



# Assessing executive functions in children: biological, psychological, and developmental considerations†

VICKI ANDERSON

**Keywords** Executive function, children, development, assessment

## Summary

Executive functions may be defined as those skills necessary for purposeful, goal-directed activity, and are generally considered to be largely mediated by the frontal and prefrontal cortices of the brain. These cerebral regions are relatively immature during childhood, with development thought to be a protracted process which continues into early adolescence. While early theorists suggested that executive skills were not functional until cerebral maturity, recent research provides evidence that such skills can be elicited in early childhood. The aim of this paper is to review current theories of development of executive functions throughout childhood. In keeping with contemporary approaches to child neuropsychology, three critical dimensions will be evaluated; biological factors, psychological dimensions, and developmental trajectories. In addition, the literature which addresses assessment of these functions will be examined, with reference to developmental trajectories observed in normal populations, and in brain-damaged samples, where there may be disruption to the underlying neural substrates thought to be subsuming these functions.

## Introduction

The concept of 'executive function', although variously defined, is generally agreed to encompass the skills necessary for purposeful, goal-directed activity [1–4]. Neuropsychological evidence suggests that these skills may be largely mediated by the prefrontal cortex of the brain and related descending systems, providing a framework within which stored information can be adaptively applied to novel, problem-oriented situations

[4–6]. These cerebral regions are relatively immature during childhood, with development thought to be a protracted process which continues into early adolescence [7–8]. Parallels between ongoing maturation of the frontal lobes and the emergence of executive capacities have been reported in a number of studies. These results suggest that, where developmentally appropriate assessment tools are employed, evidence of executive skills can be elicited in children as young as the age of 6 years [9–20].

There is now growing evidence that children sustaining brain damage exhibit deficits in executive skills. Such problems may interfere with the child's capacity to develop normally and interact effectively with the environment, thus leading to ongoing cognitive, academic, and social disturbances [21, 22]. Individual case studies provide anecdotal evidence of problems in planning, problem solving, and abstract thinking in the day-to-day lives of these children [23–25]; however, such 'executive dysfunction' is often difficult to detect using traditional assessment tools. Further evidence comes from a handful of recent studies which have examined executive functions following childhood brain injuries. Findings suggest that residual deficits in planning, problem solving, and adaptive behaviour are associated with head-injury [26–29], hydrocephalus and spina bifida [30], and cranial irradiation for treatment of childhood cancers [31, 32]. However, accurate and reliable identification of such deficits, both in clinical practice and research endeavours, continues to be limited owing to the lack of developmentally appropriate assessment tools.

The aim of this paper is to review current theoretical models of executive function in children, from a neuropsychological perspective. In keeping with contemporary approaches to child neuropsychology [33–35], three critical dimensions will be evaluated; biological factors, psychological processes, and developmental trends. In addition, the literature which addresses assessment of these functions will be examined, with reference to

*Author:* Vicki Anderson, Department of Psychology, University of Melbourne, Parkville, Victoria 3052, Australia. e-mail: vicki\_anderson.psych@muwayf.unimelb.edu.au

†This paper was originally published in *Neuropsychological Rehabilitation*, 1998, 8(3), 319–349. Reproduced by permission © 1998 Psychology Press Ltd.

developmental trajectories observed in normal populations, and in brain-damaged samples where there may be disruption to the underlying neural substrates thought to be subsuming these functions.

### Definitions of executive function

Before embarking on a discussion of executive function, issues of definition must be considered. Over time, there has been a gradual conceptual shift, with early notions describing a homogeneous set of processes, and not differentiating among individual sub-skills which might be incorporated by such a label. Currently, while the range of skills included in specific definitions varies, most authors agree that ‘executive functions’ may be best understood as an umbrella term, encompassing a number of interrelated sub-skills, necessary for purposeful, goal-directed activity [4, 36].

In a recent comprehensive review of neuropsychological assessment procedures, Lezak ([36] p. 42) states that executive functions are ‘capacities that enable a person to engage successfully in independent, purposeful, self-serving behaviours’. She suggests that they may be conceptualized as having four components: (1) volition; (2) planning; (3) purposeful behaviour; and (4) effective performance, with each involving a distinctive set of activity-related behaviours. Lezak [36] distinguishes between cognitive abilities, which may be seen as domain specific, and executive skills, which act more globally and impact upon all aspects of behaviour. She argues that the integrity of these functions is necessary for appropriate, socially responsible conduct. Stuss [37] provides an integrated model of executive function, including a set of associated skills which allow the individual to develop goals, hold these goals in active memory, monitor performance, and control for interference in order to achieve these goals. Other authors include focused and sustained attention, generation and implementation of strategies, monitoring, and utilization of feedback under the umbrella term ‘executive functions’ [6, 25, 38, 39]. Shallice [40] and Walsh [41] fine-tune the concept further, arguing that executive functions are not in maximal usage for the execution of routine, well-learned behaviours, but are specially activated in novel or unfamiliar circumstances, where no previously established routines for responding exist.

Such definitions are commonly operationalized, for the purpose of neuropsychological assessment, to include planning, problem solving, abstract thinking, concept formation, self-monitoring, and mental flexibility [5, 42, 43]. Thus, ‘executive dysfunction’ may be reflected in test performances by poor planning and

organization, difficulties with generating and implementing strategies for problem-solving, perseveration, inability to correct errors of use feedback, and rigid or concrete thought processes [6, 41]. Qualitative features of executive dysfunction may include poor self-control, impulsivity, erratic careless responses, poor initiation, and inflexibility [36]. While these behaviours are commonly considered to be ‘deviant’ in adults, a similar interpretation may not always be warranted for children. Before determining whether such behaviours are indicative of executive dysfunction in children, developmental expectations need to be considered.

### Frontal lobe function/executive function?

The terms ‘executive function’ and ‘frontal lobe function’ have developed in parallel in the neuropsychological literature. Furthermore, they are often employed interchangeably, most likely due to observations of executive dysfunction in patients with frontal lobe damage [5, 41, 44–47]. However, the practice of localizing executive functions to the frontal lobes has been questioned with similar patterns of behavioural disturbance identified in patients where pathology is not restricted to these regions [38, 46, 48]. It may be argued that, while the frontal regions play a vital role in their mediation, the integrity of the entire brain is necessary for intact executive function. Alternatively, executive function may be interpreted purely as a psychological concept, relating to a set of observable behaviours, without any reference to possible anatomical underpinnings [37]. It is this latter psychological perspective which is emphasized in the present discussion.

There is a growing body of developmental research which describes a sequential improvement of performance on executive tasks through childhood, coinciding with growth spurts in frontal lobe development [18, 47, 49–51]. Such findings have been interpreted as providing support for the mediation of executive functions via anterior cerebral regions, and the prefrontal cortex specifically. While this may be the case, these cerebral regions are dependent upon other cerebral areas for input, making it difficult to isolate frontal functions from those of other developing cerebral areas. It may be that, as for research based on brain-damaged populations, the maturation of executive function reflects the integrity of cerebral development throughout the brain. Similarly, from a cognitive perspective, the development of executive functions may be inextricably associated with the gradual emergence of other cognitive capacities, with ample evidence for associated gradual increments in skills such as language [5, 52, 53], attention [54, 55],

speed of processing [56, 57], and memory capacity [58–61].

#### PHYSIOLOGICAL DEVELOPMENT UNDERPINNING EXECUTIVE FUNCTIONS

Knowledge of central nervous system (CNS) maturation and related cognitive development is gradually increasing, with advances in technical methodologies. It is now well established that cerebral development is ongoing during childhood. Brain weight increases from ~400 grams at birth to 1500 grams at maturity in early adulthood, although most maturation is thought to occur during the first decade of life [62]. While prenatal development is primarily concerned with structural formation, post-natal development is associated with elaboration of the CNS [63, 64]. In particular, processes such as dendritic arborisation, myelination, and synaptogenesis have all been reported to progress during early childhood, in a largely hierarchical manner, with anterior regions the last to reach maturity [65–68]. Initially, developmental neuropsychology was influenced by a view that the frontal lobes were ‘functionally silent’ in infancy and early childhood, with executive skills not measurable until the second decade of life [69]. A number of neuropsychological studies now refute this view, documenting frontal lobe activity even in infancy. For example, Chugani *et al.* [70] measured local cerebral metabolic rates of glucose in infants and young children, and found evidence of frontal metabolic changes in infants as young as 6 months of age. Similarly, Bell and Fox [49] have documented changes in scalp recorded electroencephalograms (EEGs) in frontal regions during the first year of life, relating these to improvements in behavioural performance. Many workers now support the notion that these biological growth markers may explain some of the age-related variation in ‘non-biological’ development such as cognition [50, 51, 62].

