1.0 FOREWORD

This thesis had its genesis in the author's work with children with brain injuries. As an educational consultant I have been involved with the reintegration into school of children with brain injuries who had been hospitalised as a result of their trauma. I worked closely with hospital staff to assist in the children's return to school.The children had undergone extensive neuropsychological and medical examination during their hospital admission, and this information was used as a basis for educational planning. My task was to take the clinical reports and translate these into instructionally-designed programs to be used in the classroom to provide support for children during reintegration back to the school system. Class teachers were seeking information on the children's educational strengths as well as weaknesses. The school's role was to build on the strengths as well as compensate for the weaknesses by adapting the environment or curriculum.

The hospital-based neuropsychologists administered tests such as the Wisconsin Card Sorting Test, which they described as a measure of mental flexibility, and which were purported to give an explanation of adaptive behaviour. The tasks, however, did not always yield useable information that was of assistance to program designers or classroom teachers. Teachers were seeking solutions to the problems the children were facing in the classroom. Clinical tests tended to offer few insights into classroom performance because they were not developmentally specific: that is, the tests did not take account of the cognitive skills specific to the developmental age of the children.

Specific cognitive intervention programs for students with brain injuries have shown promise in overcoming problem-solving difficulties (von Cramon, Matthes-von Cramon and Mai, 1991; von Cramon and Matthes-von Cramon, 1992), although specific assessment devices have been lacking in these studies. Preliminary reading and a lot of discussion with neuropsychologists indicated that there were very few paediatric measures of adaptive behaviour that were available or in clinical use. Neuropsychologists are saying that adaptive behaviours are important because it seems to be the critical variable that determines whether you have a good outcome or a bad outcome for children. As a first step toward investigating functionally-based measures, I decided to develop a Behavioural Checklist for children with brain injuries which could be used with teachers and which were functionally based: that is, the Behavioural Checklist would measure day-to-day school behaviours which were thought to be important to functioning as an independent learner at school.

A literature search on the educational implications of brain injuries was conducted and from these studies, I developed educational profiles based on the most commonly occurring sequelae identified in the literature. The Behavioural Checklist was derived from the cognitive rehabilitation literature (Ylvisaker, 1985), which tended to categorised behaviour of children with brain injuries into three broad domains: Work Habits, Cognitive/Communicative Behaviours and Personal Social Behaviours (Bogan and Hartley, 1992). The Behavioural Checklist contained classroom behaviours which operationalised the cognitive sequelae. For example, under the heading *Cognitive/Communicative*, two such behaviours were: "Is able to follow information/procedures over time" and "Is able to sequence events/procedures, eg. follow through all steps of a stated activity". Under the heading of ***Work Habits***, two items were: "Is punctual to class", and "Completes tasks within a reasonable time frame". The behaviour profiles were used with approximately twenty children who had been referred to Westmead Hospital, a large paediatric trauma referral centre. It was apparent from using these profiles with class teachers working with children with brain injuries, that a common thread ran through the three profile areas. The greatest difficulties experienced by children with brain injuries, who were in mainstream classes in a school setting, were in adapting back into the routines of an educational system. The students had difficulties in following a timetable, in being able to start and complete their work, in being able to separate the important from the peripheral, in being able to generalise from one situation to another, and in being organised. These adaptive, or executive behaviours, as I refer to them throughout the thesis, are critical to a student's survival at school, particularly in a secondary school! In the majority of cases, however, the neuropsychological tests did not adequately account for or were not always predictive of the deficits in explaining the child's functional and educational weaknesses. The three categories of the Behavioural Checklist included those behaviours which teachers tended to report affected the students' learning in an educational setting. I believed that the Behavioural Checklist captured the significant adaptive behaviours listed under the three broad domains.

An idea began to develop that if clinical tests of adaptive or executive behaviour, based on developmental psychology and drawing on a knowledge of neurological development could be produced for children, then those measures would be sensitive to developmental changes in adaptive functioning, and the results would provide useful predictive and diagnostic information in an educational setting.

This study examines the development of executive function in children from a developmental and neuropsychological perspective. From an analysis of the developmental of neural substrates in children, a model has been produced which guided the development of appropriate paediatric measures of executive function. In addition, Piaget's (1954) theory of cognitive development has been used as a basis for examining cognitive development in relation to neural development of the child.

It is acknowledged that, taking account of neurological development in relation to psychological studies of cognitive development, has its limitations.

2.0 INTRODUCTION

2.1 Neurological Correlates of Executive Functioning

The neurobehavioural sequelae of head injury in children has been the subject of recent study and investigation. Despite the methodological difficulties of examining heterogeneous groups and differences in terminology, evidence is emerging that insult to the young brain as a result of trauma consistently produces long term behavioural disturbance despite the appearance of full physical recovery (Levin, Goldstein, Williams and Eisenberg, 1991; Mateer and Williams, 1991). In a recent Australian study, Prior, Kinsella, Sawyer, Bryan and Anderson (1994), found that children in the age range of 6 to 16 with moderate to severe closed head injuries experienced long-term cognitive and school learning difficulties. Magnetic Resonance Imaging has confirmed that the frontal region is the most common location of focal lesions after mild to moderate closed head injury, which accounts for over 75% of hospital referrals for closed head injuries in children (Levin *et al*, 1991). Given the fact that the prefrontal cortex, which comprises 30% of the cortical mantle in humans (Fuster, 1989), is intricately and exclusively connected to other cortical regions as well as to various subcortical structures, it is not surprising that damage to the frontal lobes results in wide-ranging disruption of affect, motor control, language, problem-solving and memory (Shimamura, Janowski and Squire, 1991; Ylvisaker, 1993).

According to Stuss (1992, p9), frontal lobe pathology results in a number of information-processing deficiencies, including difficulty in shifting from one concept to another, difficulty in changing a behaviour, a propensity to focus on one aspect of information with problems in relating or integrating isolated details, problems in managing simultaneous sources of information and difficulties in using acquired knowledge. These frontal behaviours are referred to as "executive". Luria (1973a) described executive function as involving a number of processes, including organisation, planning, monitoring, and execution of purposeful, goal-directed activities.

An analysis of the effects of frontal lobe injury in children highlights important considerations. Apart from age-related differences in injury, investigators have suggested that there are distinctive pathophysiological features of closed head injury in children. Diffuse brain swelling occurs more frequently in paediatric head injury, as compared with closed head injury in adults, and the full implications of head injury during infancy or early childhood may not be appreciated until complex behaviour and cognitive processes can be assessed several or even many years later (Prigatano, 1993). These neurological findings have important implications for both assessment and treatment of children and adolescents with frontal lobe involvement. In fact, there has been a realisation in the literature over the past few years that paediatric neuropsychology is an entity in its own right and its premises and theoretical foundations are quite distinct from adult neuropsychology.

The realisation that paediatric neuropsychology needs to be treated separately from adult neuropsychology has sparked renewed interest in drawing a parallel between neural development and cognitive development (Case, 1992; Thatcher, 1992). With advances in neuroimaging and neurophysiological techniques our knowledge of the brain, particularly the prefrontal cortex, has increased considerably over the past number of years. Meaningful contact is now possible between neuroscientists and developmental psychologists. There is the promise that despite the different languages used, and the differing methodologies, an exchange of knowledge between the two disciplines may shed new light on old problems, develop new principles, and produce a greater understanding of child development from a neurological perspective.

The current study maps some aspects of cognitive development on to stages of neural development, particularly with an emphasis or focus on those cognitive behaviours defined as adaptive or executive. The mapping exercise has been used to generate a model or scheme to identify possible hypothetical correlates of cognitive and neural processes. This cognitive-neurological model (CN-Model) has then been used to guide the development of computerised assessment measures of executive function in children. It is acknowledged that there are limitations to this mapping exercise. For example, it would be naive to assume that there is a one-to-one relationship between a particular cognitive function and a neural state. As will be demonstrated, there are simultaneous neural processes operating, orchestrated by the prefrontal cortex, and, as more cerebral functions begin to mature, there is an increasing capacity to interact with the cognitive demands of the environment. A simple mapping exercise cannot encapsulate the complexity of prefrontal cortex functions. However, the mapping model will be used as a basis for the development of paediatric measures of executive function.

Executive functions have been defined traditionally in neuropsychological terms as those functions that allow the individual to establish goals, develop plans for the attainment of the goals, hold the goals in active memory, monitor performance, and control for interference in order to achieve the goals (Stuss, 1992). Executive functions come into play during novel and/or complex situations where there are no preplanned or routine modes of responding, and are relatively independent of general intelligence (Stuss and Benson, 1986). Some may wish to debate this definition. For example, a distinction is usually made in the literature between those routine or automatic behaviours, often described as the realm of more posterior neural functions, and those which are executive, and attributable to prefrontal cortex (Shallice, 1988). Driving a car is an example which comes to mind. When first learning to drive, the learner has to juggle a number of complex behaviours in a particular sequence. For most, this is a novel and complex set of behaviours, the execution of which would draw on prefrontal cortex functioning. However, once the behaviour is learned and routinised, then there is a view that it is no longer prefrontal in nature. It may, in fact, be the case that prefrontal cortex or executive functioning continues to play a critical role in routinised behaviours although this does not occur at a conscious level. To continue the driving analogy, how many times have you driven home from a tough day at the office only to discover that somehow you negotiated the heavy traffic while your mind was a million miles away? It is possible that despite the fact that driving is an automatic behaviour and you were not consciously aware of the activity, your executive functions continued to monitor and direct your driving performance.

2.1.1 Executive Function defined

Given the caveat that executive function may encompass both routine and/or novel and complex behaviours, it is proposed that executive function be defined as the interaction of active memory and planning processes (Fuster, 1993). Active memory is memory for maintaining information "on-line" during the execution of a task. Other researchers have used the terms "working' or "representational" memory (Goldman-Rakic, 1987a) to describe a similar process, although the term "active" is described by Fuster to indicate that it does not represent a separate memory system. There is empirical evidence to support this definition and this will be elaborated during the thesis. The second part of the executive function definition is planning processes. These are described as goal-directed activities including monitoring of performance, adjustment of behaviour in light of environmental feedback, inhibition of inappropriate responses and cognitive flexibility. It is contended that these behaviours were all involved in the driving analogy that was presented in the previous section.

The prefrontal lobes appear to act as a control or executive centre for all higher order mental processing. They have rich connections with both cortical and subcortical structures (for a detailed analysis see Levin and Eisenberg, 1991; Fuster, 1989). There is a long-standing literature identifying the prefrontal areas in the control of executive function. It is considered beyond the brief of this thesis to examine this research in detail. It is, however, the brief of this thesis to look at the neurodevelopmental literature as it relates to the development of executive function.

2.1.2. Dual model of prefrontal cortex processing

The evidence for a role of prefrontal cortex in executive function comes from many lines of enquiry, and only some of the pertinent literature is reviewed here. Single neuron activity taken from awake monkeys performing learning tasks suggests that the dorsolateral and orbital prefrontal cortices play a major role in executive functioning (Yamatani, Ono, Nishijo, and Takaku, 1990). Yamatani *et al* (1990, p503), identified seven types of prefrontal cortex neurons that were related to attention, choice, task-unique memory, reward anticipation, laterality, initiation of movement and suppression of movement. Di Pellegrino and Wise (1993, 1991) and Boussaoud and Wise (1993), also employing single cell recording, demonstrated a specialisation of premotor and prefrontal cortex areas for a rhesus monkey performing delayed learning tasks. The authors conclude that more prefrontal neurons than premotor neurons discharge during the presentation of the first stimulus and only prefrontal neurons show phasic bursts of activity shortly after that stimulus disappears. During the instructed delay period, cells in prefrontal cortex begin activity earlier than premotor, whereas premotor neurons continue their activity longer than the prefrontal neurons (Di Pellegrino and Wise, 1991, p951). Boussaoud and Wise (1993) concluded that in prefrontal and premotor cortex, neuronal activity can be guided by both the action to be taken and the events guiding that action.

The results of research on neuronal activity within animals replicates previous findings of the functional distinctiveness of prefrontal and premotor cortex (Fuster, 1989). In a study involving healthy adults performing neuropsychological tests purported to measure executive functioning - The Wisconsin Card Sorting Test, The Tower of Hanoi, The Continuous Performance Test and Porteus Mazes - PET scans revealed selected increased activation of cerebral blood flow in frontal brain regions (Rezai, Andreasen, Alliger, Cohen, Swayze II and O'Leary, 1993). Morris, Ahmed, Syed and Toone (1993) conducted single-photon emission computerised tomography (SPECT) on seven cerebral regions of normal adults during a Tower of London activity and during a control task that did not involve planning. The authors discovered statistically significantly higher levels of cerebral blood flow in the left frontal cortex for those subjects performing the Tower of London task. "This result applied to the two areas measured, one corresponding to mainly dorsolateral prefrontal cortex and the other to superior prefrontal cortex including portions of the premotor areas" (Morris *et al*, 1993, p1375).

Goldman-Rakic's research involving monkeys performing delayed-response tasks of a visuo-spatial nature has concluded that the area in and around the principal sulcus, (dorsolateral cortex) is very active prior to and during the delay period (Goldman-Rakic, 1987a; Goldman-Rakic and Friedman 1991). In a more recent study (Funahashi, Chafee, and Goldman-Rakic,1993) evidence is presented from recordings from prefrontal neurons in rhesus monkeys trained to perform delayed anti-saccade tasks based on tests that had been used with humans. The researchers concluded that most prefrontal neurons code the location of the visual stimulus in working memory, and that this memory can be engaged to suppress as well as prescribe a response. The conclusions from Goldman-Rakic's comprehensive research is that prefrontal neurons are involved in the process of working or representational memory; groups of neurons begin firing just prior to the disappearance of the target object and others fire only during the delay period. In summary, Goldman-Rakic concludes that representational memory is a significant component of executive functioning and involves the encoding of specific neurons in dorsolateral cortex.

The evidence described in the work of Goldman-Rakic and others is consistent with results at a functional level that prefrontal cortex involves two inter-related cognitive functions: active memory and motor set, or anticipation/planning (Fuster, 1993). According to Fuster, prefrontal cortex memory and motor set "are specifically devoted to organising behaviour temporally. Thus, frontal memory is, above all, memory for action" (Fuster, 1993, p160).

Fuster proposes a dual hierarchical model of perceptual processing located within the frontal cortex - prefrontal and motor processors which represent parallel processing systems with feedback loops. Sequential motor behaviour is based on a continuous flow of information between the individual and his/her environment. This flow constitutes the Perception-action cycle (Fuster, 1993). The neural substrates for this processing lie in the basal ganglia-thalamus loop to the prefrontal cortex. The neurophysiological evidence for this model comes from a number of lines of enquiry. Goldman-Rakic and her colleagues demonstrated in delay tasks that memory and action are encoded in different neurons (Diamond, Zola-Morgan, and Squire, 1987). Evidence from thirty patients with focal brain lesions also confirms that the corticostriate system appears to mediate reactive flexibility described as monitoring and shifting cognitive and behavioural set (Eslinger and Grattan, 1993). Brown and Robbins (1991) came to a similar conclusion following visual spatial discrimination studies with rats which were clinically induced to produce unilateral striatal dopamine depletion. There was not only a marked spatial response bias towards the side of the dopamine depletion, but also an abolition of the delay-dependent speeding of reaction time that reflects motor readiness on the side contralateral to the lesion. Nonetheless, the rats were able to demonstrate that they were able to use advance information to select and prepare their responses.

"From this order of cellular engagement, the view has emerged that prefrontal neurons specialise in memory of sensory and temporal information, whereas premotor and motor neurons specialise in planning responses (set)" (Fuster, 1993, p163). Fuster's model is represented in Figure 1.

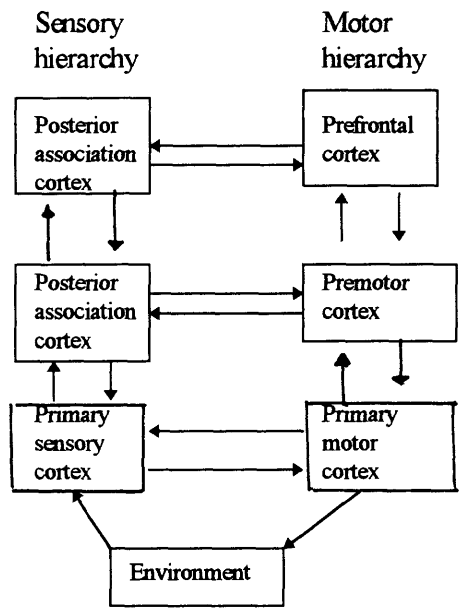

Figure 1: Schematic diagram of cortical information flow in Perception-action cycle of primate. From Fuster (1993).

Fuster (1993, p162) asserts that environmental stimuli are analysed first through sensory receptors, leading to 'conscious percepts' which are represented in the sensory channel. This information is relayed into the prefrontal cortex where the appropriate motor actions are then organised, channelled through the premotor system, which in turn, produce responses which act on the environment. These responses and the concomitant feedback cause new sensory input which in turn lead to a continuation of the Perception-action cycle.

Thatcher (1992) also proposed a similar dual model of prefrontal processing involving the lateral and medial prefrontal cortices. He presents evidence that these two systems represent independent and parallel sources which are involved in the phylogenetic development of the frontal lobes "through the temporally retrospective process of short term memory and motivation mediated by the lateral system, and through the temporally prospective process of planning mediated by the medial system" (Thatcher, 1992, p46). Thatcher's model parallels that of Fuster in terms of cognitive processing, and although he refers to apparently different neural substrates, the differences may be one of terminology rather than of structural sites. As it is generally acknowledged that frontal lateral cortex extends to the medial surface ending at the cingulate gyrus (Walsh, 1987), Thatcher's medial prefrontal cortex processor may, in fact, refer to the same site as Fuster's premotor processor.

Fuster emphasises that prefrontal lobe functioning involves the **interaction** of active memory and planning processes, two mutually complementary cognitive functions. Both functions are critical to bridging the temporal gap between perception and action. This conclusion is consistent with the view that a primary competency of the dorsolateral prefrontal cortex is the integration of memory and inhibitory control (Diamond, 1990).

The nature of the memory component of dorsolateral processing requires some elaboration. The term "active" memory is used because "working" or "representational" memory may imply a separate neural substrate and memory system, whereas active memory is simply a different state of the same neural substrate that stores long term memory (Fuster, 1993).

There is evidence of a double dissociation between active memory and planning skills. To illustrate, tasks that draw upon only one of these skills, such as the delayed non-match to sample task that make use of only active memory can be successfully solved by monkeys with lesions of dorsolateral prefrontal cortex (Bell and Fox, 1992). Evidence is also presented that tasks which utilise response inhibition skills, but not active memory skills, do not involve frontal lobe functioning (Diamond, 1990).

