRIAL |
| 1.350 | PROCEDURAL | CLEAR-BUFFER VISUAL-LOCATION |
| 1.350 | PROCEDURAL | CLEAR-BUFFER VISUAL |
| 1.350 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.435 | VISION | Encoding-complete LOC12-0 NIL |
| 1.435 | VISION | SET-BUFFER-CHUNK VISUAL TEXT27 |
| 1.435 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.460 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.510 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.520 | MOTOR | OUTPUT-KEY #(7 4) |
| 1.520 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.605 | VISION | Encoding-complete LOC12-0 NIL |
| 1.605 | VISION | No visual-object found |
| 1.605 | PROCEDURAL | CONFLICT-RESOLUTION |
| 1.610 | PROCEDURAL | CONFLICT-RESOLUTION |
| 2.400 | PROCEDURAL | CONFLICT-RESOLUTION |
| 3.900 | PROCEDURAL | CONFLICT-RESOLUTION |
| 3.900 | ------ | Stopped because no events left to process |

# Appendix B: Publications

## B.1 CogSci 2009 paper and poster

Hussain, F., & Wood, S. Computational Modelling of Deficits in Attentional Networks in mild Traumatic Brain Injury: An Application in Neuropsychology. Proceedings of the 31st Annual Conference of the Cognitive Science Society, Amsterdam, Netherlands, July 2009, pp. 2675-2680.

## B.2 ICCM 2009 paper and poster

Hussain, F., & Wood, S., (2009). Modelling the Performance of Children on the Attentional Network Test. The 9th International Conference on Cognitive Modelling, Manchester, UK, July, 2009, pp. 211-216.

### B.3 Journal publication of WAPCV 2008 paper

Hussain, F., & Wood, S. (2009). Modeling the Efficiencies and Interactions of Attentional Networks, In Paletta, L., & Tsotsos, J.K. Eds., Attention in Cognitive Systems. Lecture Notes in Computer Science-LNAI 5395, pp. 139-152, Springer-Verlag, Berlin, Germany.

## B.4 CogSci 2008 paper (accepted only as member's abstract)

Hussain, F., & Wood, S. (2008) Modelling Attentional Networks: The Modulation Effects and Simulation of Alzheimer's disease. Members Abstract, Proceedings of the 30th International Conference on Cognitive Science (CogSci08), Washington D.C., July 2008.

**B.5 International workshop on cognitive science-Moscow, 2008 poster**

Hussain, F., & Wood, S. (2008). A Cognitive Model of Attentional Networks. Proceedings of the 3rd International Workshop on Cognitive Science, Moscow, Russia, June 2008.

**Appendix C: Attached CD.**

The CD contains the following:

1. ACT-R 6.0 for Windows
2. ACL 8.1 for Windows
3. Files for each model discussed in this thesis:
   a) Model-1
   b) Model-2
   c) Model-3
   d) Model-2-AD-var1, model-2-AD-var2
   e) Model-1-mtbi-week1, model-1-mtbi-week2, model-1-mtbi-week3, model-1-mtbi-week4
   f) Model-2-mtbi-week1, model-2-mtbi-week2, model-2-mtbi-week3, model-2-mtbi-week4
   g) Model-1-child-age6, model-1-child-age7, model-1-child-age8, model-1-child-age9 (for variation 1)
   h) Model-1-child-age6, model-1-child-age7, model-1-child-age8, model-1-child-age9 (for variation 2)
   i) Model-2-child-age6, model-2-child-age7, model-2-child-age8, model-2-child-age9