It is generally agreed that the frontal lobes are hierarchically organized, with all areas receiving input from posterior and subcortical cerebral regions. In particular, the prefrontal cortex, thought to be the primary mediator of executive functions, receives input from all areas of the frontal and posterior neocortex [65, 71]. Thus sensory and perceptual data are processed by the frontal lobes, where actions are organized and executed. This pattern of connectivity suggests that, while prefrontal regions may ‘orchestrate’ behaviour, they are also dependent on all other cerebral areas for input, with efficient functioning reliant upon the quality of information received from other cerebral regions.

Development of the frontal lobes also appears to follow a hierarchical pattern, consistent with processes such as myelination, which progress through a number of stages, from primary and sensory areas to association areas and finally frontal regions [65, 72, 73]. Vestibular and spinal tracts, related to basic postural control, are myelinated as early as at term. Midbrain cortical—visual pathways show evidence of myelination by 2–3 months of age, and descending lateral cortical tracts by the end of the first year of life, when fine motor control appears [74]. Cerebellar–cerebral connections are not myelinated until the second year of life, with reticular tracts still maturing at school age and tracts connecting specific and associative areas showing ongoing development into adulthood [8].

Results from the EEG studies also indicate CNS changes through childhood. Thatcher [50, 51] has described a number of growth periods, the first between birth and 2 years, another from 7 to 9 years with a final spurt in late adolescence (16–19 years). These growth spurts are thought to be associated with increases in either the number or strength of cortical synaptic connections. Consistent with Thatcher’s findings, Hudspeth and Pribram [72] document EEG data which indicate maturational peaks and plateaux continuing through childhood and into adolescence. They report a differential progression of regional cerebral development, with simultaneous completion of maturation throughout the CNS. In frontal regions, they describe accelerated development from 7–10 years, which then terminates synchronously with development of other brain regions. Age-related pre-frontal ribonucleic acid and development, through to ~9 years of age [75], and changes in pattern of metabolic activity and levels of various enzymes [76], also support a hierarchical model of frontal lobe development.

It may be that not all CNS development conforms to this hierarchical model. An alternative argument suggests that, while measurable parameters behave in a spurt-like fashion, underlying development is essentially continuous [37]. For example, synaptogenesis appears to be simultaneous in multiple areas and layers of the cortex [77], with neurotransmitter receptors throughout the brain reported to mature at the same time [78]. Such findings suggest concurrent development, where posterior and anterior structures develop along approximately the same time-table. Not all research supports this view of simultaneous maturation, even for neurochemical markers, with some arguing that this pattern, while present in non-human species, may not hold for humans [79]. Clearly, there is a need for further research to delineate these complex issues.

To summarize, these various lines of inquiry suggest that cerebral development is likely to be primarily hierarchical, both within and across cerebral regions, with frontal areas reaching maturity relatively late, in early puberty. Further, there is substantial support for a step-wise model of development, rather than a gradual progression, with convergent evidence that growth spurts occur in early infancy, again around 7–10 years of age, with a final spurt during adolescence.

#### PSYCHOLOGICAL DEVELOPMENT

A number of parallels may be drawn between patterns of cognitive and biological development. Numerous studies have now reported that executive functions progress in a stage-like manner, consistent with growth spurts identified within the CNS. Historically, cognitive models have strongly supported such a hierarchical view of development. In particular, Piaget's theory of cognitive development [80], while providing no reference to possible neural substrates, is highly compatible with current understandings of cerebral development. Piaget describes four sequential cognitive stages including sensorimotor (birth–2 years), pre-operational (2–7 years), concrete operational (7–9 years) and formal operational (early adolescence). While more contemporary developmental psychologists may dispute some of the principles of Piagetian theory [81], it is worthy of note that the hypothesized timing of transition between Piaget's cognitive stages coincide quite closely with growth spurts identified within the CNS.

Some researchers have employed Piagetian techniques to investigate early cognitive development and its relationship with cerebral development. In a series of investigations, Diamond and Goldman-Rakic [14, 15, 82, 83] employed the classic Piagetian object permanence paradigm, as well as an object retrieval task, to investigate goal-directed behaviours in infants. To establish links with possible cerebral substrates, they compared performances of human infants to those of both adult and infant rhesus monkeys with focal lesions. They found that infants as young as 12 months were able to exhibit object permanence, as were monkeys with parietal lesions. By contrast, older rhesus monkeys with frontal lesions were unable to complete these tasks successfully. Similarly, for objective retrieval tasks, human infants showed age-related improvements in planning and self-control, mirroring those of normal infant monkeys. Monkeys with frontal lesions were unable to master these tasks. These results have been interpreted as evidence that frontally mediated, goal-directed, planful behaviour is present as early as 12 months of age in

human infants. However, such findings need to be interpreted cautiously, with the understanding that cross-species distinctions are problematic, as are comparisons between the process of normal development and the effects of acquired brain pathology.

Other studies have attempted to map developmental trajectories for aspects of executive function in older children. Passler *et al.* [19] report one of the earliest studies employing this methodology. Using measures of executive functioning adapted from adult neuropsychology, they have shown that children as young as 6 years are able to exhibit strategic and planful behaviour. Their results suggest a stage-like progression of executive skills, with mastery still not achieved by the age of 12. In a follow-up study, Becker *et al.* [84] report a similar pattern of results, once again noting a failure to achieve adult levels on executive measures by the age of 12. Using the Wisconsin Card Sorting Test as their measure of executive function, Chelune and Baer [85] report improvements in performance between 6 and 10 years, with adult performance achieved by 12 years. Further, they observed that 6-year-old children demonstrated difficulties similar to those seen in adults with focal frontal lesions!

More recently, a number of researchers have employed a 'battery model', administering a range of tests purported to measure executive functions. Such an approach, while providing developmental trajectories for each of these tasks, also enables investigation of possible relationships among measures, thus addressing the crucial issue of test validity. Levin *et al.* [18] evaluated 52 normal children and adolescents in three age bands, 7–8 years, 9–12 years, and 13–15 years. They administered a range of 'executive' measures and identified developmental gains across all tasks, reflecting progress in concept formation, mental flexibility, planning and problem solving through childhood. Although their sample size was relatively small, they performed principal components analysis on their data, identifying three factors which they argued were associated with specific aspects of executive functions, as well as unique developmental patterns. Factor 1 tapped semantic association/concept formation and Factor 3 was primarily concerned with problem solving, with each of these abilities showing a gradual progression over the three age ranges. Factor 2 was related to impulse control and mental flexibility, and these behaviours were noted to reach adult levels by the age of 12.

Welsh *et al.* [20] also studied a sample of normal children, aged 3–12 years, using a series of measures of executive function. Consistent with previous findings, their results provide evidence for stage-like develop-



ment, with some components of executive function maturing earlier than others, thus supporting a multi-dimensional notion of executive function. They argue for three distinct developmental stages, the first commencing around age 6, a second about age 10, and final spurt in early adolescence. They suggest that the ability to resist distraction is the first skill to mature, at around age 6. Organized search, hypothesis testing, and impulse control appear to reach adult levels at around age 10, with verbal fluency, motor sequencing and planning skills not at adult levels at age 12. They further investigated possible associations among their measures, and identified three discrete factors: Factor 1, described as representing speeded responding; Factor 2, an indicator of hypothesis testing and impulse control; and Factor 3, reflecting planning ability.

Anderson *et al.* [56] employed a similar methodology, with the primary aim of providing normative data for a number of commonly used clinical tests, purported to measure executive functions. Their sample included 376 children aged 7–13 years, selected to be representative of the general population with respect to social factors and gender. In line with the work of Levin [39] and Welsh *et al.* [20], results suggest continued significant improvements in test performance through middle childhood, indicating ongoing gains in executive functions. An examination of correlations among these executive measures, outlined in table 1, suggests relatively strong associations between tasks tapping problem solving and planning ability. By contrast, only a weak relationship was found between these measures and tests of concept formation, again suggesting that executive function is likely to incorporate a range of sub-skills.