A picture is beginning to emerge which suggests that prefrontal cortex functioning involves more than just adaptive behaviour during novel and complex situations, as outlined by earlier researchers (Stuss and Benson, 1986). Intact dorsolateral cortex **is** necessary in solving tasks which involve novelty and complexity. In solving these tasks, two independent and parallel dorsolateral neural systems are activated. These two systems appear to be integral to the successful resolution of executive functioning. First, a goal must be established that is then retained in active memory during performance of the task. Second, planning must occur to establish the strategies and their sequence. Through the interaction of both active memory and planning, inappropriate responses are inhibited, new strategies are developed to meet the demands of the changing environment, and the individual remains on task to complete the goal.

2.2 Prefrontal Cortex Development

The developing brain undergoes enormous changes as it moves from a birth weight of approximately 400 grams to one of approximately 1500 grams at adult maturity around eighteen years of age. The fourfold increase in volume is attributable to myelination, increase in synaptic density, and increase in the size of brain structures (Conel, 1965). In the human, the pattern and rate of myelin development follows a strict pattern, beginning with the primary sensory and motor areas and spreading to the association areas. Within the cortex, by the age of 1 to 2 years of age all cortical areas contain some myelin (Gibson, 1991). From age 2 years to adolescence in the human, myelination continues in the limbic system, reticular system and neocortex, (Staudt, Schropp, Staudt, Obletter, Bise and Breit, 1993). There is also evidence that synaptogenesis patterns differ to those of myelin patterns in rate of development, and that these differences may relate to the known functional properties of each (Kalil, 1989). For example, myelination affects speed and specificity of long distance axon impulse transmission, whereas synaptogenesis reflects the ability for an impulse to be transmitted from one neuron to another. Once myelinated, fibres remain unchanged, except in the case of disease, whereas synapses degenerate apparently through functional disuse (Gibson, 1991). One possible interpretation of these findings is that myelination represents established function and functional maturity, whereas synaptogenesis represents functional potential (Kalil, 1989).

Studies of regional patterns of enzymes in human brains have also confirmed significant developmental changes which are linked to neural function. In a study involving brains with no neurological disorder, obtained at autopsy, Court, Perry, Johnson, Piggott, Kerwin, Perry, and Ince (1993) examined the level of choline acetyltransferase (ChAT) in several brain regions of humans from 24 weeks gestation to 100 years of age. ChAT, used as a presynaptic marker of cholinergic innervation in the forebrain, is generally believed to be central to cognitive and memory processes (Dunnett, 1991). Court *et al* (1993) found levels of ChAT in the frontal cortex increased from birth until 10 years of age and then fell to a relatively constant value between the second and third decades. Morrison, Becker and Kish (1993) examined the polyamine system, particular with regard to levels of the enzyme S-adenosylmethionine decarboxylase (SAMDC) in 59 normal human brains from the age of 1 day to 103 years. Experimental studies on pregnant rats have suggested that the polyamine system may have an important regulatory role within brain development as inhibition of polyamine has resulted in retarded brain development (Bell and Slotkin, 1988). Morrison *et al* (1993) found that the highest levels of SAMDC occurred in occipital cortex, with enzyme levels rising significantly in development until 10 years of age, and then remaining generally unchanged up to 103 years of age. The authors speculate that the "polyamine system may have a function such as neuronal pruning, synaptic reorganisation and connectivity" (Morrison *et al*, 1993, p240).

In a study of the normal developmental profiles of CSF gangliosides in humans from the neonatal period to adolescence, Izumi, Ogawa, Koizumi and Fukuyama (1993) found that ganglioside accretion increased significantly up to five years of age, was marked by a statistically significant decrease until ten years of age, and then, showed a slight increase during adolescence.

PET scan data, utilising indices of cerebral glucose metabolism, suggests a regional pattern of maturation in humans similar to the profiles of CSF gangliosides. Subsequent to the first year, glucose utilisation rises considerably above that of the adult levels and remains high to 9 years of age before declining to reach adult levels in late adolescence (Gibson, 1991).

The significant increase in brain growth during maturation is highlighted by concomitant increases in neural function (Hudspeth and Pribram, 1992).

What do we know of the genesis of structures involved with executive function? The early development of these structures has been confirmed by neurophysiological analysis, including EEG and single-unit studies.

Autoradiographic investigations of fetal tissues of rhesus monkeys provide strong evidence that cortico-cortical connections in the prefrontal cortex are in place at least one month before term (Goldman-Rakic, 1987a). However, there is some difficulty in translating animal data to human development and caution needs to be applied. For example, postnatal myelination in the monkey brain is about three to four times faster than in the human brain, so it would be difficult to sustain a parallel in neurological development between the two species (Gibson, 1991). Additionally, the timing and rate of increase in the formation of synapses in each area of the cortex is surprisingly similar (Rakic, Bourgeois, Eckenhoff, Zecevic, and Goldman-Rakic, 1986). Each area of the prefrontal cortex passes through a phase of excess synapses, higher than adult levels, followed by a long period of synapse elimination when the density of synapses per unit declines to adult levels (Bourgeois, Goldman-Rakic, and Rakic, 1985). These data have been widely interpreted as suggesting that the topography of cortical connectivity is poorly specified early in development and that callosal projection neurons attain their more restricted mature distribution mainly as a consequence of the loss of so called "exuberant" axonal branches (Schwartz and Goldman-Rakic, 1991, p144).

It appears that while the rate of development of prefrontal cortex may be different to other areas of the cerebral cortex, some expression of prefrontal lobe functioning can be expected at each point in maturation. This concept of "concurrent functional development" (Schwartz and Goldman-Rakic, 1991, p144), as opposed to often held views of a hierarchical development (Stuss and Benson, 1986), emphasises the integrative nature of behaviour. The conclusions drawn by Goldman-Rakic suggest that both posterior and anterior structures of the cortex develop along approximately the same timetable with integration and coordination occurring between the two.

2.2.1 EEG Evidence

Increased cerebral growth spurts measured by electroencephalogram (EEG), computed from eight left and eight right intrahemispheric electrode pairs, have been demonstrated at birth to age 5; age 7-9; age 11-13, and age 14-16, and that most if not all of these growth spurts involve prefrontal lobe connectivity (Conel, 1965; Thatcher, 1991, 1992). In a study involving 561 normal 1 to 21 year old human subjects, Hudspeth and Pribram (1992) recorded EEG trajectories in four brain regions:parieto-occipital, temporo-temporal, centro-central and fronto-temporal. The authors found that maturation patterns were synchronised over the four regions up to ten years of age. From the age of ten years, EEG records displayed different onsets and offsets of rapid change across the four regions. The result of synchronous development in four cerebral regions of the brain up to ten years of age, provides support for Goldman-Rakic's (1986) data that the timing and rate of increases of synapses in each area of the cortex is remarkably similar. In addition, the data clearly indicate that in the frontal executive region, "accelerated development occurred from 7 years until 10 years and then terminated synchronously with that of the rest of the brain." (Hudspeth and Pribram , 1992, p 27). Hudspeth and Pribram (1992) concluded that their EEG data were consistent with previous findings of maturational peaks and plateaus in children up to adolescence.

Studies of children using EEG coherence, which is purported to measure the number and/or strength of neuronal connections, have confirmed neonatal growth spurts predominantly involving prefrontal connections (Thatcher, 1992). Thatcher, (1991, p403) provides evidence that these periods of rapid cerebral growth occur at birth to age 5, age 7 to 9, age 11 to 13, age 14 to 16 and age 18 to 20 years. Thatcher demonstrated a cyclic pattern, or wave, lasting approximately two to four years where electrical activity in the frontal lobes was increasingly coordinated with electrical activity in other cortical areas. Each growth spurt cycle involved a set sequence of a left hemisphere-bilateral-right hemisphere timetable. According to Thatcher's view, an individual's "gross anatomical structure is established early in development and the postnatal iterative sculpting process is used to fine tune anatomical structures to meet the needs of diverse and unpredictable environments" (Thatcher, 1992, p47). This "sculpting" process is not dissimilar to a notion early espoused by Goldman-Rakic (1987a) who proposed that adult competence may be achieved through synapse elimination, which occurs throughout the entire period of adolescence. Neurally, the implications of synapse elimination are that as the individual reacts with the environment and learning occurs, more efficient pathways are reinforced, and those that are less efficient are eliminated. According to Schwartz and Goldman-Rakic (1991), neural development is characterised by an oversupply of axonal connections that appear to occur without regard to an overall plan. Cognitively, synapse elimination could be demonstrated by the notion that the young child faced with a new situation may have available to him or her a range of learned behaviours which could be selected. In the early phases of learning these behaviours would be random and unplanned and inappropriate in the situation. Some of them would achieve a desired outcome although be inefficient in terms of cost benefit. Perhaps one or two would be an effective strategy. As the child experiments with these strategies and behaviours, receives feedback from the environment on their effectiveness, learning occurs, and those successful strategies are preserved to be generalised to similar situations in the future. The neuroscientific literature does not specify how synapse elimination actually occurs. However, it must be emphasised that synaptogenesis is but one aspect of neuronal growth in frontal cortex.

2.2.2 Summary of Neurodevelopment

In summary, the results of analyses of development of human brain taken from a wide range of sources, indicates significant evidence for a maturational process. This process is one of growth spurts and plateaus, and, for frontal cortex, extends into late adolescence. There is converging evidence that the peaks and troughs of neuronal growth of frontal connections in particular, and related brain neurochemistry, involve a number of underlying processes that appear to significantly change around ten years of age. Evidence has been presented that regional patterns of the enzyme ChAT in frontal cortex increase from birth until 10 years of age and then fall to reach adult levels (Court *et al*, 1993); studies of cerebral glucose utilisation follow a similar pattern of significant increases in levels above that of adult levels up to the age of 9 years before declining during adolescence (Gibson, 1991). In addition, the enzyme SAMDC also rises significantly from birth to 10 years of age and then plateaus to adult levels (Morrison *et al*, 1993).

Results of EEG studies confirm frontal lobe growth spurts at ages up to 5 years, 7-9 years, 11-13 years and 14-16 years (Thatcher, 1992). Maturational patterns recorded on EEG trajectories were synchronised for four cerebral regions up to age 10, followed by independent patterns of growth beyond 10 years of age for parieto-occipital, temporo-temporal, centro-central and fronto-temporal cerebral cortex (Hudspeth and Pribram, 1992).

Schwartz and Goldman-Rakic, (1991) present evidence that maturation of the frontal cortex follows a pattern of excess synapses which undergo a process of pruning to adult levels during adolescence.

2.3 Piagetian Cognitive Development

The complexity of neural structures involved in executive functioning has already been examined as far as the literature will allow. The question arises: "What is the relationship between neural development and Piagetian cognitive development?" Piagetian Formal Operational Reasoning, like executive functioning, represents a constellation of complex behaviours.

There is a vast developmental literature which examines cognitive development over time (For a review, see Anderson, M. 1992). Piaget, together with his followers, developed a cognitive model specifying a stage-development for the mastering of cognitive skills. There are critics of Piaget's theory of cognitive development (for a review see McShane, 1991). It has been argued, for example, that Piaget was not interested in the notion of individual differences in development, that the more recent information-processing theories of cognitive development provide a more robust explanation of mental development, (Siegler, 1991) and that Piaget's notion of stages of development are not necessarily invariant as he originally proposed (Flavell, 1992). According to Anderson, M. (1992, p115), however, "it is safe to say that, as yet, nothing has replaced Piagetian theory as a general theory of cognitive development". Piaget's cognitive stages are Sensorimotor (birth to approximately 2 years of age), Preoperational (approximately 2 to 7 years of age), Concrete Operational (approximately 7 to 9 years of age), and Formal Operational Reasoning (approximately 11 to 13 years of age) (Flavell, 1977). Cowan (1978) and Inagaki (1992) specify further subdivisions of these stages with 7-8 years being Early Concrete Operational, 9-10 years Late Concrete Operational, and

11-12 Early Formal Operational Reasoning. This thesis uses Cowan's (1978) subdivisions to specify a separation of ages and stages in cognitive development.

Although not all adolescents and adults achieve the level of Piagetian Formal Operational Reasoning, (Piaget and Inhelder, 1969), the period marks the development of the ability to solve problems in a planful manner (Ginsburg and Opper,1988), to use hypothetico-deductive reasoning (Piaget and Inhelder, 1969), to use increasingly powerful rules for solving problems (Siegler, 1981, 1991), and to develop a future-oriented perspective which breaks free from the concrete here-and-now belief system of the concrete operational child (Flavell, 1977). Piaget's stages of cognitive development represent a maturation of complex cognitive skills. Formal Operational Reasoners are generally planful, strategic, and efficient in their organisation and manipulation of the available data (Flavell, 1977).

The most significant factors differentiating the Concrete Operational Reasoner from the Formal Operational Reasoner are the underlying problem solving processes. Both Early and Late Concrete Operational Reasoners are characterised by **empirico-inductive** reasoning, whilst Formal Operational Reasoners are characterised by **hypothetico-deductive** reasoning (Flavell, 1985). The Formal-Operational thinker inspects the problem data, hypothesises that a particular theory or explanation might be the correct one, deduces from it that a particular empirical phenomenon ought logically to follow and then tests this theory by seeing if the predicted phenomenon does in fact follow. Note that this type of thinking begins with the possible rather than the real (Flavell, 1977). In other words, the Formal-Operational Reasoner is not bound by the information that is before him or her. He or she can entertain a range of abstract propositions. For example, when presented with a card displaying two types of dogs, one of which has pink fur, and asked "Are there more pink dogs than dogs?", the Concrete Operational Reasoner would be confused and probably respond "That doesn't make sense. Dogs are not pink!" The Formal Operational Reasoner, however, would perceive the logic in the question, and temporarily suspend reality while he or she works through the logic of the proposition.

The Empirico-Inductive Reasoner, on the other hand, considers propositions and facts singly, in isolation from one another, testing each in turn against the relevant empirical data. There is no attempt at deducing relationships from the array of information that is available. Consequently, the Empirico-Inductive Reasoner is often "captured" by a salient feature rather than taking all relevant information into account (Siegler, 1981). The child is also limited by the concrete here and now and cannot infer propositions that go outside his or her realm of experience.

In summary, Concrete Operational Reasoning represents "first degree" operations that deal with real objects and events, whereas Formal Operational Reasoning operations deal with propositions or statements produced by the first degree, concrete ones (Inhelder and Piaget, 1958, p64). It is also evident, from a wealth of research studies, that there is uneven development as children move through the stages (Broughton, 1981, Sternberg and Okagaki, 1989, Anderson, M., 1992) and when faced with this unevenness (termed "horizontal decalage"), Piaget could not offer an explanation (Piaget, 1971). The unevenness in performance highlights the Piagetian view that development is both continuous and discontinuous (Sternberg and Okagaki, 1989). Although Piaget (1971) maintains that the stages of cognitive development are invariant, each new stage is incremental with respect to earlier stages, incorporating them while adding something new. According to Sternberg and Okagaki (1989, p161) "the incorporation is a source of continuity with respect to the earlier stage, whereas the 'something new' is a source of discontinuity". For example, according to Fischer and Bullock (1984), research studies of children performing Piagetian tasks indicate that developmental variability appears to be more the rule for the middle years than the earlier years. One can speculate as to possible explanations. The middle years of 9-10, Piaget's Late Concrete Operational period, is a period where the child is really between two significant modes of cognitive processing: Concrete and Formal Operational reasoning. During the transition from empirico-inductive to hypothetico-deductive reasoning, the child would be caught between applying old and developing new forms of thinking processes. The uncertainty of having a foot in both camps, as it were, might lead to considerable variability in performance. At one time performance may be efficient at the higher level and at other times performance on tasks would be characterised by a regression to immature forms of responses. Flavell (1992, p1002) notes that even after children discover a new competency, they may continue for some time to use previous, less adequate approaches.

There is some empirical evidence for the 'continuity-discontinuity' theory of cognitive development espoused by Sternberg and Okagaki (1989). In a study examining graphic skills of 192 6 to 16 year old children and the underlying neurodevelopment of these skills, Kirk (1985) discovered an uneven performance of her 9 year old children, compared to 8 and 10 year olds. The graphic task was the Rey-Osterrieth complex figure (Rey, 1959), and measures were obtained on accuracy, starting strategies, level of organisation and graphic style. Although there was no appreciable difference in accuracy scores between the 8-10 year old groups, the 9 year old subjects incurred significantly more errors than the other two age groups. Kirk concluded that the "gappiness" (abrupt increases or decreases in efficiency) in the uneven performance of the 9 year old subjects represented a process of reorganisation as the child moved from one level of thought to a new level of competency (Kirk, 1985, p 215).

2.3.1 Early Concrete Operational Period

The Early Concrete Operational Reasoner (7-8 years of age) is, to some extent, still in transition from the Late Intuitive period of cognitive development (Cowan, 1978). According to Piaget (1976), the child is beginning to develop a reversible system of mental operations enabling him or her to construct stable hierarchies of classes and relations. These mental operations, however, are limited to knowledge within the child's immediate experience. Piaget (Inhelder and Piaget, 1958) demonstrated that Early Concrete Operational Reasoners begin to develop two significant new mental operations: classification and seriation. In classification experiments, 7-8 year olds are able to form consistent two-way classifications. For example, they can classify colour and shape by big-red, small-blue, or height and age by taller-older or shorter-older. This is also the period of development of planning skills in problem-solving (Cowan, 1978). In order to apply classification skills to a problem, the child must first have a plan in mind that is goal-directed. This plan will then direct strategies for classifying particular entities. For example, the Early Concrete Operational Reasoner's approach to the Wisconsin Card Sorting Test would be to classify two categories at a time (colour-shape). Once this plan was in mind, then the child would have great difficulty shifting to a third category (number), because thinking is still irreversible at this stage. In other words, the child is unable to go back to his or her original plan and think through another plan or strategy. In addition, the child would become confused in the face of negative feedback when the criterion is changed, and would persevere with the previously correct classification or use trial and error without regard to feedback.

2.3.2 Late Concrete Operational Period

The Late Concrete Operational period (9-10 years of age) is marked by the ability to operate on more complex hierarchies. Children can now deal with 3-dimensional properties and perspectives. In their attempts at classification, they go beyond simple class inclusion to produce additional levels of classification in the array (Flavell, 1985). For example, a set of pictures is divided into living versus nonliving; within the class of "living things" are animals that fly and animals that do not. Within the class of "flying animals" are insects and birds. Children are now able to "decentre" and see things from another person's point of view (Ginsburg and Opper, 1988). For the first time, reasoning is seen as independent from the child who is less egocentric than the Early Concrete Operational Reasoner.

The Late Concrete Operational Reasoner's approach to the Wisconsin Card Sorting Task would be to discover three methods of classifying the cards (colour-shape-number). There would still be confusion arising from shifts in category although the child's attempts at resolving this conflict, still using a trial and error approach, would be more systematic than the Early Concrete Operational Reasoner.