The parallels between the developmental trajectories described in these studies, and those reported in neurophysiological research are difficult to ignore. However, the situation is complex. While all measures employed in these studies provide evidence that executive function, rather than being a unitary concept, may be divided into a number of specific categories, exhibiting different developmental trajectories, and maturing at differential rates. These varying patterns may reflect mediation by

specific areas within the frontal lobes, also maturing at different rates. From a biological perspective, the possible influence of ongoing development of other cerebral areas also needs to be considered. For example, the quality of neural transmission from posterior and sub-cortical regions may impact upon the functioning of the frontal and prefrontal cortices which have rich connections with all cerebral areas. Maturation of these posterior regions may then enhance the functioning of anterior cerebral areas. From a cognitive viewpoint, similar considerations are important. The gradual emergence of greater memory capacity, more advanced language skills, and faster speed of processing will all enhance the child's capacity to function on measures of executive functioning. While tentative links have been established, there is still a way to go to define relationships between development of executive skills and frontal structures, or isolate cognitive gains specific to executive functions, divorced from lower-order cognitive capacities. Regardless, this convergence of evidence emphasizes the importance of close communication among disciplines involved in improving one's understanding of brain-behaviour relationships in the developing child.

### Assessment of executive function

The assessment of executive function is a topic which has received considerable attention in adult neuropsychology. Early, localizationist models designated tests such as the Wisconsin Card Sorting Test [86, 87] or the Complex Figure of Rey [88] as indicators of frontal lobe or executive function, based on poor performance by patients with frontal lobe pathology. Contemporary neuropsychological theory would argue that such an approach is too simplistic. The efficiency of executive skills, and also of frontal lobe functioning, is necessarily mediated by lower-order processes. It is important then to view executive functions in the context of these other functions, and to evaluate carefully assessment tools, considering the specific components of executive function they measure. In many cases this may

**Table 1** Correlations among tests of executive function from Anderson *et al.* [56]

Measure	Trails A	Trails B	CFR: copy	CFR: organization	TOL: correct
COWAT	0.20	0.06	-0.11	-0.11	0.40**
Trails A		0.37**	-0.22	-0.21	-0.28**
Trails B			-0.30**	-0.32**	-0.35**
CFR: copy				0.48**	0.37**
CFR: organization					0.31**

\*\* $p < 0.001$ .

COWAT: Controlled Oral Word Association Test; CFR: Complex Figure of Rey; TOL: Tower of London.

be difficult to tease out, and often the ‘endpoint score’ is not particularly sensitive to executive functions, as it commonly summarizes performance on a variety of different cognitive components. Assessment and isolation of executive deficits may rely on administration of multiple tests, each focusing on specific aspects of function, and sequentially ruling out skills as deficient.

A number of authors comment on the problems of assessing executive function. In addition to being accessible only through tests which include lower-order functions, deficits in these skills are often difficult to detect within the clinical context, using standardized assessment tools. Typically, the neuropsychological assessment is conducted in a well-structured clinic setting, where the examiner plans and initiates the majority of the evaluation. Lezak [36] emphasizes these problems, noting that deficits in executive function are rarely reflected in test scores, as the majority of assessment tools are also highly structured. Parker and Crawford [45], in a review of assessment procedures, claimed to measure executive functions, found ‘disappointingly few sensitive and reliable tests which the clinical neuropsychologist can depend upon’ (p. 286). They go further to argue that, when evaluating executive function, the clinician is often forced to rely on qualitative observations and informed judgement, as well as reports from family and social contexts.

### Child assessment

Whilst some researchers [69] have suggested that executive functions do not emerge until early adolescence, recent studies provide compelling evidence that these skills are assessable even in the preschool child, provided appropriate measures are employed. Given the vulnerability of executive functions to early brain damage [25], the importance of intact executive function to ongoing cognitive development [22], and to the success of treatment and rehabilitation programmes, there is a need to devise valid and well-standardized assessment measures, specifically designed for children, and based on current understandings of the nature of both cerebral and cognitive development through childhood.

There are many papers and even entire tests devoted to neuropsychological assessment of children. A perusal of chapter topics and subject indexes suggests that executive function is frequently neglected [24, 34, 89–91]. Further, most available or commonly utilized tests purported to measure executive function in children have been developed for use with adults, with their inclusion in test protocols for children based on the assumption that they will detect similarly localized dys-

function in both groups. Such assumptions remain untested, suggesting that caution is required when providing localizing interpretations of test performance [92]. At a more practical level, these tests may be of little interest or relevance to young children, and frequently lack normative information with respect to developmental expectations. Todd *et al.* [93] stressed the importance of establishing expected normal levels of executive function in children and adolescents, when they compared the results of head-injured and healthy adolescents on tests of planning ability. They found that, while deficiencies in planning were evident in their head-injured sample, this was also true for healthy adolescents. The clinical implications of such findings are of significance, when it may be that such deficits are inaccurately interpreted by clinicians as injury-related consequences, rather than developmentally appropriate levels of skill.

To establish valid measures of executive function, which overcome the problems described above, it is essential to evaluate their capacity to measure the primary skills included in definitions of the concept: planning, problem solving, abstract thinking, concept formation, self-monitoring, and mental flexibility [5, 42, 43, 47]. Walsh [41] argues that, in order to tap these skills effectively, tasks require several characteristics: novelty, complexity, and the need to integrate information. In support of Walsh’s ‘formula’ for assessment of executive functions, Shallice [40] states that routinized tasks can be performed almost automatically, without reference to executive skills. However, novel or complex tasks require the individual to develop new schema, formulate new strategies, and monitor their effectiveness, thus activating executive skills.

The most widely accepted measures of executive function have been designed or borrowed from cognitive psychology, with these basic requirements in mind. One of the greatest problems, however, is the lack of consensus as to which of these measures is a valid indicator of executive function. A review of a number of recent studies which have been designed to assess executive skills shows that individual researchers vary in their understanding of which tests provide the best measures of executive functions. Table 2 lists the tests included in a number of recent child-based studies, each of which employed multiple measures of executive functions. Clearly, some measures are more universally accepted. For example, the Controlled Oral Word Association Test (COWAT) [52] was employed in half of the studies reviewed, and was generally described as a measure of abstraction or concept formation. Similarly, the Wisconsin Card

**Table 2** Tests purported to measure executive functions in child-based studies

Study	WCST	TOL/ TOH	Go/ no go	COWAT	CFR	Porteus mazes	Category test	Trail Making test	MFFT	TOVA/ CPT	Twenty questions	Stroop test
[84]	—	—	*	—	—	—	—	—	—	—	—	—
[33]	—	—	—	—	—	—	*	*	—	—	—	*
[39]	—	—	—	*	*	*	—	—	—	—	*	—
[18]	*	*	*	*	—	—	—	—	—	—	*	—
[20]	*	*	—	*	—	—	—	—	*	—	—	—
[94]	—	*	—	*	—	—	—	—	—	—	—	—
[95]	*	—	—	*	*	—	—	—	—	*	—	*
[96]	*	—	—	*	*	*	—	*	—	*	—	*
[56]	—	*	—	*	*	—	—	*	—	—	—	—
[97]	—	—	—	*	—	—	—	—	*	—	*	—
[98]	—	*	—	—	*	—	—	—	—	—	*	—
[99]	*	—	—	*	*	—	—	—	—	*	—	—

WCST: Wisconsin Card Sorting Test; TOL/TOH: Tower of London/Tower of Hanoi; COWAT: Controlled Oral Word Association Test; CFR: Complex Figure of Rey; MFFT: Matching Familiar Figures Test; TOVA: Test of Visual Attention; CPT: Continuous Performance Test.

Sorting Test (WCST) [87], variations of the Tower of London (TOL) [2], the Complex Figure of Rey (CFR) [88], and Trail Making Test [100] were also commonly included in batteries purported to tap executive skills in children. Details of each of these tests are provided in the following discussion.

**METHODS OF ASSESSMENT**

*Standardized measures*

There are a range of child-based battery-style psychometric tests available; however, they commonly pay scant attention to the measurement of executive function (e.g. Halstead Reitan Neuropsychological Test Battery for Children [101]; Reitan–Indiana Neuropsychological Test Battery for Younger Children [102]; Luria–Nebraska Neuropsychological Battery [103]). For the Wechsler scales (Wechsler Intelligence Scale for Children—III [104]; Wechsler Preschool and Primary Scale of Intelligence—Revised [105]), there is a similar lack of focus on measures of executive function, although, from adult samples, it has been argued that individual subtests may measure aspects of executive function. For example,

Block Design [41], Picture Arrangement [45] and Similarities have been earmarked as measures of planning, problem solving, and abstraction, respectively. Even more recently developed, process-based assessment batteries (e.g. McCarthy Scales of Children’s Abilities [106]; Kaugman Ability Battery for Children [107]) include no specific analysis of these skills. Lezak [36] argues that, in general, these tests may be too highly structured to tap executive functions accurately, which may be best identified on the basis of careful observation of qualitative features of test performance and from information provided by family and educational sources with respect to day-to-day functioning.

*Individual test procedures*

One method of rationalizing the current relatively arbitrary use of individual tests purported to measure executive function is to categorize each test (or test component) according to the skills they are thought to measure. Table 3 provides one possible example, listing commonly used measures, according to the primary aspects of executive function involved in each task.

**Table 3** Tests purported to tap specific aspects of executive function

Executive function	Test	Standard administration	Normative data
Planning and organization	Complex Figure of Rey	Yes	For 6 years and older
	Porteus Mazes	Yes	No
Problem solving	Tower of London	Several versions	For 6 years and older
	Tower of Hanoi	No	No
Abstraction/concept formation	Controlled Oral Word Association	Yes	For 6 years and older
	Twenty Questions	Several versions in use	No
Mental flexibility	Wisconsin Card Sorting Test	Yes	Yes
	Trail Making Test	Yes	For 6 years and older
	Stroop Test	Yes	No

Dev Neurorehabil Downloaded from informahealthcare.com by Yeshiva University on 03/03/13  
For personal use only.

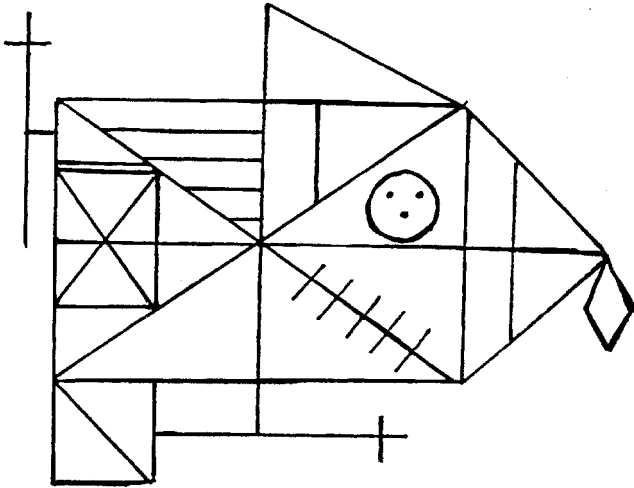


Figure 1 The Complex Figure of Rey.

What follows is a brief description of some of these measures, with discussion restricted to those tests for which there are standardized administration procedures and adequate developmental norms.

#### PLANNING ABILITY

*The Complex Figure of Rey* (CFR) [88] requires the child to copy a complex geometric design, illustrated in figure 1, and then redraw it from memory following a 3-minute delay. It is generally described as a test of planning and organization skills; however, other lower-order skills are also important to efficient performance. These skills include visual perception, visuo-motor skills, fine motor skills, and visual memory. All might contribute to overall performance. Scores have been devised for copy accuracy, recall, and organizational efficiency, with a number of references providing scoring protocols and developmental norms [56, 108, 109]. Accuracy, recall, and organizational scores have been shown to improve through childhood, as illustrated in figure 2 [56], and figure 3 provides examples of copies produced by normal children of varying ages, emphasizing individual differences in performance, even within age bands.

With respect to executive functions, one of the greatest breakthroughs has been the development of organizational measures, rather than simple accuracy and recall indices. Waber and Holmes [109] devised one of the earliest versions of organizational scoring, employing a 5-point scale to rate productions in terms of outcome. Because of perceived limitations in this method, Anderson *et al.* [110] have developed an alternative model which specifically addresses the ‘process’ em-

ployed in copying the figure. This procedure is based on scoring the copy as the child is drawing, noting the order in which component parts are produced, and whether the child has employed a logical, planful approach, or a more piecemeal random method. As with other organizational scores, there is a gradual improvement in organizational level with age. Further, and perhaps not surprisingly, there is a close relationship between quality of organization of copy and quality of recall, emphasizing the importance of intact planning for day-to-day functioning.

A number of clinical studies have included the CFR in their test protocols, with deficient performances observed in a range of patient populations, including learning-disabled children [111], head-injured children [98], post-meningitic children [112], and cranially irradiated children [31, 113]. However, while these findings provide support that the CFR is a useful measure of planning ability in children with both developmental and acquired CNS disorders, there is no evidence as yet that performance on the task is specifically related to frontal lobe dysfunction.

*Maze Tasks* (Porteus Mazes [114]; Mazes, Wechsler Intelligence Scale for Children—III [104]; Wechsler Preschool and Primary Scale of Intelligence—Revised [105]) have also been employed to assess planning and foresight in children. Specific maze formats and administration procedures vary across tests, but each provide some developmental data, enabling interpretation of performance with respect to age expectations. As for the CFR, the evaluation of executive functions via maze tasks is confounded by other skills required for efficient performance, including fine motor skills, visual perception, and speed of response.

#### PROBLEM SOLVING

*The Tower of London* (TOL) [2] measures problem-solving aspects of executive functioning. The task involves 12 items, with each requiring children to rearrange three coloured balls to a configuration presented on a stimulus card, and in a prescribed number of moves. Where a child fails to complete an item correctly, the balls are replaced in their original configuration, and the child has the opportunity to try again. Scores include number of items correct, number of failed attempts, planning time, and time taken to complete each item. An example of one of the items in the test is shown in figure 4.

Shallice [2] argues that the TOL involves minimal contribution of lower-order skills, such as perceptual and motor abilities, short-term memory, and sustained



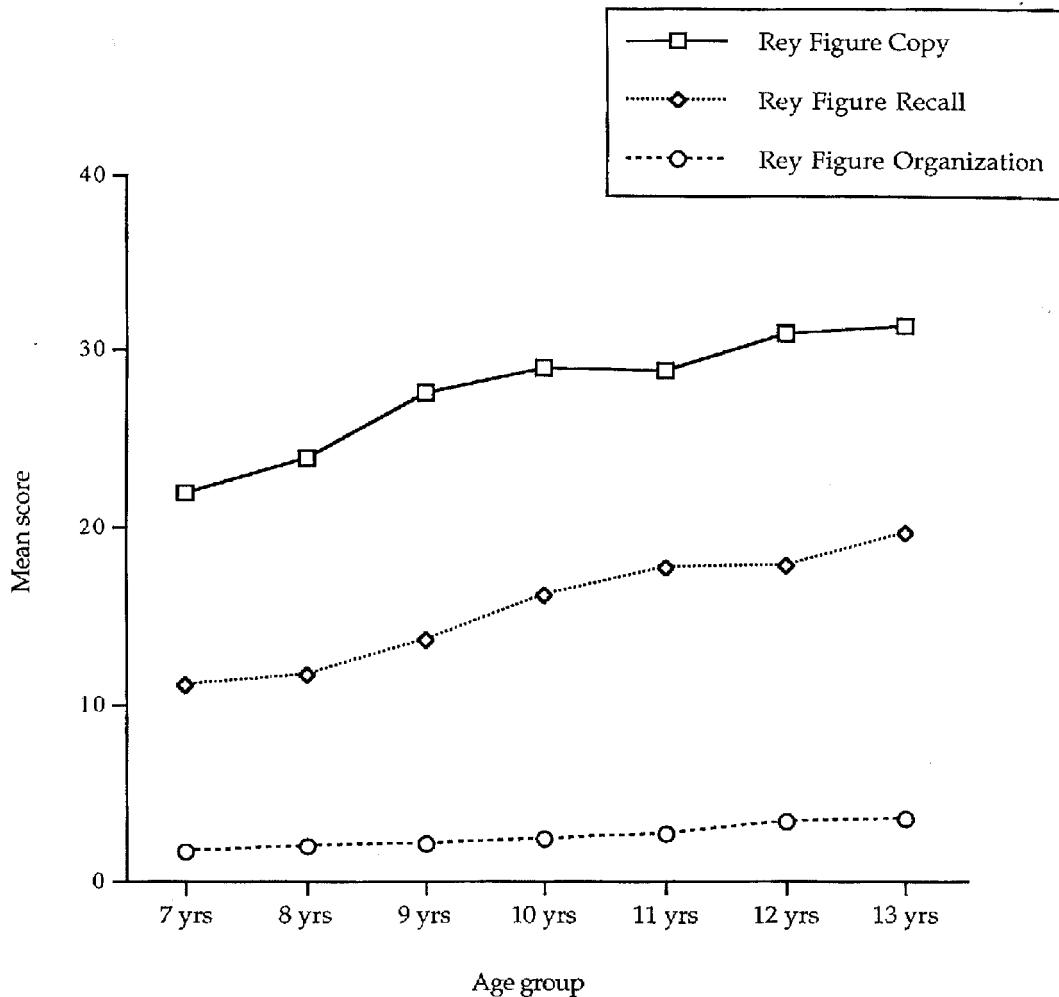


Figure 2 Development trajectories for the Complex Figure of Rey.