2.3.3 Early Formal Operational Period

The Early Formal Operational period (11-12 years of age), marks a significant shift to hypothetico-deductive reasoning. This period in cognitive development signals the highest level of equilibration which matures at the Late Formal Operational period at around 15 years of age (Inhelder and Piaget, 1958). (The notion of "equilibration" will be elaborated in the following section). The Formal Operational Reasoner can deal efficiently with the complex problems of reasoning and can imagine the many possibilities inherent in a situation. Unlike the Concrete Operational child, whose thought is tied to the concrete, the adolescent can now deal with hypothetical propositions and can compensate mentally for transformations in reality (Ginsburg and Opper, 1988).

Behaviour is therefore characterised by the ability not only to generate a plan, but monitor that plan and construct alternative solutions in the face of environmental feedback. The ability to construct these alternative plans and strategies is dependent on the development of reversible mental operations which the Early Formal Operational Reasoner has now developed (Cowan, 1978). If one strategy fails, the child can now return to the original plan or proposition, modify it, and develop a new strategy. Flexibility of thought is a hallmark of this period of cognitive development. This implies the ability to use active memory in order to hold the goal on line while alternative solutions are generated.

In a series of sixteen experiments with children from four to eighteen years of age, Inhelder and Piaget, (1958) discovered four interrelated achievements which marked the emergence of Formal Operational Reasoning:

(1) discovery of the world of the hypothetical - observation is considered in relation to the set of all logically possible outcomes.
(2) creation of experiments in an attempt to examine the relation between hypothesis and data.
(3) reasoning goes beyond concrete grouping.
(4) addition of new formal schemes in reasoning - proportion, probability, volume, speed and perspectives.

In summary, the Early Formal Operational Reasoner reasons about the logical relations that hold amongst two or more propositions. The period entails thinking about propositions rather than about reality directly. The child's approach to the Wisconsin Card Sorting Test would be to discover immediately three categories of classification (colour-shape-number). When the category shifts, the child would deduce a correlation between negative feedback and the necessity of shifting set. As the child's thinking is now reversible, he or she would return to the original classification and develop a new hypothesis based on one of the other two categories. In contrast, the Concrete Operational Reasoner's thinking is still mostly irreversible so would cling to the original classification despite continued negative feedback.

2.3.4. Assimilation, Accommodation and Equilibration

The descriptions that have been provided of the three periods of cognitive development, beg a question. What underlying processes move a child from one period to another? Piaget was not inclined to provide a neurological explanation of the processes involved in cognitive development. The underlying frustration at Piaget's refusal to become involved with explanations of his cognitive descriptions can be detected in Klahr's (1989, p80), comment: "For 40 years now we have had assimilation and accommodation, the mysterious and shadowy forces of equilibration. Why is it that we know no more about them than when they first appeared on the scene? What we need is a way to get beyond vague verbal statements of the nature of the developmental process".

Klahr raised an important issue and distinction. It should be made very clear at the outset that Piaget was not interested in individual differences and the terms that he used to describe behaviour were never intended to **explain** behaviour. However, several writers (such as Flavell, 1992, p1001) refer to Piagetian terms as if they were explanations of underlying processes of cognitive development, and, it is contended that this has only added to the confusion. In Section 2.6 of this document, an explanation will be provided of the underlying processes. What theoretical scaffolding did Piaget provide in order to build his description of cognitive development? Piaget states that the skills leading to the development of Formal Operational Reasoning are symptomatic of an important reorganisation of intellectual structure - the emergence of a system of reversible mental operations or groupings (Piaget,1954). Like all cognitive organisations, groupings have three functional properties: assimilation, accommodation and equilibration (Cowan, 1978). These three cognitive constructs describe how the child moves from one cognitive stage to the next (McShane, 1991). Assimilation refers to the adaption of external stimuli to one's own internal mental structures while accommodation refers to the converse or complementary process of adapting those mental structures to the structure of these same stimuli (Flavell, 1977). Equilibration, on the other hand, refers to the cognitive-developmental process by which assimilation and accommodation interact to move the child to a higher mental level.

For Piaget, the most important aspect of a grouping is that it describes an equilibrated system which reaches its highest potential during the period of Formal Operational Reasoning. Reasoning is flexible and reversible so that when one strategy fails the individual can return to the beginning and generate another plan and alternate route. Thus, Piaget's cognitive system is an equilibrated system with a self-regulating mechanism (Cowan, 1978). To illustrate how assimilation, accommodation and equilibration interact to produce cognitive growth, the following example of a child in the Early Concrete Operational Reasoning period is offered.

Jenny, an eight year old child, is given the Balance Beam task for the first time. She observes that there are an equal number of disks on each side of the fulcrum and she understands the instructions given to her. Jenny has been playing on the see-saw in the playground and has developed an understanding that the see-saw will remain in the horizontal position if children of equal weight are on each side. From this previous experience with her environment she has developed a rule which says that equal numbers or weight will balance a see-saw, and unequal numbers and weight will tip the arm in favour of the heavier objects.

Jenny is presented with a Balance Beam problem where equal weights are placed at different distances from the fulcrum. She assimilates this information, through active memory, into her existing internal mental structure, based on her experience with the see-saw, and concludes that the Balance Beam will remain in the horizontal position. This is based on the previously learned rule that equal weights will balance a see-saw. She responds, and discovers that the Balance Beam tips to the left. This negative feedback from the environment creates a cognitive disequilibrium, or internal mental conflict. The next two trials also produce negative feedback as Jenny perseveres with the one strategy. As an eight year old, Jenny is still in the Early Concrete Operational Reasoning period where her reasoning is at the empirico-inductive level. She has not yet developed a reversible set of mental operations so finds it difficult to return to her original proposition and formulate a new strategy for solving the Balance Beam. In addition, she treats each Balance Beam trial as a single event and operates on each problem in isolation, rather than inferring or deducing relationships from previous trials. However, the disequilibrium provided by the negative feedback creates the conditions which may push her through her impasse and to the next cognitive level.

Faced with a strategy which obviously does not work in this situation, Jenny then begins to develop hypotheses and tests these in action. It is at this point that assimilation and accommodation interact to push Jenny through the disequilibrium. Each hypothesis, or goal, is assimilated into her previous knowledge. The accommodation process involves the development of plans to test hypotheses using feedback from the environment. The plan may be simply trial-and-error to test a range of hypotheses and thinking may still be at an empirico-inductive level. Jenny is attempting to actively accommodate the new information to her internal mental structures.

According to Piaget, equilibration at this point directs assimilation and accommodation to move Jenny to a higher level of cognitive growth. To solve the Balance Beam, Jenny discovers through her planning and experimentation, that distance from the fulcrum, as well as number of disks, must be taken into account. At this point she may not have fully comprehended that the rule is **distance times weight**, although she has discovered another rule or strategy which she can apply in other situations. What has been described may occur over a two year period with a range of environmental interactions before Jenny has moved to the next cognitive level. This example highlights the developmental sequence that may occur throughout cognitive development as the child moves from one cognitive stage to another. The model is dynamic and developmental.

As previously mentioned, although equilibration is critical to and underlies Piaget's cognitive-developmental model, he does not offer an explanation for the mechanism which drives this process (Flavell, 1992). Despite Piaget's biological training, his reluctance to map equilibration to a neural substrate is a reflection of the state of neuroscientific knowledge of the time. With advances in neuroimaging, however, it is contended that it is now possible to provide that mapping onto neurological functioning. This undertaking forms a central part of the argument of this thesis.

It is contended that Piagetian stages of cognitive development mirror those of pre-frontal lobe development. The developmental changes leading to full maturation of Formal Operational Reasoning parallel those leading to maturation of executive functions. There are correlates at both a functional and a neural level to sustain this assertion. Some of the evidence has already been examined.

There is a weight of supporting evidence specifying 11-12 years of age as the attainment of adult levels of executive functioning (Fuster, 1989, Levin, Culhane, Hartmann, Evankovich, Mattson, Harward, Ringholz, Ewing-Cobbs and Fletcher 1991). Stuss (1992) cites evidence supporting the notion that adult level performance of executive functions seems to be reached in three stages: (1) simple planning and organised visual search at around six years of age, (2) set maintenance, hypothesis testing and impulse control by age 10 years and (3) complex planning, motor sequencing and verbal fluency from age 12 years.

2.4. Neural and cognitive data for children

There is a striking similarity between the cycles of EEG coherence documented by Thatcher (1992) and the cycles of cognitive growth documented by contemporary investigators in the field of cognitive development (Case, 1992). In a meta-analysis of cognitive developmental case studies, Case (1992) presents strong evidence that graphs depicting the rate of EEG coherence involving frontal connections, identified by Thatcher and his colleagues, show a remarkable similarity to graphs of children's results on numerous cognitive tasks measuring Formal Operational Reasoning abilities. The age ranges for both groups were 1.5 years to 11 years.

Case (1991) documented a heuristic four-stage model drawing a parallel between neural and cognitive development. He mapped changes in psychological functions identified by Piagetian cognitive development to the EEG coherence data identifying differentiation of cortical connections. For each stage or substage in the developmental cycle, there was a corresponding stage or substage in the EEG cycle. The evidence presented is that there are data charting neural developmental changes involving frontal connections in children between the ages of 1.5 years to 11 years. These data document periods of rapid growth in frontal connectivity. The growth spurts have been identified at birth to age 5, age 7-9 and at age 11 years. At the same time there is another set of data, based on Piagetian cognitive development which also charts development of children during the same age ranges. (For example, age 7-9 is the period of Concrete Operational Reasoning and 11 is the beginning of Formal Operational Reasoning). What do we discover when we look at these two data sets? Those same age ranges identified by the neural data correspond to periods of rapid cognitive development identified by Piaget. Increases in prefrontal cortex development in children are associated with progression to a higher level of cognitive processing. The similarity of data is more than coincidental.

There is also further supporting evidence for a mapping of neural to cognitive development from the work of Conel (1967). From his evidence, there is a view that the timetable for myelin development mediates the maturation of intelligence in childhood (Gibson, 1991). From Conel's extensive work, we know that the upper layers of cortical association areas begin to myelinate between the ages of 5 and 8 years. As children mature during the Preoperational Period of reasoning and move toward the Early Concrete Operational Period between 7-8 years of age, a hallmark of their cognitive functioning is the ability to hold more concepts in mind simultaneously and to organise conceptual hierarchies composed of larger numbers of subconcepts. Case (1985,) proposed that myelination was critical in the development of these conceptual skills because it permits greater speed and efficiency of information transmission. The period of maturation of Early Concrete Operation Reasoning corresponds to the period of maturation of myelin development. In fact, Conel's (1967) investigations confirmed that myelin development continues through to adolescence, maturing at approximately the same age ranges as Piagetian Formal Operational Reasoning.

There exists a similar relationship between neural and cognitive data for other primates. For example, there is a striking similarity in the neurological and cognitive timetables for emergence and improvement of delayed-response tasks in rhesus monkeys. It seems remarkable that the period of growth in the principal sulcus, which in the monkey occurs between 2 and 4 months of age, coincides with the period of emergence and improvement of three cognitive tasks all of which depend upon this region of the prefrontal cortex and all of which involve the basic capacity to guide response choice by stored information (Goldman-Rakic, 1987b).

2.5 Assessment of Prefrontal Function in Children: from a Neural to a Cognitive Basis

Having established that there is substantial evidence for a corresponding timetable for both neural and cognitive development, it is contended that a cognitive rationale is now available to explain prefrontal cortex functioning in children and adolescents. Neural data establish a maturational timetable for prefrontal cortex functions and provide a direction and a focus which offers a richer explanation of cognitive development. The stage is now set to examine the Piagetian measures of cognitive development in light of prefrontal cortex function. Recall that Fuster's (1993) model of prefrontal cortex involved an interaction between active memory and planning processes. With this in mind, it is proposed to examine measures of Piagetian Formal Operational Reasoning.

2.5.1. Tower of Hanoi (TOH)

The Tower of Hanoi, (TOH), (Piaget, 1976), is one cognitive task that has been used with young children to evaluate problem solving strategies (Anzai and Simon, 1979; Borys, Spitz and Dorans, 1982; Klahr and Robinson, 1981; Piaget, 1976), rule-acquisition events (Vanlehn, 1991), self-monitoring behaviour (Welsh, 1991), and planning (Shallice, 1982, 1988). The original TOH consisted of three vertical pegs of equal size and a pyramid of doughnut-like n disks of decreasing size from bottom to top. The "n" referred to the number of disks, which usually involved problem types involving two, three and four disks. The goal of the task was to move the entire n-disk stack to another peg subject to the rules that only one disk was to be moved at one time, at no time can a larger disk be placed on top of a smaller disk on any peg, and that disks can only be held in the hand or on a peg.

Piaget (1976) claims that the mastering of this task marks the attainment of Formal Operational Reasoning which occurs at 11 to 12 years of age when subjects become more planful and inferential in their responses. Piaget (1976) used the TOH with children in the age range from 5 to 12. He identified three stages leading towards successful solution of the 3-disk problem. Stage I (5 to 7 years) subjects could solve the 2-disk problem with some difficulty but could not transfer to the 3-disk problem. Stage II subjects (7 to 9 years) could eventually solve the 3-disk problem although incurred errors along the way, and Stage III subjects (11 to 12 years) could successfully and rapidly solve the problem, generalise their solutions and recognise the importance of the first move. It is no coincidence that these three stages in the resolution of the TOH correspond to the three critical stages in cognitive development discussed previously. Stage 1 subjects correspond to Preoperational Reasoners (age 5-7 years), Stage II reasoners correspond to Concrete Operational Reasoners (7-10 years) and Stage III reasoners correspond to Early Formal Operational Reasoners (11-12 years of age). The quality of the problem-solving processing employed by each group of children is limited by their method of reasoning. For example, Stage II subjects includes both Early and Late Concrete Operational Reasoners who are bound by empirico-inductive reasoning (Flavell, 1985), while Stage III subjects would utilise a more sophisticated hypothetico-deductive type of reasoning (Cowan, 1978). Consequently, the older group of children are able to plan at least three moves ahead, would base their decisions on taking account of all available information, including learning from previous trials, and are able to return to their original hypothesis and develop a different strategy if the first did not work.

A number of researchers have employed the TOH as a means of studying young children's problem-solving strategies. Borys, Spitz and Dorans (1982, p 89), for example, compared the performance of nonretarded 6 to 10 year olds and retarded, institutionalised young adults classified as "trainable, educable and borderline". They found significant developmental differences between the nonretarded groups (12 children in each age group) on the 3-disk problem and identified six strategies, listed in order of level of sophistication, that accounted for the difference in subjects' responses. The authors concluded (p109) that the superior strategies by the more mature groups were related to increasing depth-of-search capacity (holding moves in active memory and planning moves ahead), and that the retarded group's limited search capacity is largely responsible for their pronounced maturational lag.

The TOH demands a number of cognitive skills. Welsh, Pennington and Groisser (1991), in a study with young children administered the TOH with other neuropsychological tests and concluded that it loaded onto a separate "planning" factor. In their study, Welsh *et al* (1991) allowed their subjects to move the pieces and hence receive feedback on the efficacy of their responses.

Klahr and Robinson (1981, p120), on the other hand, employed the same task in the "pure planning mode". Subjects were instructed to verbalise their moves to reach the goal-state without the benefit of actually physically executing the moves. This procedure places a heavy burden on memory and is a major departure from traditional administration of either the TOH or variations to this task as used by other researchers (Saint-Cyr, Taylor and Lang, 1988; Owen, Downes, Sahakian, Polkey and Robbins 1990). In their "pure planning mode", Klahr and Robinson (1981, p132) identified three general strategy principles which children used to solve the TOH problems:

- *Subgoal selection*: which of the cans (disks) not on its goal peg should be attended to next?
- *Obstructor detection and removal:* if the subgoal move can't be made, then which of the obstacles should be moved, and to where?
- *Effort determination*: how much effort should be allocated to achieving the current subgoal?

An analysis of these three general principles for solving the TOH identified by Klahr and Robinson (1981) indicates that the first two relate to planning processes and the third relates to active memory. Subgoal selection and obstructor detection relate to the employment of hypothetico-deductive reasoning and planning in order to achieve a given outcome. Effort determination or depth of search, relates to the number of moves one has to hold in active memory in order to solve the problem. These three strategies have much in common with other descriptions of rule-guided strategies employed by children solving the TOH (Anzai and Simon, 1979; Van Lehn, 1991).

The pure planning mode considerably increases the complexity of the task. For example, in a study involving 100 children aged 3 to 12 years of age, Welsh (1991) found that performance on the TOH was considerably enhanced when children were allowed to execute the moves, given feedback on their performance and thus encouraged to self-monitor their behaviour. Welsh's study clearly demonstrates that removal of the memory component, such as in the pure planning mode, makes the TOH a different type of test which produces less discrimination amongst subjects. Memory appears to be a major discriminator in the successful performance of the TOH. It is proposed that the term "active memory" mode is preferable to "pure planning mode" as used by Klahr and Robinson (1981) as it is a more concise explanation of the processes involved in solving the task.

VanLehn (1991) reanalysed the Anzai and Simon (1979) data of a child learning the TOH and discovered a pattern which cut across all phases of the TOH. He used the analysis of one subject's protocol over a 90 minute period and found that all the subject's additional talk, lengthy delays and negative comments occurred on moves 1, 5, 9, ..4k+1. The subject appeared to struggle at each of these move points.

At each of the 4k+1 moves, the subject has a choice between two legal moves and illegal moves. A correct decision is critical to the overall correct solution to the task. A wrong choice can still result in finishing the task although not in the minimum number of moves.

VanLehn speculated that correct solution at move 4k+1 involved strategy modification where the subject "interrupts her normal problem solving, switches her attention to the problem of modifying her strategy and begins to mutter goals appropriate to that task instead of her normal disk-moving goals" (VanLehn, 1991, p5). VanLehn's subject employed a scientific discovery approach during these moves and set up experiments to test her thinking. This discovery behaviour is comparable to hypothetico-deductive reasoning, a hallmark of Formal Operational Reasoning. VanLehn (p26) proposed that the 4k+1 move point represented an impasse for the subject which triggered a "rule acquisition event". He speculated that it was only at the 4k+1 moves where subjects struggled, where lengthy pauses in responses occurred and where these pauses were associated with additional talk. It was at these points that new learning occurred and subjects acquired new strategies for solving the TOH.