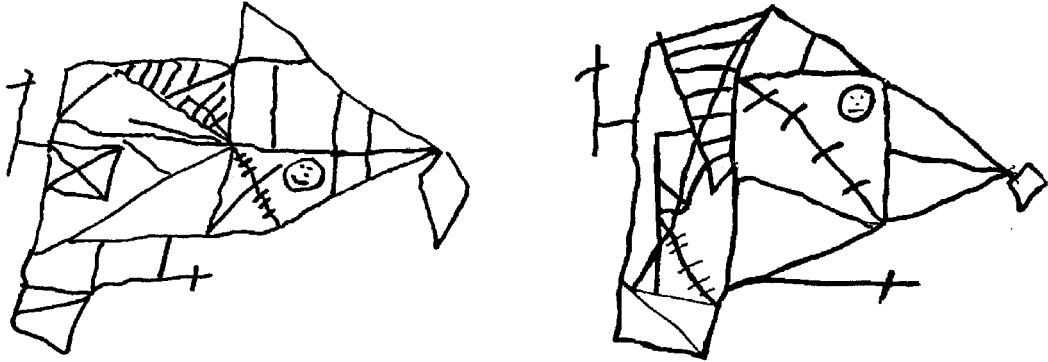
attention, based on low associations noted between the TOL and other cognitive measures. If this is the case, then the TOL may overcome some of the difficulties of other executive tests. In addition, the test may be utilized to tap a number of components of executive function, including planning speed, impulsivity, and flexibility. While originally designed for use with adults, the TOL has a number of features that allow it to be readily applicable to pediatric populations. First, the task is generally challenging and attractive to children of varying ages. In addition it incorporates a range of difficulty levels, so that even young children are able to complete initial items.

Despite its potential advantages, clinical use of the TOL has been restricted, owing to the lack of standardized administration protocols and normative data. However, two recently published studies provide alternative testing protocols, and both include developmen-

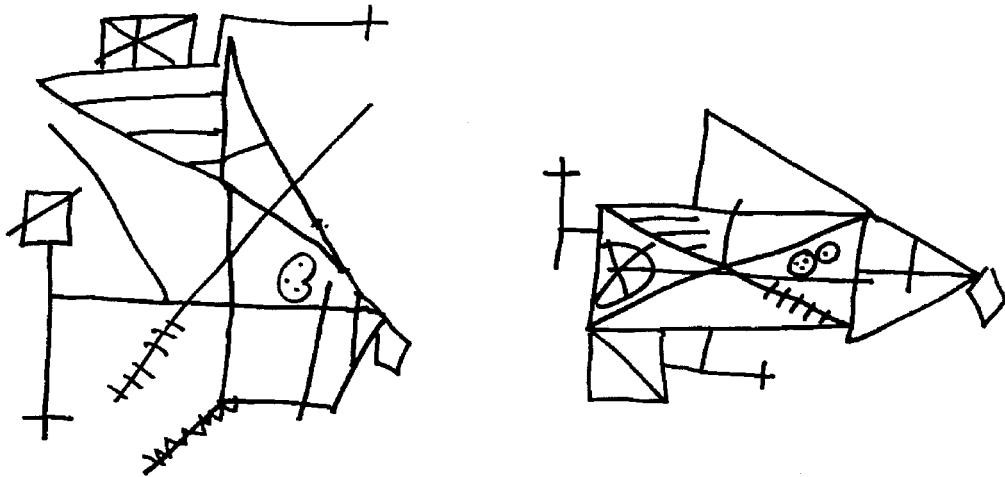
tal data [9, 115]. These findings describe continued improvements in test performance through childhood, with some evidence for developmental spurts at around age 8–9 and again around age 10–11. Developmental trajectories for the TOL from the Anderson *et al.* [9] sample are shown in figure 5. Finally, the TOL is one of the few executive measures which has been directly related to frontal lobe damage in children. Levin *et al.* [116] found deficient performance on the TOL to be associated with head injury in children. In addition, they identified a specific contribution of frontal lobe damage to performance levels, and in particular to the frequency of rule-breaking behaviours.

The Tower of Hanoi (TOH) [16, 61] is a similar disk-transfer task, requiring a child to solve a problem to which the solution is not immediately apparent, but requires the formulation of a new plan. Similar to the TOL, the child is directed to plan a sequence of legal

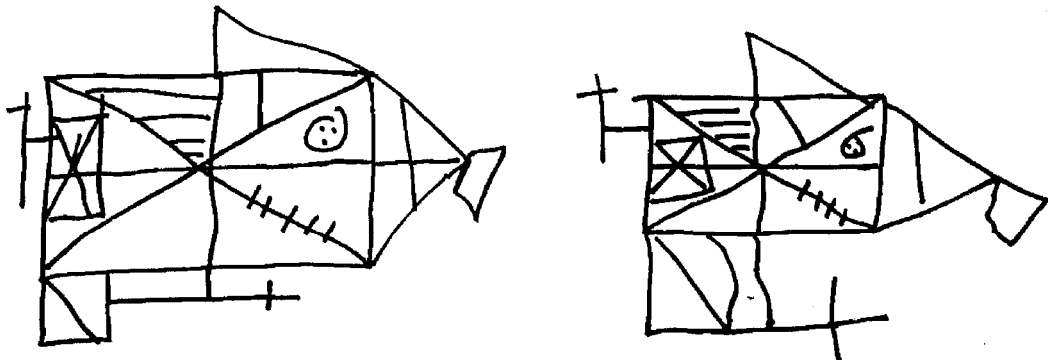
(a)



(b)



(c)



**Figure 3** Examples of normal children's productions of the Complex Figure of Rey. (a) 6-year-old children, (b) 8-year-old children, and (c) 12-year-old children.

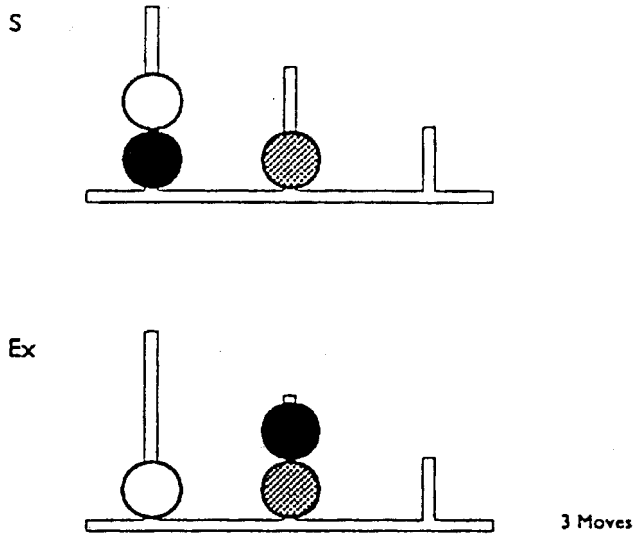


Figure 4 The Tower of London.

moves in order to transfer the initial configuration into a target configuration, using as few moves as possible. There are several versions of this task; however, no uniform administration procedures or normative data are available, limiting its use in child assessment.

ABSTRACTION AND CONCEPT FORMATION

*Controlled Oral Word Association Test (COWAT)* [52] is a measure of verbal fluency and the ability to generate words based on a set of arbitrary rules. Children are asked to generate words beginning with a certain letter in a 1-minute period. These words must be selected with consideration of two rules: (1) No words must begin with a capital letter, and (2) each word must be used only once. Scores include total number of words generated over three letter trials, number of words repeated, and number of rule breaks. While some normative data