2.5.2 Balance Beam

Another test used by Piaget as a measure of Formal Operational Reasoning was the Balance Beam (Inhelder and Piaget, 1958). This consists of a beam with unequal weights which can be balanced at uneven distances from the fulcrum. Siegler (1978, 1981) developed six problem types for solving the Balance Beam and predicted that subjects would respond to the task according to four hierarchical rules. The problem types were based on conflict between numbers of disks placed on pegs and distance of those pegs from the fulcrum. Siegler developed twenty four items, four from each of the following six problem types listed in Table 1:

Table 1: Problem-types for the Balance Beam

Problem Type	Explanation
Equal	Equal disks placed on corresponding pegs
Dominant	Unequal disks placed on corresponding pegs- solution with larger disks.
Subordinate	Equal disks placed on non-corresponding pegs- solution with disks furthest from fulcrum.
Conflict-Dominant	Unequal disks placed on non-corresponding pegs- solution as per dominant case.
Conflict-Subordinate	Unequal disks placed on non-corresponding pegs- solution as per subordinate case.
Conflict-Equal	Unequal disks placed on non-corresponding pegs- solution as per "Equal" problem-type.

In a study involving children aged 3 to 17, Siegler (1981) reported significant effects for age, problem-type and age times problem-type interaction on the Balance Beam. It is argued that the Balance Beam demonstrates a developmental sequence with increasing complexity requiring subjects to simultaneously attend to more than one dimension and to inhibit competing responses. Siegler strongly asserts that solution to this task is governed by rule-guided behaviour. The provision of immediate feedback on performance provides the opportunity to adjust behaviour in the face of new information.

Subjects who do not follow a rule approach to solve the problems will be "captured" by one or two features such as the number of disks on one side of the fulcrum, but fail to process all the features in order to solve the problem. Siegler (1981), employed the Balance Beam as a means of identifying developmental sequences in the way children used rules to solve problems. He identified four hierarchical rules that were needed. Siegler demonstrated that of the one hundred and twenty 5, 9, 13 and 17 year olds tested, the hierarchical rule model that he proposed accurately predicted the performance of 80% of the 5 year olds and 100% of the 17 year olds. It is contended that in addition to predicting the particular rules that subjects may use to solve the Balance Beam, an hypothesis regarding the relationship between stage of cognitive development and success on the Balance Beam could also be advanced.

If success is dependent upon attending to more than one dimension, then those subjects still at an empirico-inductive stage of problem-solving, those Early (7-8 year olds) or Late Concrete Operational Reasoners (9-10 year olds), would have difficulty solving the Conflict-type problems listed in Table 1. On these problems, unequal numbers of disks are placed on non-corresponding pegs on each side of the fulcrum. The Early Concrete Operational Reasoner can usually think in terms of two categories (Flavell, 1985), although in a conflict situation, where unequal numbers of disks are placed on noncorresponding pegs, would be caught by the most salient feature which is number of disks. This strategy would work for the Conflict-Dominant type where solution is based on the number of disks. However, on the Conflict-Subordinate and Conflict-Equal problems, where solution is based on taking into account both number of disks and distance from the fulcrum, the 7-8 year old is likely to continue with a judgment based on number of disks. Each problem would be treated in isolation, with little attempt at inferring a solution on the basis of feedback.

The Late Concrete Operational Reasoner, on the other hand, manages to think in more than two categories or dimensions (Ginsburg and Opper, 1988). During the Conflict-Subordinate and Conflict-Equal problem types, the 9-10 year old, faced with the conflict of being incorrect, would resort to a trial and error approach to "solve" the problem. Success on these Conflict-type problems would be at chance level. The Late Concrete Operational Reasoner would test out hypotheses, some of which would be based on distance from the fulcrum and some in terms of numbers of disks. The child is therefore likely to achieve some success although not know why. He or she would still be employing an empirico-inductive method of problem-solving, so attempts at testing hypotheses would not be systematic and would tend to be a little erratic.

The Early Formal Operational Reasoner (11-12 years of age), on the other hand, would be employing hypothetico-deductive reasoning. Faced with a conflict, he or she would formally test out hypotheses, taking all the relevant data into consideration. When hypothesis testing, this child would hold one dimension constant and vary the other to determine the basis for a correct decision.

On face value, the Balance Beam, which is a measure of Formal Operational Reasoning, involves a number of subroutines including the use of feedback to adjust performance, inhibition of responses captured by one dimension only, and the adjustment of behaviour in the face of errors. There is also a clear relationship between children's progression through the Balance Beam tasks and the development of their active memory (Case, 1992). In an earlier study, Case (1985) demonstrated that a direct manipulation of attentional capacity produced a corresponding effect on the level of performance on the Balance Beam. As with the TOH, it is clear that memory is an important component of the Balance Beam task.

2.6 A Cognitive-Neurological Model (CN Model) of Executive Function

It is suggested that the next logical step in the search for a paediatric assessment of executive function is the development of a model which maps cognitive to neurological processes. As mentioned previously, it is not argued that there is a one-to-one relationship between cognitive processes and neurological processes. It is asserted that the neurological data suggest a direction and a focus for cognitive processes. There is a clear coincidence between stages of neurological development and stages of cognitive development. This notion is consistent with the view that brain development complements but does not replace psychological explanations of development (Segalowitz and Rose-Krasnor, 1992). Drawing a parallel between cognitive development and neural development, or mapping cognitive to neurological processes, begs the question of whether there is a one-to-one relationship between the two. It should be stated, quite clearly, that this thesis does not enter the philosophical debate about mind-brain-identity theory. It is acknowledged that there are philosophical difficulties with the current mapping exercise, although it is not considered the brief of this thesis to fully articulate the issues in identity theory. Frith (1992, p25), for example, believes that the philosophical problems of mapping cognitive processes to neurological processes "will dissolve or at least become radically reformulated as a consequence of new developments in cognitive science and neurophysiology". This is one point of view. There are others. For a comprehensive analysis of the issues involved in this debate, consult Borst (1970).

The coincidence between neurological and cognitive development may be examined in the same manner that Frith (1992) examined the system of schizophrenia. He developed neurological and psychological explanations of schizophrenia and generated a model specifying associations between the two. It should also be noted that the model maps cognitive processes rather than behaviour. The model developed in this thesis, as did the model developed by Frith (1992), will be used to predict rather than discover associations between neurological and cognitive processes.

The CN model developed in this thesis is an extension of the work of Piaget (1976), Thatcher (1992) and Fuster (1993) and is represented in Figure 2. The figure details the proposed CN Model of executive functioning. Information from the external environment is fed through the sensory processing system which in turn goes through a hierarchical process with feedback loops between both sensory and motor dorsolateral systems (Fuster, 1993). Active memory, encoded in sensory processors of dorsolateral cortex, maintains information on-line while planning, monitoring and behavioural adjustments are processed through premotor processors. The psychological processes of assimilation and accommodation are posited to have a functional parallel with these sensory and motor dorsolateral frontal systems. It is contended that both neurological and cognitive systems are involved with the process of adapting to the outside environment.

Fuster's (1993) explanation of his Perception-action cycle centres on information being received from the outside environment, processed through sensory processors and an action or planning set then being generated. As this is a dynamic process, feedback on the efficacy of these actions is received from the outside environment and behaviour is subsequently modified or corrected according to this information. At a psychological level, interaction between the two processors involves the interaction of active memory and planning functions. At a neurological level, interaction occurs between the sensory and motor processing systems in dorsolateral cortex.

In the CN model described here, Piaget's assimilation and accommodation represent parallel processes that interact in cognitive development, in the same manner that the sensory and motor neural systems interact in prefrontal cortex development. Thatcher (1992), briefly discussed the notion of assimilation and accommodation being tied to neural substrates, but did not articulate, in any detail, a working model of how these processes would operate in the developing child. It is contended that active memory is part of the assimilation process and is concerned with adapting external stimuli (through sensory information from the external environment) to existing internal mental structures. Accommodation, on the other hand, involves anticipation, planning, and an action-oriented approach to reorganisation of mental structures to accommodate new information/experiences. Accommodation is dependent upon feedback from the environment in order to facilitate change within the individual's cognitive system. Assimilation and accommodation on their own are inadequate to account for cognitive growth; together they function to create an integrated logical structure to maintain equilibrium within the organism and its environment (Cowan, 1978).

Consider the example of a child attempting to solve the Seals 3-ball problem for the first time. (For an explanation of the Seals task, see Section 3.1.1.). She has played games where she has to move pieces onto empty squares on a board game, and she assimilates this information into an examination of the current problem. The Seals test is another game which requires the movement of pieces (balls), onto squares (one of three seals). In the current problem, changes to her pre-existing cognitive schemes of activity make it possible for her to assimilate the new experience of solving the Seals task. The child now appears to have an understanding of the requirements of the test. The three rules of the game are stated. At this stage, the child has a limited number of strategies for solving the task. She must retrieve and hold in active memory the particular scheme or strategy that she is going to use to solve the test. She understands that a ball can be placed onto an empty seal, and on the first move she places the small green ball onto the nose of the middle seal, which is the first empty seal. There is no attempt to plan moves ahead or to use hypothetico-deductive reasoning to consider all possible moves that may lead to the end-state. On the second move she places the middle ball onto the third, empty seal. All seals now have balls resting on them.

The child has now exhausted her strategies for solving the test. There is no empty seal onto which she can move a ball! The strategy that she has been using will not work on move number three. She consequently rethinks the possible strategies that she can use. This 'rethinking' involves an attempt at accommodating the information before her by restructuring her understanding or developing a new competency. It is argued that the 'accommodation' process of mental change involves planning, monitoring of performance, and an active motor set. These cognitive behaviours have their neural correlates in the premotor cortex described by Fuster (1993) in his Perception-action cycle.

To return to the Seals test, the child now searches, through active planning, to discover a new strategy. She is now aware from feedback, that her previous strategy of moving a ball onto an empty seal will no longer work as all seals each have a ball on them. Through this searching for a possible strategy, she seeks clarification, and recalls one of the rules of the test: a larger ball cannot be placed on top of a smaller ball. She considers the balls and hits on the idea that she can move the small green ball back on top of the red ball. At this stage, she is still considering each move in isolation, without regard to an overall plan or goal. The child moves and is correct! She has now accommodated her strategies to suit the new information before her, and, in so doing, has learned a new strategy for solving the Seals test. In moving a ball backwards, that is, on top of a larger ball, she has discovered that you can free up a space to place the largest ball. The child has inadvertently discovered an 'obstructor detection and removal strategy' described by Klahr and Robinson (1981). The process of cognitive change involved an active search through planning, and a consideration of the feedback from the environment to adjust behaviour.

The same child is then presented with the 4-ball Seals problem. She uses her previously successful strategy of moving balls onto empty seals and then discovers that the 'obstructor detection' strategy only works up to a point. It does not free the yellow ball! She no longer has a strategy for solving the task. There is now a mismatch between the cognitive demands of the task and the child's current repertoire of strategies for solving the task. The child is unable to take account of and coordinate two or more changes, or subgoals, that occur simultaneously. Moving three balls onto one seal so that a space is free for the largest fourth ball to be moved into position requires two subgoal routines. The child is unable to "de-centre" (Wood, 1988, p41), a skill that requires attending to more than one dimension or point of view at the same time. The child's attempts at accommodating the new information are unsuccessful. It is contended that it is at this point that equilibration comes into play to move the child through this cognitive conflict.

It is proposed that both Piagetian equilibration and executive function, are the overarching psychological constructs which map onto prefrontal cortex processing. Both equilibration and executive function describe the process which "drives" or motivates adaptive behaviour in cognitive development. The evidence presented suggests that equilibration is a process of employing assimilation and accommodation to overcome conflict between two cognitive entities in order to make cognitive progress (Flavell, 1985). This is a dynamic process. There are periods in an individual's cognitive development where rapid and larger cognitive gains are made in a relatively short period of time. The period between Late Concrete Operational and Early Formal Operational

Reasoning, where thinking and problem-solving processes move from one based on empirico-inductive to one based on a more sophisticated hypothetico-deductive reasoning would be one of those rapid periods in development. It is suggested that at least two neurological processes, myelination, and changes in levels of neurochemical functioning, underly these rapid advances in cognitive development.

Cognitive disequilibrium, or internal conflict, may occur as a result of neurological changes and prepares the child for a shift from one stage of cognitive development to a higher level. Each shift to a higher level of mental development, up to the Late Formal Operational Reasoning period around 15 years of age, occurs within a two year period. The timetable for cognitive growth has a parallel in the cycles of anatomical continuity and discontinuity described by Thatcher (1991, 1992), and Hudspeth and Pribram (1992).

To return to the Seals problem, the child is now faced with internal conflict because neither assimilation nor accommodation on their own were successful in resolving the problem. According to Wood (1988, p41), "The mental state (of disequilibrium) is intolerable and motivates thought and action". Through the interaction of both assimilation and accommodation, the child holds a particular strategy in active memory, plans the steps involved in solving the problem, or considers the consequences of a particular strategy, and actively tests a particular theory that she holds for successful solution. Equilibration will eventually lead her to restructure the way she thinks in order to accommodate the internal conflict.

The age ranges identified by Piaget as critical in the shift to a higher level of cognitive processing, through equilibration, mirror those same age ranges identified by later neuroscientists as indicative of brain growth spurts implicating frontal lobe connections. Neural development establishes the parameters for cognitive development for without such biological development, cognitive development would not occur. For example, damage to the neural system will place limits on cognitive development. The CN Model presented here, serves to provide a theoretical basis for the development of paediatric measures of executive function. The CN Model is therefore seen as a possible extension of Piaget's work in providing an explanation of cognitive development in terms of neural development. It was mentioned earlier that Piaget did not attempt to offer a neurological explanation of his cognitive theory of development. The CN Model is offered as a possible explanatory model for Piaget's theory. It is acknowledged, however, that there are limitations to the CN Model. For the purposes of this thesis, the model will be used in select ways. In the current study, the CN Model is used **only** as a basis for developing a range of tests which are developmentally based and take account of the underlying neural substrates of executive functioning. The empirical evidence which is presented in this study is **not** a test of the CN Model. Substantial research will be needed to fully test all elements of the CN Model.

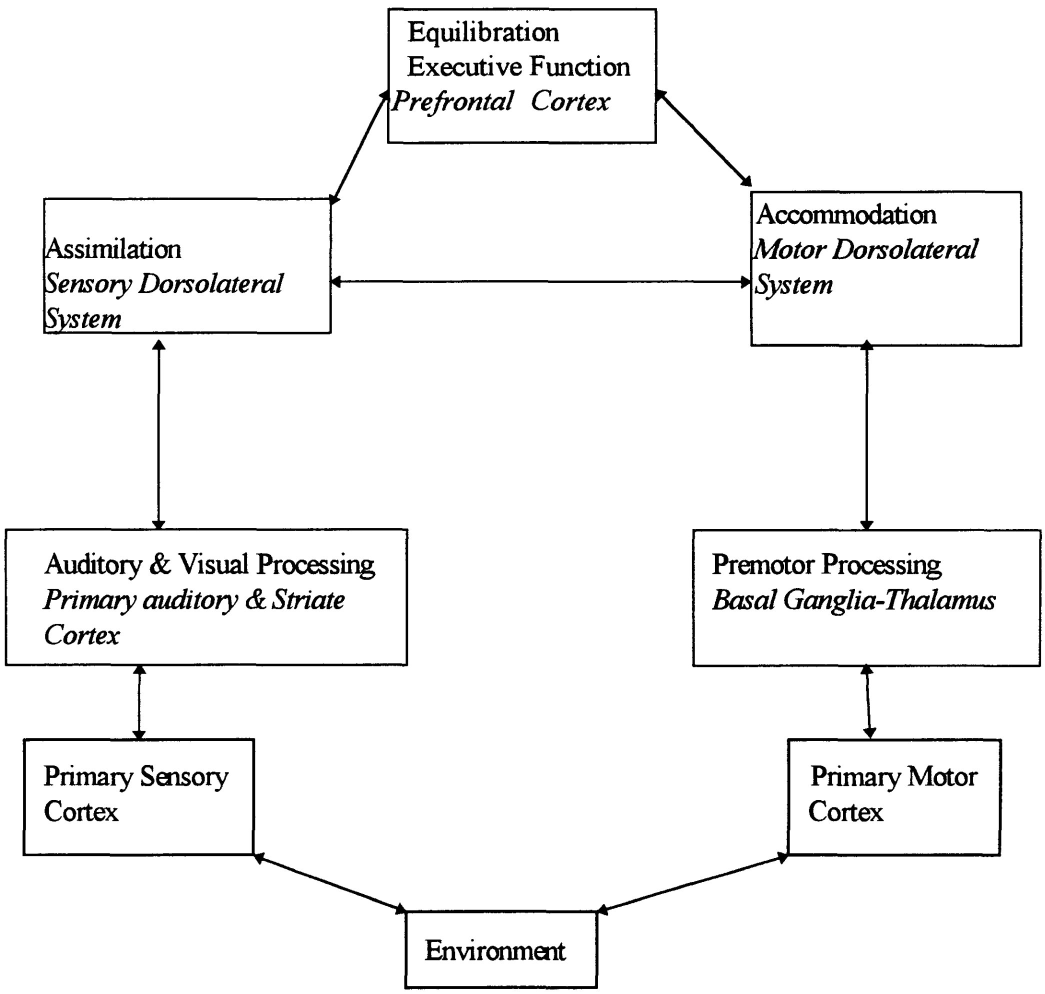

Figure 2: Cognitive-Neurological Model (CN Model) of Executive Function based on Fuster (1993).

It is asserted that the CN Model described in Figure 2 provides a basis for the development of tools to assess executive function in children and adolescents. On a functional level, the evidence presented here suggests that executive functions represent at least two interactive cognitive processes: active memory and planning. Planning includes using hypothetico-deductive reasoning, monitoring of the plan and adjusting behaviour in the light of environmental feedback. These two cognitive processes have correlates in two parallel and related neural systems (Fuster, 1993). It is argued that executive functions are more than just active memory and planning ability taken singly. The evidence supporting dissociation of active memory and planning provides encouragement for this view. It follows that executive function tasks must also involve holding a memory trace during a period of delay **and** planning. These cognitive functions have their neural substrates in the two dorsolateral systems. The planning aspect represents the active motor component and includes motor set and response inhibition. In order to develop and follow through with a plan, there must be an active monitoring component to inhibit inappropriate or previously learned responses so that the goal (which is held in active memory), can be attained. This would include making adjustments to responses following feedback from the environment. Evidence is beginning to emerge, at both a neurophysiological and functional level, to support this contention. Further research is required at a paediatric level, however, to confirm the dissociation between the two neural systems in their role in executive function.

On a developmental level, the evidence presented and encapsulated in Figure 2 suggests that developmental measures of Formal Operational Reasoning, provided they conform to the requirements stated above, should be appropriate measures of executive function in children. A search for paediatric assessments of executive function which are sensitive to developmental changes in children from aged 7 to 12 years, for example, should investigate tests of Formal Operational Reasoning which involve the integration of active memory and planning/motor set.

It is a central part of the present argument that those cognitive skills as measured by tests of Piagetian Formal Operational Reasoning, such as the TOH in the active memory mode and the Balance Beam, draw on the same skills demanded of executive functioning. Tasks of Formal Operational Reasoning have been developed specifically for children, are therefore age appropriate and satisfy the requirements of novelty and complexity (Stuss and Benson, 1986). They are usually based on a graded level of difficulty as opposed to a static level. Support for this contention has come from a very recent study by Levin, Mendelsohn, Lilly, Fletcher, Culhane, Chapman, Harward, Kusnerik, Bruce and Eisenberg (1994). The authors investigated the relationship of performance on developmental tasks to severity of brain injury in children, as confirmed by MRI. They concluded (Levin *et al*, p175) that severity of brain injury "had a significant effect on all Tower of London measures of performance. Apart from solving fewer problems, the severely injured children more frequently broke rules and were slower to initiate their first move".

In summary, the CN Model is proposed as a possible bridge between developmental psychology and neuropsychology. The model is an extension of Piagetian theory and is posited to have explanatory power in mapping Piagetian cognitive developmental theory to neural substrates. However, it is also clearly acknowledged that for the purposes of this thesis, the CN Model may appear to be unnecessary. Measures of executive function developed in this study would have been comfortably derived without regard to the model. In fact, many adult neuropsychological measures are atheoretical in nature, and many paediatric measures in particular, are not related to developmental theory or research (Welsh and Pennington, 1988). The CN Model serves two functions: a stimulus for further theorising and research in the area of developmental neuropsychology, and an attempt at building a theoretical scaffold for the development of paediatric measures of executive function. However, the model is presented as a first step toward linking developmental psychology to neuropsychology. It is considered beyond the scope of this study to validate the model, and it is acknowledged that the CN Model may pose more questions than it answers.

2.7 Paediatric Assessment of Executive Function

Given the developmental schedule for maturation of executive functions, there is a need to acknowledge that measures of executive function should be sensitive to periods of discontinuities or cognitive changes in development. There are, however, very few studies reported in the neuropsychological literature which address the issue of paediatric development. An examination of the neuropsychological assessments used with children indicate that they do not adopt a paediatric perspective and are influenced more directly by adult neuropsychology than by traditional developmental theory or research (Welsh and Pennington, 1988). It appears that the notion that the prefrontal cortex is essentially silent until the age of 12 years (Golden, 1981), still carries some currency in test development!

When used with children, the majority of neuropsychological tests have a floor effect, are usually not age appropriate, and do not have adequate normative data. Both neuropsychological and developmental branches of psychology have a unique contribution to make to the search for a neuropsychological assessment of children's developing capacity.

There is a strong case for a study of the functions of the prefrontal lobes using healthy young children. If an understanding of the functioning of children with brain damage is going to be gained, then it is important to have good normative data based on healthy children. Moreover, to gain an understanding of the developmental nature of brain function, it is necessary to study brains with intact connections.

According to Brown (1985), however, "a great deal more has been learned about the function of the brain without the frontal lobes than has been learned about the function of the frontal lobes themselves, (p27)". To only study a brain-damaged sample ignores the multiplicity of cortical and subcortical connections to the prefrontal cortex.

The few studies which involve healthy child subjects have confirmed developmental improvements in performance on neuropsychological tests purported to measure prefrontal lobe functioning. These studies have shown adult performance at 10-11 years of age (Chelune and Baer, 1986; Levin *et al* 1991).

An additional consideration in the study of paediatric executive functioning is its relationship to other cognitive activities, notably general intelligence, school ability and memory. It has already been noted that there is compelling evidence dissociating executive functions from general intelligence (Fuster, 1989; Levin and Benton, 1991; Stuss and Benson, 1986). Segalowitz, Unsal and Dywan (1992a) found that compared to their aged peers, academically and intellectually superior 12 year olds did no better on executive function tasks, such as the Wisconsin Card Sorting Test. In a study involving 160 learning disabled children, neuropsychological assessment revealed that the sample as a whole performed within the average range on standardised intellectual measures, but achieved poor results on measures of executive functioning (Anderson, V.,1992). The evidence cited adds weight to the argument that intelligence tests do not measure executive function in any meaningful way. Walsh (1987) presents a comprehensive summary of the literature relating to the relationship of general intelligence to executive function and concludes: “it remains a truism of clinical practice that patients with frontal lobe lesions appear essentially normal until they are examined with appropriate tests” (Walsh, 1987, p124).

Recent case studies of children with acquired brain injury have not only confirmed that tests of intelligence do not generally discriminate children with brain injuries, but also indicate that general academic skills remain largely intact following an acquired brain injury (Williams and Mateer, 1992).

Williams and Mateer (1992) studied two cases of children who sustained frontal lobe damage, one at age 8 years 11 months and the other at age 11 years. Unusual in clinical studies, the younger child had had a full psychometric assessment just 17 days prior to his accident. Follow-up testing 12 months, and then seven years post injury confirmed that general intellectual functioning continued in the superior range. General academic skills also appeared to be well developed in follow-up studies, despite an MRI which revealed an abnormal left frontal lobe and a small area of atrophy in the left temporal tip.

The older child in the Williams and Mateer study continued to have difficulties in mental flexibility, attention and maintenance of a response set, all of which are expected behavioural sequelae of bilateral frontal contusions. However, results of psychometric and academic skills assessment 12 months postinjury indicated that the child maintained the same high level of test results on the Wechsler Intelligence Scale for Children and on measures of school ability.

The issue of the importance of the integrity of the frontal lobes to memory performance is a controversial one. One view is that memory functions *per se* are not impaired in subjects with frontal lobe damage and that deficits on tests of memory are secondary to disorders of on-line processes such as encoding, attention and disinhibition (Shimamura, Janowski and Squire, 1991). Another view has emphasised the primary role of the frontal lobes on memory tests of delayed-response and memory for temporal order (Fuster, 1989). A recent study involving the assessment of seventy-seven patients with brain injuries concluded that the integrity of the left frontal lobe was indispensable for normal strategic retrieval and for the suppression of potentially interfering items in verbal memory (Della Rocchetta and Milner, 1993).

2.7.1 Displacement Tasks

In addition to an investigation of paediatric measures of executive function, it is proposed in the current study to also develop tests, based on developmental psychology, which measure response inhibition and control of interference and memory for delay. These skills are considered to be components of executive functioning (Fuster, 1989). The developmental literature has reported an ongoing interest in Piaget's (1954) concept of object permanence specifically as it relates to an infant's ability to retrieve a hidden object from a hiding place following a short delay. This classical A-not-B paradigm, according to Sophian and Yengo (1985), demonstrates the "perseverative error" which consists of returning to an initial hiding place (commonly designated A) after seeing the experimenter hide the object in a new place (designated B).

Piaget (1954, p63), offered three explanations for this perseverative error: "defect of memory, defect of spatial localisation and defect of objectification". However, Piaget consistently posited that perseveration occurred because the infant defined the position of objects in terms of his own actions upon the objects, and referred to this perseveration as a deficit in objectification.

Interest in this phenomenon has resulted in a range of studies which have interpreted the findings in terms of lapses of attention (Yates and Bremner, 1988), memory deficits (Cummings and Bjork, 1983), object identity (Butterworth, Jarrett and Hicks, 1982) information-processing deficits (Sophian and Sage 1983; Sophian and Yengo, 1985) ,inferred-location (Wellman, Cross and Bartsch, 1986) and memory plus inhibition (Diamond, Cruttenden and Neiderman, 1994).

In a meta-analysis involving thirty studies of the A-not-B paradigm, Wellman, Cross and Bartsch (1986), observed that the differences in findings and explanations may have been a function of the differences in parameters of the tasks as each varied with respect to number of locations (ranged from 2 to 6 locations), the length of delay between hiding and search (0 to 7 seconds), presence of distractors, the distances between locations and the distinctive visual properties of the hiding arrays.

Cummings and Bjork (1983), in a study of the A-not-B paradigm, used a five-choice visible displacement task following a three second delay. They found that infant search attempts at the correct location and the two closest holes to the correct location were more frequent (90% of attempts) than would be expected by chance during each B and C hiding trial. The authors concluded that contrary to the traditional Piagetian perseveration explanation, infant search behaviour is "consistent with the memory account ..in which it is assumed that infants comprehend the objective nature of objects and space, and that their search errors can be accounted for in terms of deficits in encoding , storage, and/or retrieval processes" (Cummings and Bjork, 1983, p284).

Cummings argued that the two-choice search task constrains subjects to perseverate so that the traditional Piagetian explanation is, in fact, an artifact of the task. The authors maintain that by limiting subjects' choices to just two possible search points (either A or B), the conclusions that one can reach regarding possible explanation of subjects' responses are limiting. For example, in a study involving infants searching for a toy hidden in one of seven wells, Diamond *et al* (1994, p205) demonstrated that poor memory alone could not account for the errors that were made. "Infants must also resist or inhibit the predisposition to repeat a response that succeeded just earlier".

Sophian and her co-workers (Sophian and Sage, 1983, 1985; Sophian and Yengo, 1985) also pursued the memory explanation for infant search behaviour and experimented with transposition displacement tasks. Objects were initially hidden in one of several containers, and then that container interposed with another. This more complex search activity was not able to be solved by 21 month year old infants.

Yates and Bremner (1988), also proposed a memory factor for the resolution of these displacement tasks, although the authors claimed that this interacted with a distraction variable. The combination of memory and distraction factors was used to explain the search phenomenon. Visual displacement tasks, particularly in the multiple-choice location paradigm, appear to be tapping prefrontal functioning. The task requires subjects to keep in active memory an internal representation of the goal and to hold that representation during a period of delay in order to perform the response that completes the goal. Fuster (1991, p60) refers to this process as the Perception-action cycle, which "applies to all behavioural sequences with substantial temporal separations between mutually contingent events". There is much in common with this concept and Fuster's (1989) 'active memory', Goldman-Rakic's (1987a) 'representational memory' and Luria's (1973) 'regulatory function of speech'.

Luria (1980), maintains that frontal lobe lesions often result in perseveration and a lack of inhibition and that this is primarily due to the dissociation between inner speech and motor control. Young children, or those with immature frontal lobe development, would have difficulty with the visual displacement task. They would be unable to inhibit competing or distracting responses, or use inner speech to maintain the goal in active memory because this inner speech has not been fully integrated with motor behaviour. Luria (1966), postulated that it is not until children are between the ages of 4 and 7 years that they finally achieve verbal regulation over behaviour.

One researcher to explore the A-not-B visual displacement task in the context of prefrontal functioning is Goldman-Rakic and her co-workers at Yale University. The classical two-choice Piagetian search paradigm was employed by Goldman-Rakic (1987a) in a series of experiments comparing the performance of infant humans, infant rhesus monkeys and of adult rhesus monkeys. Some of the monkeys had neuroanatomical lesions. In these experiments, the subject watches as a reward is hidden in one of two separate locations; a delay of a few seconds follows and then the subject is allowed to find the reward.

Goldman-Rakic and her co-workers (Diamond and Goldman-Rakic, 1983; Diamond, 1985; Goldman-Rakic 1987a), "established that A-not-B, like delayed response, is impaired selectively by dorsolateral prefrontal lesions in adult rhesus monkeys, and that the pattern of errors displayed by the operated monkeys closely resembles that exhibited by human infants" (Goldman-Rakic, 1987a, p 604).

Comprehensive evidence for the localisation of the delayed-response tasks in rhesus monkeys specifically to the principal sulcus (Walker's area 46) is presented by Goldman-Rakic (1987b). In addition, Diamond, Zola-Morgan and Squire (1987) discovered that adult monkeys with parietal and hippocampal lesions did not have difficulty with the A-not-B paradigm.

In summary, the results from Goldman-Rakic's laboratory confirmed that infants from twelve months of age were able to hold the representation of the object in active memory and successfully find the hidden object. She concluded that delayed-response and A-not-B tasks measured the emergence of representational memory, (active memory), which she considered "a building block, if not a cornerstone, of cognitive development in man." (Goldman-Rakic 1987a, p 604).

The visual displacement or A-not-B activity contains elements of both Fuster's (1989) and Goldman-Rakic's (1987a) notions of active memory.

2.7.2 Visual Scanning

Tasks which appear to depend on an action/motor set capacity (Fuster, 1993) are those reported by Teuber (Teuber and Weinstein, 1956). The first is a visual scanning task adapted from one used by Teuber, and employed by Welsh *et al* (1990) with early treated PKU children and a matched control group of "average" children. The task, involving forty black and white drawings of common objects, required the subject to find all the pictures that looked the same as the circled target at the top of the page. Teuber and colleagues claimed that this task was differentially sensitive to frontal lesions, and in their analysis Welsh, Pennington and Groisser (1991), concluded that Visual Search loaded onto a factor which they called "speeded organised responding".

Deficits on visual search tasks were demonstrated where subjects, presented with a number of sheets of paper containing the same pictures repeated throughout the different sheets, had to point to one picture on each sheet and avoid touching the same picture (Milner and Petrides, 1984; Wiergersma, Van Der Scheer and Human, 1990). Petrides and Milner (1982), concluded that patients with frontal-lobe lesions were significantly impaired on these tasks, while patients with temporal-lobe lesions were unimpaired.

In the developmental literature, Brown and DeLoache (1978) describe visual scanning tasks as a naturally-occurring ability that shows interesting refinement and increasingly conscious control with age and experience. The authors argue that "efficient visual scanning requires a high degree of executive control and that many aspects of development can be attributed to the expanding role of internal, planful, self-regulation of scanning and the concomitant decreasing importance of external variables" (Brown and DeLoache, 1978, p21).

The authors present evidence involving filmed eye-movements attesting to the young child's difficulty in systematic search and scan techniques, in being "captured" by a single feature, and difficulty in ignoring the irrelevant features of a display. There is much in common with the process of systematic search and the processes of cognitive development. The notion of being 'captured' by a single feature is a theme which figures in Concrete Operational Reasoning. The child who functions at this level does not take all the relevant information into account, relies on empirico-inductive logic, is limited to direct empirical data and is consequently unable to make deductions based on a logic of all possibilities. It is not until cognitive development reaches the stage of Formal Operational Reasoning that the child is able to systematically scan and search all relevant features and make deductions based on both past and present information. Therefore, the child at the stage of using hypothetico-deductive reasoning would consider the visual presentation in relation to both current and previous presentations, would develop an hypothesis about the features to be scanned and would test this hypothesis in a systematic fashion, making adjustments to the search on the basis of new information. The empirico-inductive reasoner, on the other hand, would treat each presentation of a visual stimulus on an individual basis as though it were presented in isolation from other presentations. It is argued that the concept of visual search would follow a developmental sequence that would be tied to Piagetian stages of cognitive development.

To summarise, given that prefrontal lobe neurological development represents a dynamic unfolding process then it follows that developmental measures of executive functioning should be sensitive to this change over time. In order to test for these developmental changes, there is a logic which suggests that it is simply not a matter of renorming adult measures using a child sample to capture this change process. There is clearly a need to develop separate measures of executive functioning for children based on developmental psychology and drawing on neurological substrates. It is contended that paediatric measures of prefrontal or executive functioning should be built on a theoretical foundation that takes account of developmental psychology, neuropsychology and neurology.

2.8 Adult Measures of Executive Function used with Children

In order to fully understand the developmental aspects of executive functions, some review of the adult literature is necessary. There are, for example, a number of measures of executive functions, developed for adults, which have gained some currency in paediatric clinical use. Although the tests have been used with children, the question arises whether in fact they are sensitive to cognitive developmental changes in a paediatric population. A brief review of the literature will follow, with the focus on examining those adult measures which have been administered to children. As part of this study, adult tests were administered to children, in order to assess their sensitivity to developmental shifts. Past research findings that related to a paediatric population were also considered. A brief outline of research with children as well as an examination of the underlying skills involved in the assessments follows. An analysis has also been conducted on how each adult measure conformed to Fuster's (1993) definition of executive function.

2.8.1 Wisconsin Card Sorting Test (WCST)

The WCST was developed by Grant and Berg (1948) as an objective measure of the ability to deduce abstract categories and to shift cognitive set. In 1981, Heaton published a comprehensive manual that standardised administration and scoring of the test. He concluded that of the eleven scores generated from the WCST, "the perseverative response score is the most useful diagnostic measure" (Heaton, 1981, p22). Researchers have suggested that the WCST is sensitive to dorsolateral frontal damage and the instrument is used widely in the assessment of patients with acquired brain damage (Greve, 1993). A double dissociation, using the WCST, has been found between children diagnosed as having Attention Deficit Hyperactivity Disorder (ADHD) and a matched group having a reading disability (Pennington, Groisser and Welsh, 1993). It has been categorically stated that "there is no question that patients with frontal lesions are prone to perseverate on the WCST" (Lezak, 1982, p284).

Research using normal children in the age range of 6 to 12 years of age indicates that children make gains in the number of categories achieved and reduce the number of perseverative errors with advancing age such that by the age of 11 to 12 years their performance is indistinguishable from that of adults (Rosselli and Ardilla, 1993). Major gains were found primarily between the 7-8 and 9-12 year old groups on the WCST measures (Chelune and Baer, 1986).

In contrast to the results of Rosselli and Ardilla (1993), Chelune and Baer (1986) and Passler, Isaac and Hynd (1985) found adult performance on the WCST by 10 years of age. Rosselli and Ardilla explain the different findings in terms of sample differences.

The WCST is also not significantly correlated with general intelligence nor academic achievement in a normal population of children 3 to 12 years of age (Welsh, Pennington, and Groisser, 1991; Rosselli and Ardilla, 1993). Studies have highlighted considerable variability in WCST performance. For example, Anderson, Damasio, Jones and Tranel (1991) found no difference in performance among young subjects with frontal versus subjects with nonfrontal damage.

Recently, some modified versions of the WCST have been implemented. Nelson, (1976) modified the test by removing the response cards which shared more than one attribute with the stimulus cards, thus eliminating any ambiguity. This resulted in a presentation of only 64 cards rather than the standard 128 card presentation. The Nelson (1976) modification of the WCST has gained some currency in clinical practice (von Cramon, Matthes-von Cramon and Mai, 1991). In a further abbreviation of the test, Lau and Perdices (1990) developed a computerised version of the WCST involving a 48 card presentation. There is evidence that the abbreviated form of the WCST produces results not significantly different from the standard presentation (Axelrod, Woodard and Henry, 1992). Therefore it is considered that the abbreviated version of the WCST used in the present study will yield a valid interpretation of test performance.

The WCST requires subjects to hold in active memory a representation of the targeted sort, whether that be by colour, shape or number. Each new stimulus presentation is then checked against that target. When the computer shifts to a different classification, the subject must then apply hypothetico-deductive reasoning to plan a different sorting category, while holding a target stimulus in active memory. Using feedback from correct or incorrect responses signalled by the computer, the subject must then either make an adjustment to the plan and develop a new hypothesis, or continue with the existing plan. On *a priori* grounds, the WCST appears to comply with the definition of executive function in that it involves an interaction between active memory and planning skills.