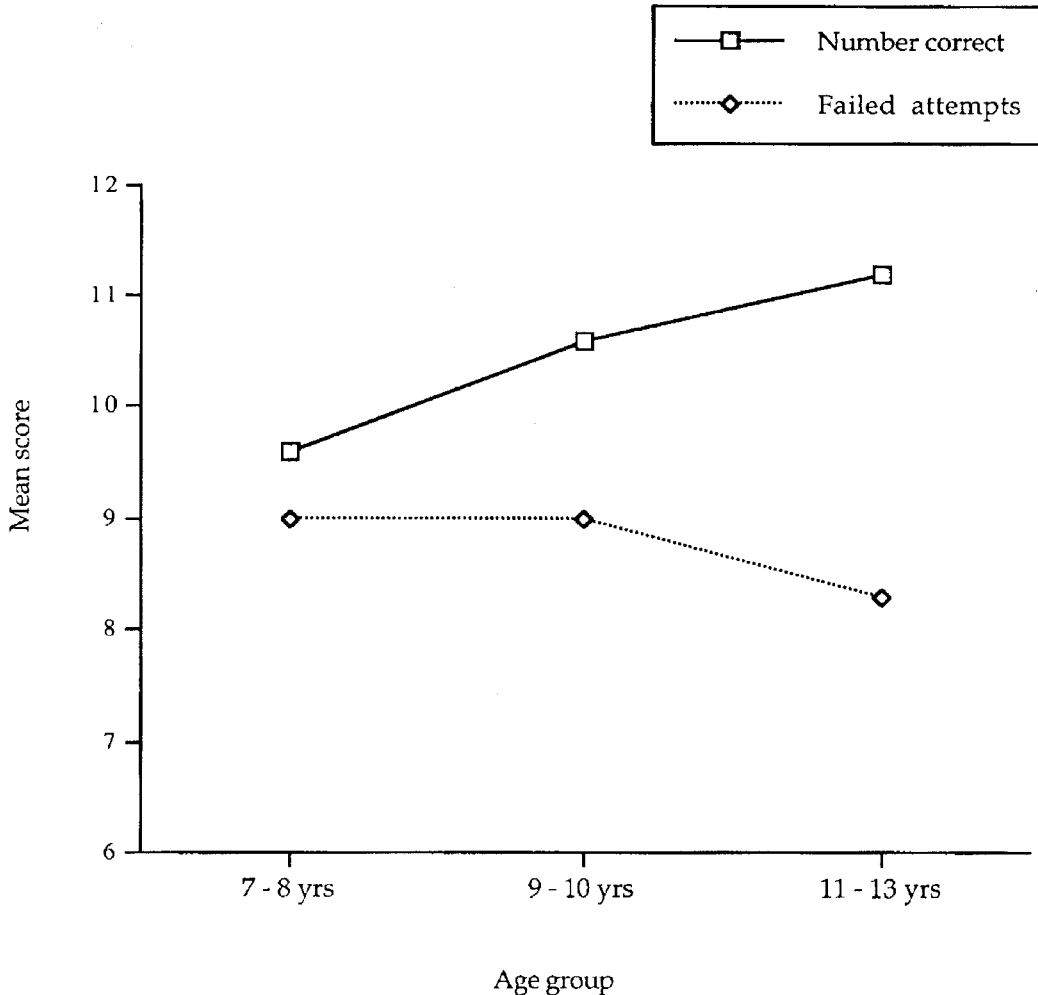


Figure 5 Developmental trajectories for the Tower of London.

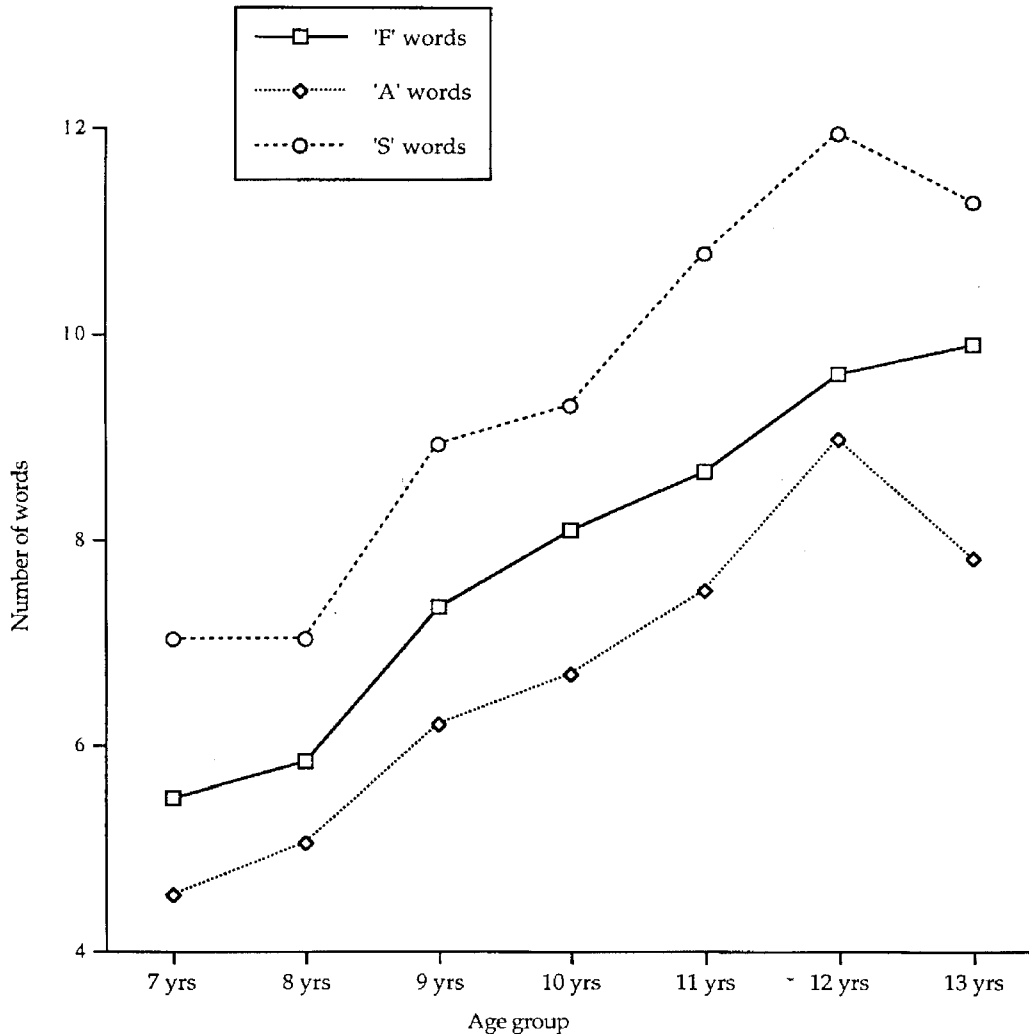


Figure 6 Developmental trajectories for the Controlled Oral Word Association Test.

were included in the original description of this task, subsequent studies have provided more substantial normative data [53, 56], making it a more useful clinical tool. Changes in performances with age, as reported by Anderson *et al.* [56], are given in figure 6.

The COWAT is one of the most commonly used measures of executive function in pediatric research. Deficient performances on this test have been described following pediatric head injury [117], and childhood meningitis [118], as well as for children with Tourette syndrome [99], although not for focal frontal involvement. Interpretation of the COWAT is problematic within the pediatric population. The lower-order skills required for the task include phonological awareness, which is not well developed in younger children. It is not uncommon for children to provide words such as

elephant or uncle when asked to generate words commencing with the letter A, and concept of 'capital letters' may not be adequately established for some age groups. Thus, the interpretation of this measure as one of executive function needs to be made cautiously, with such developmental considerations taken into account. To emphasize this point, a number of studies of reading-disabled children, who are thought to experience specific phonological deficits, have reported deficits on the COWAT [119, 120].

*Twenty Questions* [121] is a test of a child's ability to utilize feedback and re-evaluate goals to reach a correct response. The child is shown a card with 42 hand-drawn pictures which may be grouped into various categories (for example, animals, plants, utensils). The child is asked to identify which picture the examiner has in



mind, and is able to ask 20 questions to do so. Only questions necessitating a yes or no response are allowed. Scoring may include time taken to detect target and total questions asked. Unfortunately, developmental norms are not available for this task, and administration protocols vary considerably. The task can, however, provide qualitative information regarding the child's concept-formation strategies, by dividing questions into specific categories. For example, hypothesis-seeking approaches such as 'is it the pot plant?' are inefficient as they only eliminate one of the pictures. By contrast, constraint-seeking questions, such as 'is it alive', will eliminate several possibilities, and thus are more efficient. Levin *et al.* [18] utilized this measure in their study of executive function, and found that older children needed to ask fewer questions to identify target pictures, suggesting better capacity to form concepts and utilize feedback. Garth *et al.* [98] employed the Twenty Questions test with children who had sustained frontal lobe damage. They found no differences between a clinical group and controls on summary measures of total questions asked and time to completion. Using a qualitative analysis of the nature of questions posed, they identified less efficient performance by children with frontal lesions. This group exhibited higher frequencies in the hypothesis-seeking and pseudo-constraint-seeking categories and lower frequencies of the more effective constraint-seeking questions. These findings provide some initial support for a link between performance on Twenty Questions and specific frontal lobe involvement.