2.8.2 Austin Maze

The origins of the Austin Maze can be traced back to the stepping-stone maze described by Barker (1931). In a neuropsychological context, it was first reported by Milner (1965) who used it to differentiate the learning performance of adults with a variety of cerebral lesions. Milner's clinical group made many more errors of a qualitative nature such as back tracking, diagonal moves, jumping steps and repetitive errors.

The Austin Maze was popularised by Walsh (1985) who developed an electronic version to study self-corrective behaviour and the ability to follow rules in a clinical neuropsychological population. Many of Walsh's patients with brain injuries suffered from an "imperfect learning deficit" in that despite making only a relatively small number of errors at the outset, did not improve their performance on subsequent trials. Walsh (1991) has interpreted this performance to a problem with "error utilisation", which he attributes to damage in the prefrontal cortex.

Studies with children have found a large variability in error scores when the Austin Maze was employed with a normal sample of 7, 8 and 9 year olds (Hume, 1986). Hume (1986) did not find evidence of a clear developmental pattern of performance across her three age groups nor a significant gender difference in performance. In fact she noted a decrement in performance for the nine year old subjects. For example, mean errors for the 7, 8 and 9 year old subjects were 129.8, 89.1 and 95.7 respectively. The 9 year old group as a whole incurred more errors than the 8 year olds, although still considerably less than the younger age group. In addition, there was greater variability in performance on the Austin Maze amongst the 9 year olds when compared to the 8 year olds, with standard deviations of mean errors being 74.3, 46.4 and 66 for the 7, 8 and 9 year olds. It appeared that her 9 year old sample was operating somehow quite differently to the two younger age groups. Hume did not offer an explanation for this but to conclude that it may have been a function of her low sample size with a total of only 72 subjects.

The Austin Maze requires subjects to move, through trial and error initially, along a hidden pathway until they come to the end. Each successive trial requires the subject to profit from the previous one in reducing errors until there are two error-free trials in succession. In terms of the definition of executive function, this task draws heavily on active memory and utilising feedback from the environment to alter one's responses. Subjects must hold an internal representation of correct moves along the pathway in active memory, and on each move and trial, update this information to piece together the entire correct sequence of moves. Correct solution involves the interaction of active memory and planning/motor set and is consistent, on *a priori* grounds, with the stated definition of executive function.

2.8.3 Auditory Verbal Learning Test (AVLT)

The AVLT (Rey, 1964), has been demonstrated to measure three stages of verbal memory: registration, storage and retrieval (Vakil and Sheleff, 1990). According to Lezak (1983), the AVLT measures immediate memory span, retroactive and proactive interference, and retention following an interpolated activity.

As a measure of memory impairment, its utility has been confirmed (Rosenberg, Ryan and Prifitera, 1984). Age effects, with improved performance in the older children, in a sample of 7 to 15 year olds on the AVLT, have been demonstrated for two variables: the total number of words learned and retrieval efficiency (Forrester and Geffen, 1991). The authors demonstrated that the youngest group of children (7-8 years) differed significantly from the older three groups (9-10 years, 11-12 years, and 14-15 years) in total number of words learned and retrieval efficiency. "Remarkable stability between 7 and 15 years was found for acquisition rate, serial position effects, the effects of interference, forgetting, and source memory" (Forrester and Geffen, 1991, p356). The authors found no significant gender differences. It should be noted, however, that sample sizes were small, with only 20 subjects in each age group.

There is some recent evidence that measures of proactive interference in word-pair learning activities are related to prefrontal functioning (Uhl, Podreka and Deecke, 1994). Using a SPECT analysis of 12 normal adults performing a word learning task similar to the AVLT proactive inhibition condition, Uhl *et al* (1994) found significant increased anterior frontal cerebral activation during the proactive interference condition.

In the current study, the AVLT was used as a measure of memory. In light of the Uhl *et al* (1994) study, the possibility is raised that the AVLT may also be measuring executive functioning. This issue was examined.

2.9 Sensitivity, Specificity and Predictive Power of Neuropsychological Tests

In order for a test to have clinical utility, not only must it demonstrate statistical significance between groups (clinical versus nonclinical) but it must also consistently separate cases from noncases (desRosiers, 1992a). According to Elwood (1993, p224), although significant group differences in test scores, using *t*-tests or MANOVA, are the standard in research, they are usually irrelevant to the clinical decisions they are used to support. A clinician would want to know with what level of accuracy a particular test will correctly diagnose pathology in a given patient.

To help a clinician in deciding about a test's potential, Bayesian derivations can be applied to compute conditional probabilities that estimate a test's sensitivity and specificity (Willis, 1984). "Sensitivity, or true positive rate, is the proportion of subjects with a target disorder who are identified by a positive test finding (ie an abnormal test score). Conversely, specificity, or true negative rate, is the proportion of subjects without the disorder correctly identified by a negative test result (ie a normal score)" (Elwood, 1993, p225). A test which has high sensitivity is most useful when a subject's score is negative because it increases the clinician's confidence that the subject's condition is due to factors other than the one targeted by the test. When that same subject is then given a test which has a high degree of specificity, and the subject again tests negative to the targeted pathology, the clinician can be assured that the possibility of the subject not having the pathology is further enhanced.

Baldessarini, Finklestein and Arana, (1983) introduced the notion of a binary table for estimating sensitivity and specificity, in addition to Positive Predictive Power (PPP) and Negative Predicitve Power (NPP). According to Elwood (1993), PPP is the ratio of true positives to test positives and NPP is the ratio of true negatives to all test negatives. The more sensitive a test is, the greater its negative predictive power, and the more specific it is, the greater its positive predictive power (desRosiers, 1992b). The binary matrix and the concept of predictive power have been applied recently to the diagnosis of dementia (desRosiers, 1992a, 1992b).

In current practice, diagnosis is usually carried out in two steps (desRosiers, 1992a, p310). In the first-stage assessment (screening), diagnostic hypotheses are usually narrowed down by ruling out normality. Tests that are highly sensitive are important in this first step of diagnosis, in that they increase the degree of confidence that a patient does not have the pathology in question. According to desRosiers (1992a), second-stage measures serve to pursue specific suspicions and tests that have high specificity are critical in that they increase confidence that the condition suspected is really present and that results are not due to spurious conditions. "To help confirm the presence of a targeted condition, a test must be specific. To help exclude the presence of the condition, a test must be sensitive" (desRosiers, 1992a, p311).

Consider the case of a child referred to a neuropsychologist with a query of brain pathology. As a first screening test, the clinician would select a test that has a high degree of sensitivity to brain damage for a population of children. Let us assume that the particular test that is chosen has a Positive Predictive Power of 95% for discriminating brain damaged children from normals. The child then tests positive. The neuropsychologist knows that there is a 5% possibility that this child does not have a brain pathology. Her poor score may be due to other confounding factors. The child may have a severe learning difficulty, or may be suffering from anxiety. As a second-stage assessment, the clinician then selects a test that has high specificity for separating normals from those with brain pathology. Assume this second test has 94% Negative Predictive Power for a population of normal children. If the children tests positive on this second test, then this increases the clinician's confidence that the child indeed does have brain pathology.

When sensitivity increases specificity decreases, and vice versa, and one clinical exercise is to determine the best cut-off point at which predictive power is maximised (desRosiers, 1992b). In the present study, the concept of sensitivity, specificity, and predictive power was applied to the developmental and neuropsychological tests used with the normative and brain-injured groups.

2.10 Purpose of Present Study

In 1982, Lezak noted that, although executive function, for both children and adults, was critical to normal behaviour, there were not many assessment methods available for examining them. She concluded that "without assessment techniques that can be standardised and that can produce data subject to statistical analysis, much of our understanding of executive functions will remain at an anecdotal level", (Lezak, 1982, pp281-282). Very little has changed since Lezak's comments. The developmental evaluation of executive function remains an area which requires further investigation. It is contended that there is a need to explore the notion of developing executive function measures, based on both cognitive and neurological development. The purpose of the present study was to develop measures of executive function for children which are developmentally based and sensitive to age differences in a population of children 7 to 12 years of age.

Of the current measures which are used to assess executive functions of children, few, if any, are based on principles derived from developmental psychology. It is contended that developmental measures of Piagetian Formal Operational Reasoning which are consistent with the proposed CN Model of executive functioning outlined in Figure 2, are hypothesised to be measures of executive functions. It is anticipated that with increasing age, children will be able to successfully solve tasks of increasing complexity. As the underlying neural substrates mature, the child is able to cope with tasks of increasing cognitive demands and complexity. For example, the Early Formal Operational Reasoner begins to move toward a logic of 'reversible mental operations', where a plan is held in active memory while testing out a number of assumptions. A consideration is made of all available options, and then, the starting point is remembered in order to devise a new plan. The Early Concrete Operational Reasoner, on the other hand, uses a logic based on empirico-inductive reasoning, where propositions are considered singly without regard to all the available information. It follows that assessment tools for children should be sensitive to these shifts in cognitive and concomitant neurological function, and should contain a graded level of difficulty that provides differential cognitive demands that are tied to stages of development. The adult measures of executive function, used in the current study, were given to children to determine whether the tests were sensitive to developmental changes.

The developmental relationship among measures of Piagetian Formal Operational Reasoning which comply with the CN Model, as well as other standard adult measures of executive functioning, are examined in this study. The experimental developmental measures, based on Piagetian Formal Operational Reasoning, have been developed from the Tower of Hanoi and the Balance Beam. Although the neuropsychological literature reports the use of the Tower of Hanoi in the assessment of executive functions, (Saint-Cyr, Taylor and Lang, 1988; Owen *et al*, 1990, Welsh, 1991), these presentations, traditionally, do not usually involve an active memory component as in the present study. Subjects are able to manipulate the items and although active memory is still involved in the execution of the task, there is not the stress placed on active memory as there is in the active memory mode where subjects have to remember **all** their moves as well as planning future ones. Given the evidence presented, it is contended that the TOH in the active memory mode, is a valid representation of the neural correlates of executive functioning. It is also contended that the TOH, in the active memory mode, will be sensitive to developmental changes. It consists of graded problems, beginning with a 2-ball problem which according to Piaget (1976) can be solved by subjects at a Preoperational Reasoning level, the 3-ball problem which can be solved by subjects at a Concrete Operational level, and the 4-ball problem solved by those at a Formal Operational level.

In the 'active memory' mode, subjects not only have to plan their moves, modify their performance from feedback given at the beginning of each trial, but hold their moves in active memory. The task is also considered a valid representation of Piagetian stages of cognitive development as previously discussed. The TOH is also consistent with the notion of interaction between active memory and planning, a necessary condition for bridging temporal discontinuities (Fuster, 1993; Bell and Fox, 1992; Diamond, 1990). In the standard presentation, the TOH appears to load onto a separate 'planning' factor (Welsh, Pennington and Groisser, 1991). As well as developing experimental developmental tests based on the Balance Beam and the Tower of Hanoi, the current study develops measures based on a visual displacement (delayed-response activity) and a visual scanning paradigm (inhibition/monitoring activity). These measures have been used to assess an hypothesised dissociation between executive function and motor set/inhibition. The four experimental developmental tests have been computer programmed for presentation to a sample of 7-12 year old subjects.

In addition to these four developmental tasks, standard neuropsychological measures purported to be sensitive to prefrontal lobe functioning - the Wisconsin Card Sorting Test, the Auditory Verbal Learning Test and the Austin Maze have also been administered. The relationships between the various measures and indices of school ability and memory have been investigated. These relationships test previous reports in the literature of the correlation between executive function deficits and performance on school or academic tests, and measures of memory (Williams and Mateer, 1992). There is a view, for example, that executive function performance in children is not influenced by intelligence and academic ability (Segalowitz *et al*, 1992a).

The level of sensitivity, specificity and predictive power of the developmental measures and the standard neuropsychological tests will be determined to assess their clinical utility in the single case situation.

It is proposed to test the following hypotheses:

1. Piagetian measures of Formal Operational Reasoning which satisfy the criteria for inclusion as a test of prefrontal lobe functioning, will be sensitive to changes in executive function development in children aged 7 to 12 years.

2. There will be a dissociation between executive functioning and school ability. That is, tests of executive function will be independent of school ability as measured by the OLSAT.

3. Piagetian measures outlined in Hypothesis 1 should have greater predictive validity than adult measures of executive functions or nonexecutive measures, in separating a population of children with acquired brain injury from a matched normative sample. To test this hypothesis, normative data from a non-clinical population of children in the age ranges of 9-10 years will be compared with a sample of children, in the same age range, who have an acquired brain-injury. Both groups will then be administered the same battery of tests, and an analysis of the predictive validity of the developmental executive function tests in separating the two groups will be determined.

2.11 Predictions of Test Outcome based on CN Model

Based on the CN Model, proposed in Figure 2, what predictions can be made about the tests that will be used in the current study? What tests conform to the CN Model and can be predicted to be a measure of executive function? To answer these questions, the underlying skills and concepts which underpin the tests were task-analysed and compared with those components specified in the model. The degree of convergence between the underlying skills contained in the tests and those specified in the CN Model were examined so that predictions could be made. Each test has been separately analysed and the results depicted in Table 2.

Table 2: Prediction of Executive Function (EF) tests based on the CN Model.

Test	Active Memory Skills	Planning Skills	Inhibition Skills	Test of EF	Paediatric Test of EF
1. Seals Task	To remember past and present moves	To plan at least two moves ahead.		Yes	Yes
	To remember the three stated rules	To apply the stated rules in solving the task.	To inhibit responses which violate the rules		
2 Balance Beam	To remember previous moves and strategies for solving the task.	To take into account information from more than one dimension.		Yes	Yes
		To maintain a particular strategy for solution.	To inhibit previously correct responses		
		To apply mental flexibility and planning in adjusting to changes in criterion as the problem shifts from solution based on one dimension to two dimensions.			
3. Piggy Bank	To remember position of coin during a delay period.		To inhibit distractors and previous moves.	No	No
4. Fish	To remember that presentation of the Background Fish does not require a response.		To inhibit responses following presentation of Background Fish.	No	No
5. WCST	To remember past and present moves in maintaining a particular match.	To apply mental flexibility in adjusting to changes in criterion.	To inhibit competing matching criterion responses.	Yes	No
6. Austin Maze	To remember previous moves.		To inhibit previously incorrect responses.	Yes	No
	To remember the stated rules	To apply the stated rules.			
		To use feedback from the environment to adjust responses.			
7. AVLT	To remember words immediately presented.		To inhibit previously presented words.	No	No

3.0 DEVELOPMENT OF EXPERIMENTAL EXECUTIVE FUNCTION TESTS:

3.1 Pilot Study

A Pilot Study was conducted in February 1992. Its purpose was to refine both the computer presentation and the scoring procedures for the four experimental developmental tasks developed for children by the author. Subject selection was based on taking a small probe of a sample of children at the three age groups which were to be employed with the main study.

Twelve subjects, four from each of Year 2, 4, and 6 (7 years, 9 years and 11 years of age) were randomly selected by class teachers at Pendle Hill Public School, a government primary school in Sydney. Pendle Hill Public School is situated in the Western region of Sydney and contains a blend of middle and working class families. The four tasks are described here in detail:

3.1.1. Seals Task

The Seals task is based on the Tower of Hanoi, a developmental measure used in problem-solving, and described previously. The TOH (Piaget, 1976) consists of three pegs with doughnut shaped wooden pieces of varying sizes. Subjects move the pieces according to set rules: only move one piece at a time; at no time should a larger piece be placed on top of a smaller piece; and the goal state is to be reached in the minimum number of moves. The TOH was consequently modified and programmed for presentation on an Apple Macintosh Computer using Authorware Professional 2.0, an authoring multimedia package. The Seals Task was constructed so that it retained the format and set rules of the TOH. Presentation was in the 'active memory' mode where subjects were not given the opportunity to actually manipulate the pieces, but had to rely on memory processes to remember the moves.

The task consists of three seals each resting on podiums equidistant from each other. In the beginning-state, coloured balls of varying sizes balance on the nose of the seal to the left of the screen. The goal-state to be achieved is always displayed in an insert at the top of the computer screen. The Seals Task is considered appropriate for use with young children since the rules are minimal, it can be non-verbal in nature (subjects can point to the balls) and it can be made increasingly more difficult by simply adding more balls.

In this Pilot version of the Seals Task, only the 3-ball and the 4-ball problems were developed. The 3-ball problem consisted of three balls, green, red and blue, in descending order of size, balancing on the nose of the seal to the left of the screen. Correct solution involved seven moves. The 4-ball problem consisted of four balls, green, red, blue and yellow in descending order of size. Correct solution to the 4-ball problem is achieved in fifteen moves. The task was programmed so that it began with all the balls on the first Seal, with the goal-state to move all the balls to the third Seal. With each successive error, the Experimenter pressed the <Enter> key on the computer which moved the balls one move closer to the goal-state. Subjects were presented with the Seals problem in descending order of difficulty, with increasingly less moves to be made to achieve the goal-state. The computer presentation is appealing to children and the content is perhaps more motivating than the traditional TOH, although this notion was not formally tested.

While the internal structure and the rules for administration of the TOH are preserved in the development of the Seals test, there are also important differences from traditional testing procedures. For example, only 6 trials are given for each of the 2, 3 and 4-ball problems for a total of 18 trials. This is in contrast to previous presentations of the TOH, such as that of Welsh (1991), where 6 trials were given for each separate move within a problem type. In her presentations, Welsh gave her subjects 6 trials for the 7-move 3-ball problem, then 6 more trials for the 6-move 3-ball problem, and so on. The reason for the current departure from traditional presentations lies in the motivation for the development of the Seals test. The present study aimed to develop a measure which would discriminate the performance of subjects across a broad range, from 7 to 12 years of age. The task needed to be challenging to the older subjects and at the same time not pose too great a challenge for the youngest age group. It was felt that the change to the rules would provide the necessary challenge needed to differentiate performance as a function of age.

In contrast, previous researchers have been more interested in examining problem-solving strategies and self-monitoring behaviour and using the TOH as a vehicle to study these processes. In these studies, it is important that subjects are given every opportunity to master the task, hence the exposure to a large number of learning trials. Through an examination of subjects' learning profiles, judgments are then made about the extent of monitoring or use of particular problem-solving strategies. The present approach, however, employs the Seals test in a more demanding fashion such that it allows better discrimination among age groups.

The scoring *proforma* for the Pilot Study consists of blank spaces for each of six possible trials for each problem type. Consequently, separate *proformas* were developed for the 3 and 4-ball problem types. The researcher coded responses by describing the position of each ball for each move. For example:

R		
B	_	G

which describes a red ball on top of a blue ball for the first seal, the middle seal empty and the third seal with the green ball. Figure 3 depicts the balls in the above position on the computer screen .

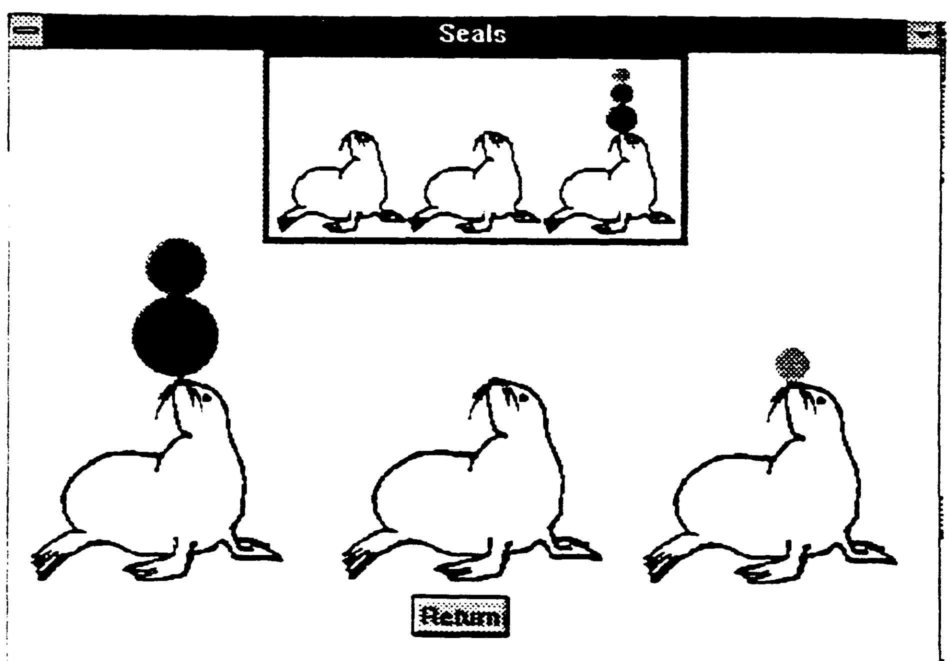

Figure 3: Example of computer screen for Seals Task. Three-ball problem after the first move.

Scoring was based on Borys, Spitz and Dorans (1982) where six trials were given for each problem type and criterion for completion was the correct solution in the minimum number of moves over two successive trials. A score of six was given for correct performance on Trials One and Two, five for Trials Two and Three, four for Trials Three and Four, three for Trials Four and Five and two for Trials Five and Six. If Trial Five was incorrect, the sixth trial was not administered. The results for the 12 subjects are set out in Table 3 below:

Table 3: Pilot Study Results of the Seals Task.

Subject	Age (Yrs)	Score for 3-ball	Trials to solve 3-ball	Score for 4-ball	Trials to solve 4-ball
#1	7.09	83%	3	0	-
#2	7.02	0	-	0	-
#3	7.08	33%	6	0	-
#4	7.02	33%	6	0	-
#5	9.01	67%	4	0	-
#6	9.05	83%	3	0	-
#7	9.06	100%	2	0	-
#8	9.02	50%	5	0	-
#9	11.00	100%	2	0	-
#10	11.06	100%	2	33%	6
#11	11.04	83%	3	0	-
#12	11.06	100%	2	33%	6

Mean scores for each problem type and age group are detailed in Table 4 below:

Table 4: Summary of Seals Mean Percentage Scores for Pilot Study

Age	Mean for 3-ball	Mean for 4-ball
7 yrs (n=4)	37.3%	0%
9 yrs (n=4)	50%	0%
11 yrs (n=4)	95.8%	16.5%

A *post hoc* comparison of the raw scores reveals a developmental trend. Mean percent correct is clearly lower for the younger groups than the older ones although the small sample size limits tests of statistical significance. It is apparent that the 4-ball problem was too difficult for the younger children with only the 11 year olds registering any success.

Observations of subjects' responses indicate difficulties remembering the three stated rules, with majority of errors involving rule violations. The younger subjects experienced difficulty with the 3-ball problem and many expressed 'amazement' when confronted with the 4-ball problem. There is a need to introduce this task at a simpler level, and to ensure that subjects have an opportunity to familiarise themselves with the three rules before proceeding to more psychologically demanding tasks.

The researcher also experienced some difficulty "keeping up" with subjects both in recording responses and anecdotal information relating to self-corrections and rule violations. It was proposed that the Seals should begin with a 2-ball problem to introduce the task at a lower level of difficulty for the youngest children. At the same time the 2-ball problem would become a vehicle for reinforcing the three rules. Whenever subjects violated a rule during this problem task, the rule would be immediately stated by the researcher. In addition, it was proposed to introduce a number of computer screens which had all instructions in text. The researcher would then read the instructions from the screen. The following instructions were developed for use in the final normative study:

Screen 1: *There are three seals, one of which is balancing coloured balls on its nose. You have to tell me how you would move the balls, one at a time, so that they finish in the same position as the seal in the box at the top of the screen.*

The researcher reads the above instructions to the subject, and then adds:

There are three rules you have to remember:
** You can only move one ball at a time and you must start with the ball at the top of the stack.*

The researcher demonstrates by explaining, with the two-ball example on the screen, that you start with the red ball first.

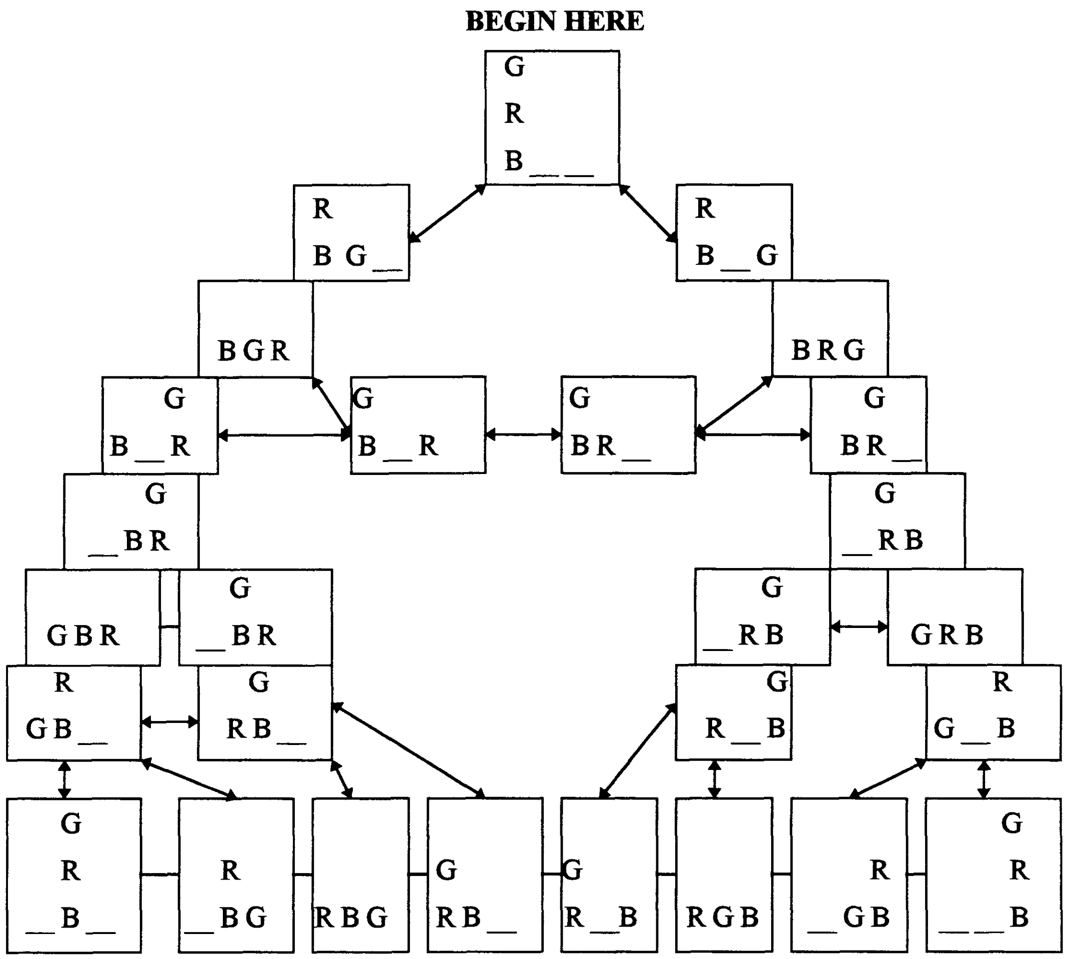

Figure 5: State Space for the 3-ball problem.

3.1.2 Balance Beam Task

This task was first employed by Inhelder and Piaget (1958) to test for the Formal Operational Reasoning stage of cognitive development. The Balance Beam consists of a beam with a fulcrum located in the centre of eight equally spaced pegs onto which metal disks of equal weight can be placed. The arm of the beam can tip to the left, to the right, or remain on a horizontal level. The arm, however, is held in the horizontal position until the child predicts the outcome. Siegler (1981) developed twenty four items, four from each of the six problem types detailed in Table 1.

In a study involving sixty children aged 3 to 17, Siegler (1981) reported significant effects for age, problem-type and age times problem-type interaction on the Balance Beam. It is argued that the

Balance Beam demonstrates a developmental sequence with increasing complexity requiring subjects to simultaneously attend to more than one dimension and to inhibit competing responses. Siegler strongly asserts that solution to this task is governed by rule-guided behaviour. The provision of immediate feedback on performance provides the opportunity to adjust behaviour in the face of new information. The task is both novel and complex and, on face value, satisfies the requirements for an executive function test described previously.

Four examples from each of the six problem-types were randomly drawn and programmed onto a computer using Authorware Professional 2.0, an authoring software program. Each balance beam was hand drawn and then scanned into the computer. The task was developed so that subjects were presented with a practice example which had four weights placed on the second peg from the fulcrum on the left hand side and three weights placed on the second peg on the right hand side of the fulcrum. Figures 6.1 and 6.2 depict one example of the Balance Beam. In the first screen (Figure 6.1) the problem is presented, and subjects respond by clicking on the icon at the top of the screen. In the second screen (Figure 6.2), the beam moves so that subjects receive feedback on their responses. The full program is listed in Appendix 1 .

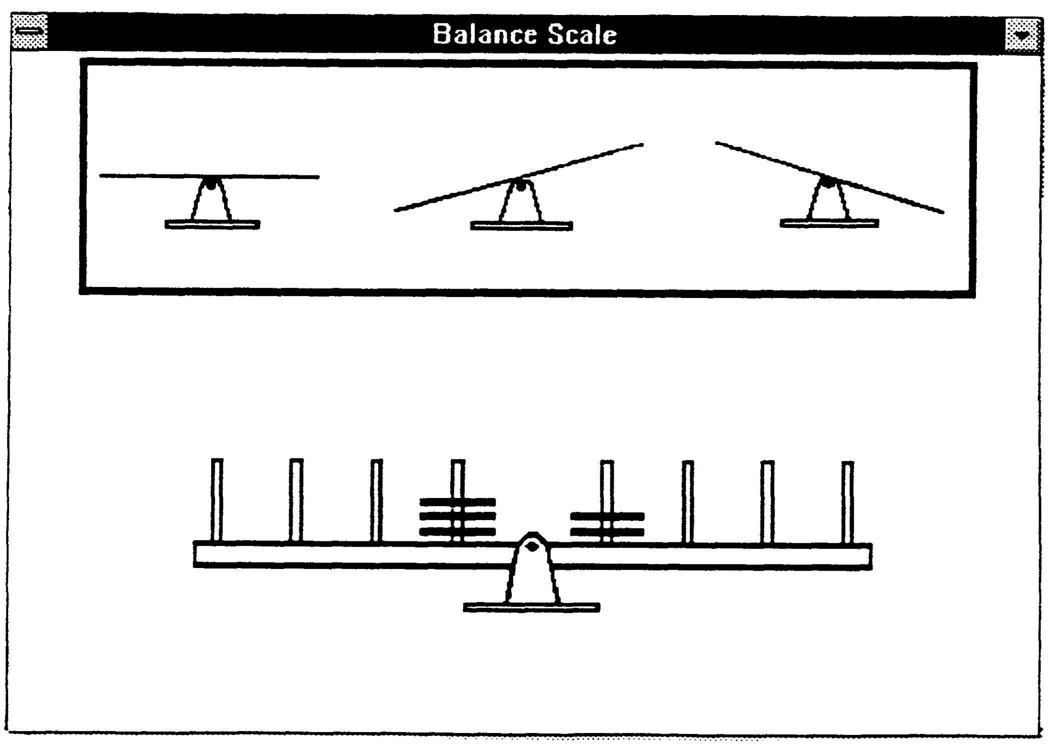

Figure 6.1: Example of computer screen for Balance Beam Task. Subjects are instructed to click on the icon at the top of the screen indicating which way they believe the beam will drop.

The Total Scores indicate a developmental progression by age. For example, the mean score for 7 year olds is 54%, for 9 year olds is 59%, and for 11 year olds is 74%. Anecdotal information on subjects' performances was also recorded. Subjects were asked, at the end of the task, how they solved the problems. The majority of the 7 year olds did not verbalise a strategy. Most of the 9 year olds indicated that they counted the number of disks on each side of the fulcrum. Two of the 11 year olds indicated that not only did they count the disks but that they looked for ones which were placed at the end of the balance beam. One of these 11 year olds indicated that the distance from the fulcrum was important.

Given that subjects respond by choosing one of three options (beam dropping to the left, to the right, or remaining in the horizontal position), it is considered that in its present form, the Balance Beam is a cognitively demanding task for the three age groups. It was proposed, however, that the task presentation would be altered to allow subjects to develop a systematic response to each item. This was to be achieved by grouping the problem types and introducing each group of problems in ascending order of difficulty rather than having a random presentation. It was proposed that the number of problem types would be reduced to four, with the total number of presentations remaining at twenty-four. The problem types are as follows:

Dominant: Disks placed on corresponding pegs on each side of the fulcrum. Solution is based on the number of disks only. Items #1- #8.

Subordinate: Disks of equal size placed on pegs not in corresponding position from each side of the fulcrum. Solution is based on distance from fulcrum. Items #9- #12.

Conflict-Subordinate: For items #13- #22, the disks are randomly placed and subjects solve the problems by taking into account **both** numbers of disks and distance of disks from fulcrum.

Conflict-equal: Disks randomly placed. Solution as per "Equal" problem-type. Items #23- #24.

To control for guessing, the solutions to the twenty-four items were arranged so that eight involved the horizontal position, eight involved the left hand side dropping down, and eight involved the right hand side dropping down. Thus, if subjects guessed the same response for all items they would score a 33% accuracy. A major modification to the computer presentation was the establishment of its capacity to keep running records of subject's scores. The Balance Beam was programmed so that each student's score, listing percentage correct as well as individual trial scores, would be saved to the hard disk drive for later retrieval and analysis. A score of "1" indicated a correct response, and a score of "2" indicated an incorrect response. See Appendix 2 for an example of a printout of the Balance Beam student results.

It was hypothesised that the modified order of presentation would introduce a progression in difficulty level from which subjects could apply rules in a systematic fashion to solve problems. The Balance Beam task would contain a graded level of difficulty that was perceived to be sensitive to shifts in cognitive demands and complexity. The modified version of the Balance Beam task was not tested before use in the final study.

3.1.3 Fish Task

The Fish task is a visual scanning exercise involving the ability to inhibit a response to a commonly presented stimulus. Visual scanning or 'searching' tasks have been demonstrated to be differentially sensitive to frontal lesions (Milner and Petrides, 1984; Welsh, Pennington, Ozonoff, Rouse and McCabe 1990; Wiergersma, Van Der Scheer and Human, 1990). In their analysis, Welsh, Pennington and Groisser (1991) concluded that Visual Search loaded onto a factor which they called "speeded organised responding".

Welsh *et al* (1990) conducted a study involving early-treated PKU children and a matched control group of 'average' children who were required to find all the pictures that looked the same as the circled target at the top of the page. They found that this visual search exercise discriminated significantly between the two groups.

In the developmental literature, Brown and DeLoache (1978) describe visual scanning tasks as a naturally-occurring ability that shows interesting refinement and increasingly conscious control with age and experience. The authors argue that "efficient visual scanning requires a high degree of executive control and that many aspects of development can be attributed to the expanding role of internal, planful, self-regulation of scanning and the concomitant decreasing importance of external variables" (Brown and DeLoache, 1978, p21). It is contended that visual scanning exercises follow a developmental pattern of improvement which relates to Piagetian cognitive development.

The Fish task was developed as a measure of visual scanning and response inhibition. It consists of line drawings of fish presented individually on the computer screen at 3 second intervals. There are two types of fish - **Background fish, and Target fish.** There is one Background fish which remains constant. Its presentation on the screen is repeated on a number of trials. Subjects are instructed to click on the mouse whenever a fish that is different to the Background fish appears on screen. The Background fish becomes the distractor from which subjects must inhibit a response. In this Pilot version of the task, forty fish are presented, twenty-five of the same Background fish and fifteen different Target fish. The task begins with five Background fish presented, with the remaining thirty-five fish presented at random on the screen.

The fish have been drawn as simple line drawings which have been scanned into the computer. They are clearly quite different in appearance and would not require extensive visual scanning in order to discriminate between a Background and a Target fish. Three of the fish have been reproduced below in Figure 7: the Background fish and two Target fish.