#### MENTAL FLEXIBILITY

*Wisconsin Card Sorting Test (WCST)* [86, 87] is also commonly considered to tap aspects of executive skill, in particular the ability to form abstract concepts and shift and maintain set. The test begins with the child being presented with four stimulus cards, the first showing a red triangle, the second two green stars, the third three yellow crosses, and the fourth four blue circles. The child is then given 128 response cards, each with configurations similar to those appearing on the stimulus cards, but each varying with respect to colour, number, and geometric shape. The child is directed to match each card to one of the four stimulus cards and informed that they will be told whether or not each response is correct. Initially, the correct sorting criteria is colour, and once the child has achieved 10 correct responses, the examiner shifts the target dimension to form. Subjects are not informed directly of the particular dimensions for sorting, but must determine this on the basis of feedback

from the examiner. The test continues until six correct categories have been achieved, or until all cards are sorted. Scores derived from the test include number of categories achieved, total number of errors, and percentage of perseverative errors.

Chelune and Baer [85] provide normative data for children aged between 6–12 years on the WCST, indicating improvements in performance throughout childhood, reflecting increasing abilities in concept formation and ability to shift a set flexibly. The test has also been employed with a number of clinical samples, suggesting that the task is sensitive to the generalized impact of head injury [117, 122], cranial irradiation [118], as well as developmental disorders including Tourette syndrome [99] and attention deficit hyperactivity disorder [123, 124]. Currently, there is no evidence that the test is able specifically to differentiate frontal lobe dysfunction in children.

*Trail Making Test* [100] measures speed of visual search, attention, mental flexibility, and visuo-motor function. The children's version of the task has two levels. Trails A consists of 15 circled numbers randomly positioned on a page. Children are required to connect the numbers in order by making pencil lines. This level provides a baseline indication of speed of visual search and visuo-motor functioning. The second level, Trails B, requires children to connect 15 numbers and letters in alternating order. This level incorporates an additional component of shift or mental flexibility. Completion time and number of errors are recorded for each level. There are a handful of clinical studies which have employed this task and identified reduced performances associated with developmental disorders and generalized cerebral dysfunction [96, 117, 120, 122]. Age-related performance patterns for normal children are illustrated in figure 7.

*Stroop Test* [125] is a popular measure of cognitive flexibility, tapping a child's ability to shift a cognitive set to conform with changing demands, and suppress a habitual response in favour of a more novel one. The task includes three subtests: First, the 'Word' condition, where the child reads out a list of colour names printed in black type; secondly, the 'Colour' condition where the child must name the colour of groups of dots; and thirdly, the 'Colour/Word' task, where colour names are presented in coloured ink, with the two dimensions not always compatible. The requirement is to ignore the verbal content and name the colour in which the words are printed. For each condition, number of errors is recorded, and if a time-limited administration is not employed, time taken to completion may also be scored. There are several published versions of the Stroop

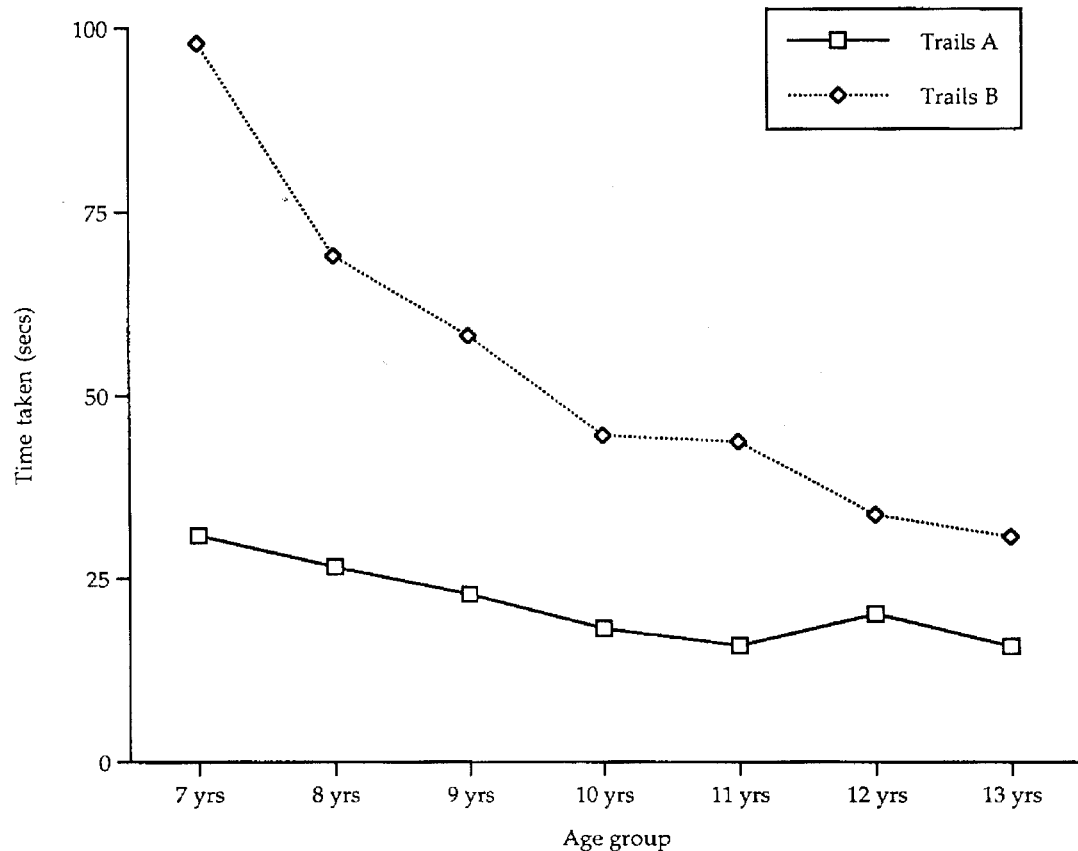


Figure 7 Developmental trajectories for the Trail Making Test.

paradigm, with one designed specifically for children [126]; however, normative data are limited. Despite its popularity, many child-based studies report that this measure is not a good indicator of cerebral dysfunction in general or frontal lobe damage in particular [96, 127].

#### QUALITATIVE APPROACH

While a number of these traditional executive measures employ 'endpoint' or summary scores as indicators of performance, it may be argued that qualitative aspects of performance or 'microanalysis' of individual skills required for adequate performance provides a more accurate picture of executive functioning. In the adult literature, a number of such approaches has been developed, and found to be sensitive to subtle deficits in executive function not apparent on standard measures [128, 129]. Discourse analysis procedures [130, 131], involving fine-grained analysis of language transcripts, have also been employed to investigate subtle differences in conversation patterns between clinical and control

groups, with some success. Outside the neuropsychological literature, several researchers have investigated functional planning skills in children and adolescents [132, 133]. In these studies, information such as the use of strategies, presence of purpose, and assistance gained by aids has been analysed to determine what constitutes good planning. Some researchers have begun to use these approaches in clinical populations [93, 98, 134, 135] to fractionate aspects of executive skills exhibited by children with disabilities. Information obtained from such qualitative analysis of behaviour may be usefully employed in the design of rehabilitation programmes and remedial interventions.

#### Future directions

Several lines of evidence now provide a picture of ongoing development of executive functions throughout childhood. Physiological research describes substantial CNS development continuing at least into early adolescence, with anterior cerebral regions maturing relatively late, and showing a series of growth spurts.

Neuropsychological studies have also identified 'growth spurts' represented by distinct improvements in performance on tests purported to measure executive functions. Further, there is a suggestion that these physiological and cognitive 'spurts' may coincide, with transitions in cognitive development reflecting ongoing cerebral development.

The immaturity of these executive skills through childhood suggests that they may be vulnerable to the impact of early cerebral insult, where emerging and developing abilities have been noted to be particularly at risk [22]. The presence of 'dysexecutive syndrome' early in life may have important implications for ongoing cognitive development. The lack of ability to plan, reason, abstract, and think flexibly may impinge on a child's capacity to learn and benefit from the environment. Clinical observations of brain-injured children support this notion, with recent research also demonstrating the presence of residual executive dysfunction following early cerebral insult. To describe accurately the range of deficits associated with childhood brain insult, and provide appropriate treatment, neuropsychologists need to include measures tapping these skills in their assessment protocols. At present, there are few useful tests of executive function available for childhood populations. Of those currently employed, most have been designed for adult populations. Many lack standardized administration and scoring procedures. Few have adequate developmental norms, precluding accurate interpretation of developmentally appropriate levels of performance. As a consequence, clinicians are often required to base their analysis of executive function on qualitative observation and contextual data.