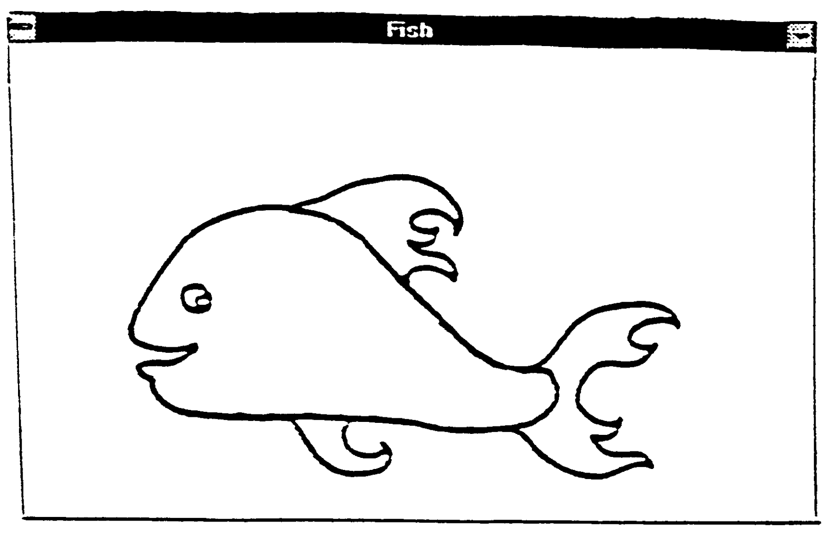

Figure 7.1: Example of Background fish presented on screen

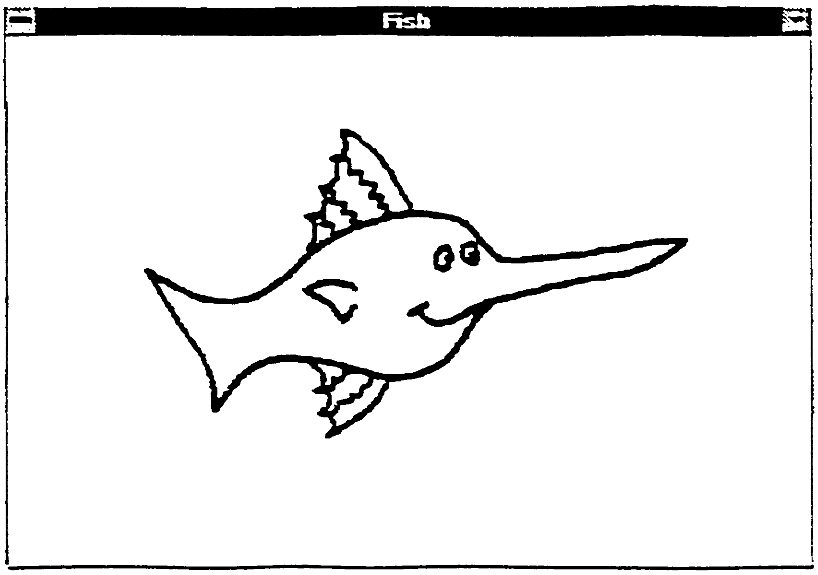

Figure 7.2: Example of Target fish presented on screen

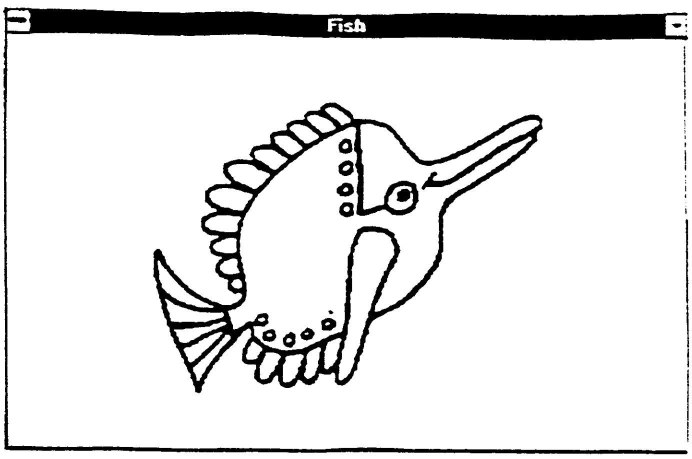

Figure 7.3: Example of Target fish presented on screen

The Fish task was programmed onto a Macintosh computer using Authorware Professional 2.0, a multi-media software package. A *proforma* was developed so that all responses could be recorded manually by the researcher.

The Fish task requires subjects to scan the stimulus on screen, categorise the fish as either Target or Background and to respond by either clicking on the mouse whenever they detect a Target fish, or by refraining from making a response on detection of a Background fish. It also involves the ability to inhibit inappropriate responses or previously correct responses. Successful performance on the Fish task draws on active memory processes, monitoring of the fish presented on screen and inhibiting a previous response to ensure that only a response to a newly presented Target fish is made. The results for the 12 subjects are detailed in Table 6:

Table 6: Results of Fish Task for Pilot Study

Subject	Age	Score (% correct)
#1	7.09	100
#2	7.02	88
#3	7.08	100
#4	7.02	88
#5	9.01	100
#6	9.05	98
#7	9.06	100
#8	9.02	100
#9	11.00	100
#10	11.06	100
#11	11.04	100
#12	11.06	100

It is evident from Table 6 that this particular task does not discriminate significantly across the age ranges. Mean percentage score for the 7 year olds is 94%, 99.5% for the 9 year olds and 100% for the 11 year old subjects. It is apparent that the task is not sufficiently challenging.

In order to increase the difficulty level it was decided that the fish would be presented in 1.5 second intervals rather than the 3 second interval presented in the pilot study. It was reasoned that the reduced presentation time on screen and the reduced decision time would increase the demands of the task. To introduce the task, three Background fish are presented first, followed by the remainder in random order. The number of trials was cut from forty to thirty-five, with the Background fish physically altered so that it resembled a number of the Target fish. This was achieved by drawing stripes on the body of the fish not unlike the stripes on some of the Target fish. The new Background fish is presented in Figure 8. The modified version of the Fish task contained twenty of the same Background fish and fifteen different Target fish.

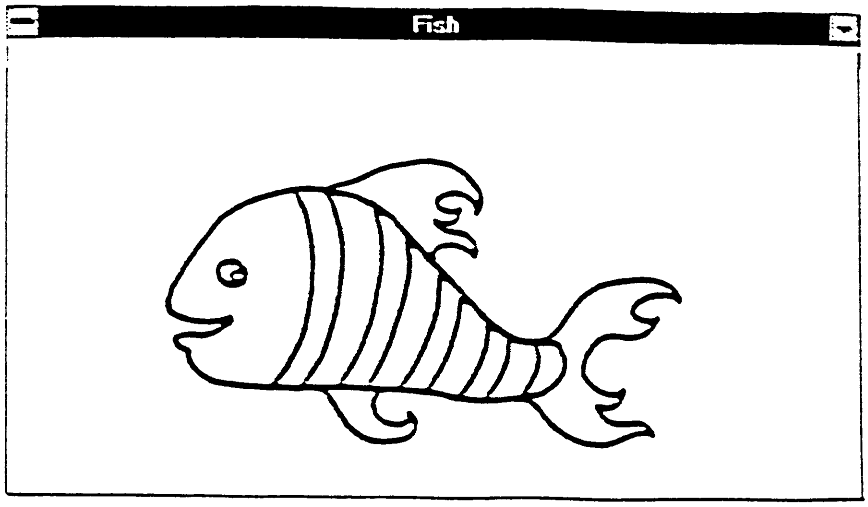

Figure 8: Modified Background Fish

See Appendix 3 for the complete modified Fish Task in order of presentation. In addition to the physical change in the Background fish, the program was enhanced so that it was able to record student results to be saved to the hard disk drive for later retrieval and analysis. See Appendix 4 for an example of a computer printout of student results. The modified version of the Fish was not tested prior to its employment in the final study.

3.1.4 Piggy Bank Task

The Piggy Bank task is based on Piaget's (1954) "object permanence" tasks with an extension of this paradigm involving transpositions of objects. It is hypothesised that the Piggy Bank task would have an active memory component as subjects hold a visual representation of the position of the coin in their active memory during a period of distraction and delay.

The task consists of hand-drawn piggy banks presented individually on the computer screen until there are five in a row. A coin then moves from right to left across the screen and is deposited into one of the piggy banks. You cannot see the coin once it is deposited into the piggy bank. Two sets of transpositions of piggy banks then occur. These are animated on the screen. For example, Piggy Bank #1 changes place with Piggy Bank #5, and then Piggy Bank #5 changes place with Piggy Bank #3.

The screen then changes, and a series of distractors appear on the screen. These distractors are coloured balloons of varying sizes which individually appear until the screen is filled with balloons. There is a ten second delay period while the screen fills with balloons. The computer then returns to the previous screen with the five Piggy Banks and subjects respond by clicking on the piggy which they believe contains the coin. The task was developed on computer using Authorware Professional. See Figure 9 for an example of a computer screen for the Piggy Bank task. Figure 10 depicts the distractor screen which fills with balloons during the delay period. Six trials were developed for the Pilot version of the task. Details on transpositions are as follows:

Trial	Coin placed in	Transpositions	Delay
1	#2 piggy (L-R)	#1-#5; #2-#4	10 sec
2	#1	#2-#4; #3-#5	10 sec
3	#1	#2-#5; #1-#4	10 sec
4	#2	#2-#5; #1-#4	10 sec
5	#3	#1-#5; #2-#4	10 sec
6	#4	#1-#3; #2-#5	10 sec

Reading across the first line of the above table, Trial 1 involved a coin placed into the second piggy (second from the left). When the coin disappears on screen, the first piggy and the fifth piggy then change positions on screen, followed immediately by the second piggy and the fourth piggy swapping positions. Coloured balloons then appear for a ten second period and the screen returns to the five piggy banks.

Although each trial involves two transpositions of piggy banks, the piggy with the coin does not necessarily move on each occasion. In fact, given that this task relies on active memory during a period of distraction and delay, it was decided to use the transpositions themselves as distractors. Consequently, three of the six trials involved transpositions where the piggy with the coin did not move at all. The other three trials involved one movement of the coin during the transpositions. Figures 9, 10 and 11 demonstrate a sequence during one trial of the Piggy Bank task. In Figure 9 the coin is shown moving across the screen to be deposited into one of the piggy banks. The coin then disappears. In Figure 10, the first of the two transpositions occurs, with piggy banks changing positions on screen. In Figure 11, the piggy banks disappear off screen which then fills with balloons, one at a time. All test results were recorded manually by the researcher. These are detailed in Table 7:

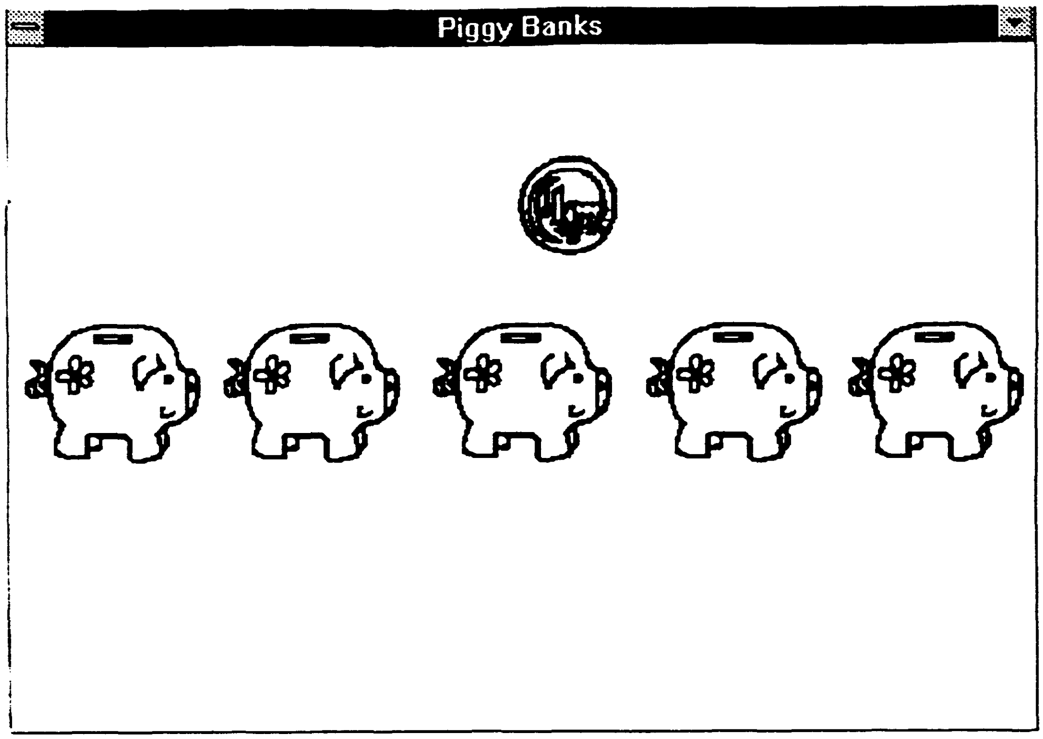

Figure 9: Example of computer screen for Piggy Bank task. The coin is placed into one of the piggy banks.

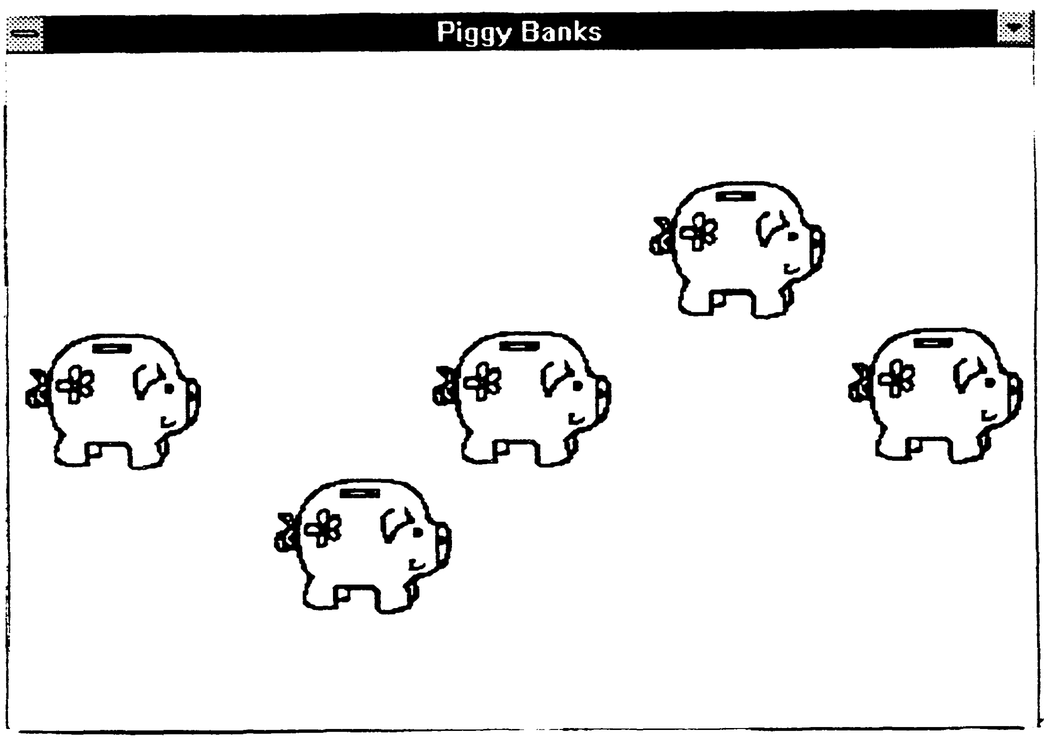

Figure 10.: Two transpositions of piggy banks occur on screen. Here, the first transposition occurs.

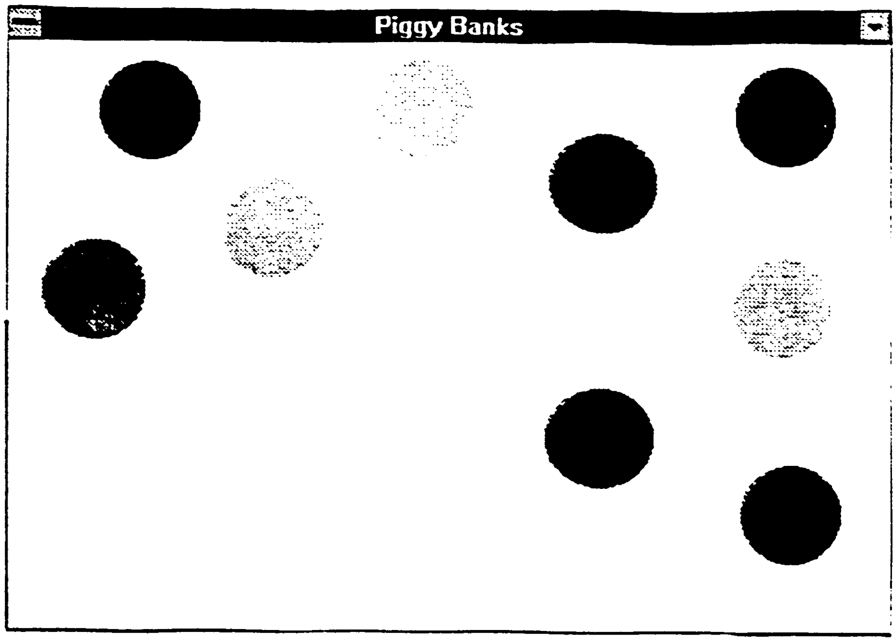

Figure 11: Example of distractor screen for Piggy Bank. The balloons appear one at a time until the screen is filled.

Table 7: Results of Pilot Study for Piggy Bank

Subject	Age	Score (%)
#1	7.09	83
#2	7.02	100
#3	7.08	100
#4	7.02	67
#5	9.01	100
#6	9.05	100
#7	9.06	83
#8	9.02	100
#9	11.00	100
#10	11.06	100
#11	11.04	83
#12	11.06	100

On face value, it appears that this task does not offer a cognitive challenge for subjects, nor does it discriminate between the age groups. Half of the 7 year olds had perfect scores with a mean score of 87.5% for the group. This compares with a mean score of 95.8% for both the 9 and 11 year olds. A decision was made to retain the basic concept of the measure with significant modifications that increased the difficulty level. To increase task demand, the following changes were made to the Piggy Banks task:

1. Four additional trials were added giving a total of ten trials for the task.
2. The new trials were:

Trial	Coin Placed	Transpositions	Delay
7	#5 piggy	#2- #5; #1- #4	20 sec
8	#3	#1- #3; #2- #5	20 sec
9	#4	#4- #5; #1- #4	25 sec
10	#5	#2- #5; #2- #4	25 sec

3. The delay period was extended with Trials 1-4 involving a fifteen second delay, Trials 5-8 a twenty second delay and Trials 9-10 a twenty-five second delay.

The modified version of the Piggy Banks offered ten trials, a delay period which was graded at three levels, and a mix of transpositions which were used as distractors, single movement and double movement of coins. Trials #7, #8, and #9, for example, involved one movement of coins, and Trial #10 involved a double movement of the piggy carrying the coin. Of the ten trials, three involved no movement of the pig carrying the coin, six trials involved one movement of the pig carrying the coin, and one trial involved a double movement.

Because this task involved movement of both coins and piggy banks across the visual field, an attempt was made to balance this movement across the ten trials. The visual field was divided into three segments, Left, Middle, and Right, with the two piggy banks on the left constituting the Left Field, the piggy bank in the middle of the screen constituting the Middle Field, and the two piggy banks on the right constituting the Right Field. The coin could be placed in any of the three visual fields and it could move across to any of the three visual fields. Table 8 details movement of coins across the fields.

Table 8: Visual Field Placement for Piggy Bank Task

Trial	Coin Begins in	Coin Moves to
#1	Left Field	Right Field
#2	Left Field	Left Field
#3	Left Field	Right Field
#4	Left Field	Right Field
#5	Middle Field	Middle Field
#6	Right Field	Right Field
#7	Left Field	Right Field
#8	Middle Field	Left Field
#9	Right Field	Right Field
#10	Right Field	Right Field

Five trials involved coins placed in the Left Visual field, three trials in the Right Visual field and two in the Middle field.

In addition to the change in content, the program was enhanced so that it had the capacity to record student results for storage to the hard disk drive of the computer. The student results could then be retrieved for later analysis. See Appendix 5 for an example of a computer printout of student results. The modified version of the Piggy Bank was not tested prior to its use in the final study.