In order to establish valid and reliable assessment of executive function in children, further research is essential. First, traditional tests need to be normed for children, to provide information with respect to age-appropriate test performances, thus enabling detection of deviant results. Secondly, rather than restricting interpretation to summary scores, maximum information may be obtained from these tests through a micro-analysis of test performance, where individual test variables are considered and interpreted with respect to specific components of executive function. Thirdly, drawing on both adult tests and developmental psychology, new 'child-friendly' procedures need to be designed and validated. Further, current findings are largely based on cross-sectional studies. Longitudinal studies, mapping developmental trajectories for individual children, may provide additional insights into the pattern of development of executive skills through childhood.

## References

- LURIA, A. R.: *Higher cortical functions in man* (New York: Basic Books), 1966.
- SHALLICE, T.: Specific impairments of planning. *Philosophical Transactions of the Royal Society of London*, **298**: 199–209, 1982.
- SPREEN, O., RISSER, A. H. and EDGELL, D.: *Developmental Neuropsychology* (New York: Oxford University Press), 1985.
- STUSS, D. T. and BENSON, D. F.: *The frontal lobes* (New York: Raven Press), 1986.
- LURIA, A. R.: *The working brain* (New York: Basic Books), 1973.
- STUSS, D. T. and BENSON, D. F.: The frontal lobes and control of cognition and memory. In: E. Perecman (editor) *The frontal lobes revisited* (New York: IRBN Press), pp. 141–158, 1987.
- RABINOWICZ, T.: Morphological features of the developing brain. In: M. A. B. Brazier and F. Coceani (editors) *Brain dysfunction in infantile febrile convulsions* (New York: Raven), pp. 1–23, 1976.
- YAKOVLEV, P. I. and LECOUCRS, A. R.: The myelogenetic cycles of regional maturation of the brain. In: A. Minkowski (editor) *Regional development of the brain in early life* (Oxford, UK: Blackwell), pp. 3–70, 1967.
- ANDERSON, P., ANDERSON, V. and LAJOIE, G.: The Tower of London Test: validation and standardization for pediatric populations. *The Clinical Neuropsychologist*, **10**: 54–65, 1996.
- BRUNER, J.: Organization of early skilled action. *Child Development*, **44**: 1–11, 1973.
- DELOACHE, J. S. and BROWN, A. L.: Where do I go next? Intelligent searching by very young children. *Developmental Psychology*, **20**: 37–44, 1984.
- DENNIS, M.: Frontal lobe function in childhood and adolescence: a heuristic for assessing attention regulation, executive control, and the intentional states important for social discourse. *Developmental Neuropsychology*, **7**: 327–358, 1991.
- DIAMOND, A.: The development of neural bases of memory function as indexed by the AB and delayed response tasks in human infants and rhesus monkeys. In: A. Diamond (editor) *The development of neural bases of higher cortical function* (New York: New York Academy of Science Press), pp. 267–317, 1990.
- DIAMOND, A. and GOLDMAN-RAKIC, P. S.: Comparison of human infants and rhesus monkeys on Piaget's AB task: evidence for dependence on dorsolateral prefrontal cortex. *Experimental Brain Research*, **74**: 24–40, 1989.
- GOLDMAN-RAKIC, P. S.: Development of cortical circuitry and cognitive function. *Child Development*, **58**: 601–622, 1987.
- KHLAR, D.: Goal formation, planning, and learning by preschool problem solvers or: 'My socks are in the dryer'. In: R. Siegler (editor) *Children's thinking: What develops?* (Hillsdale, NJ: Lawrence Erlbaum Associates Inc.), pp. 181–211, 1978.
- KLAHR, D. and ROBINSON, M.: Formal assessment of problem solving and planning processes in preschool children. *Cognitive Psychology*, **13**: 113–148, 1981.
- LEVIN, H. S., CULHANE, K. A., HARTMANN, J. *et al.*: Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology*, **7**: 377–395, 1991.
- PASSLER, M. A., ISAAC, W. and HYND, G. W.: Neuropsychological development of behavior attributed to frontal lobe functioning in children. *Developmental Neuropsychology*, **1**: 349–370, 1985.
- WELSH, M. C., PENNINGTON, B. F. and GROISSER, D. B.: A normative-developmental study of executive function: a window on prefrontal function in children. *Developmental Neuropsychology*, **7**: 131–149, 1991.
- ANDERSON, V. and MOORE, C.: Age at injury as a predictor of outcome following pediatric head injury. *Child Neuropsychology*, **1**: 187–202, 1995.
- DENNIS, M.: Language and the young damaged brain. In: T. Boll and B. K. Bryant (editors) *Clinical neuropsychology and brain func-*

- tion: *Research, measurement and practice* (Washington: American Psychological Association), pp. 89–123, 1989.
23. ANDERSON, V.: Recovery of function in children: the myth of cerebral plasticity. In: M. Matheson and H. Newman (editors) *Brain Impairment. Proceedings from the Thirteenth Annual Brain Impairment Conference*, Sydney, pp. 223–247, 1988.
  24. EWING-COBBS, L. and FLETCHER, J. M.: Neuropsychological assessment of head injury in children. *Journal of Learning Disabilities*, **20**: 526–535, 1987.
  25. MATEER, C. A. and WILLIAMS, D.: Effects of frontal lobe injury in childhood. *Developmental Neuropsychology*, **7**: 69–86, 1991.
  26. ASARNOW, R. F., SATZ, P., LIGHT, R. *et al.*: Behavior problems and adaptive functioning in children with mild and severe closed head injury. *Journal of Paediatric Psychology*, **16**: 543–555, 1991.
  27. FLETCHER, J. M., EWING-COBBS, L., MINER, M. E. *et al.*: Behavioral changes after closed head injury in children. *Journal of Consulting and Clinical Psychology*, **58**: 93–98, 1990.
  28. PENTLAND, L., TODD, J. A. and ANDERSON, V.: The impact of head injury severity on planning ability in adolescence: a functional analysis. *Neuropsychological Rehabilitation*, **8**: 319–335, 1998.
  29. PERROTT, S. B., TAYLOR, H. G. and MONTES, J. L.: Neuropsychological sequelae, familial stress, and environmental adaptation following pediatric head injury. *Developmental neuropsychology*, **7**: 69–86, 1991.
  30. LANDRY, S. H., JORDAN, T. and FLETCHER, J. M.: Developmental outcomes for children with spina bifida and hydrocephalus. In: M. G. Tramontana and S. R. Hooper (editors) *Advances in child neuropsychology*, Volume 2 (New York: Springer-Verlag), pp. 85–118, 1994.
  31. BROUWERS, P., RICCARDI, R., POPLACK, D. Attention deficits in long-term survivors of childhood acute lymphoblastic leukemia. *Journal of Clinical Neuropsychology*, **6**: 325–336, 1984.
  32. STEHBENS, J. A., KALEITA, T. A., NOLL, R. B. *et al.*: CNS prophylaxis of childhood leukemia: what are the long term neurological, neuropsychological and behavioral effects? *Neuropsychological Review*, **2**: 147–177, 1991.
  33. HOLMES-BERNSTEIN, J. and WABER, D. P.: Developmental neuropsychological assessment: the systemic approach. In: A. A. Boulton, G. B. Baker and M. Hiscock (editors) *Neuromethods: Volume 17: Neuropsychology* (Clifton, NJ: The Humana Press Inc), pp. 311–371, 1990.
  34. ROURKE, B. P., FISK, J. L. and STRANG, J. D.: *Neuropsychological assessment of children: A treatment oriented approach* (New York: Guilford), 1986.
  35. TAYLOR, H. G. and SCHATTSCHNEIDER, C.: Child neuropsychological assessment: a test of basic assumptions. *The Clinical Neuropsychologist*, **6**: 259–275, 1992.
  36. LEZAK, M.: *Neuropsychological assessment* (New York: Oxford), 1993.
  37. STUSS, D. T.: Biological and psychological development of executive functions. *Brain and Cognition*, **20**: 8–23, 1992.
  38. GLOSSER, G. and GOODGLASS, H.: Disorders in executive control functions among aphasic and other brain damaged patients. *Journal of Clinical and Experimental Neuropsychology*, **12**: 485–501, 1990.
  39. LEVIN, B.: Organizational deficits in dyslexia: possible frontal lobe dysfunction. *Developmental Neuropsychology*, **6**: 95–110, 1990.
  40. SHALLICE, T.: *From neuropsychology to mental structure* (New York: Cambridge University Press), 1990.
  41. WALSH, K. W.: *Neuropsychology: A clinical approach* (New York: Churchill Livingstone), 1998.
  42. DUNCAN, J.: Disorganization of behavior after frontal lobe damage. *Cognitive Neuropsychology*, **3**: 271–290, 1986.
  43. NEISSER, U.: *Cognitive psychology* (New York: Appleton-Century-Crofts), 1967.
  44. BENTON, A. L.: Differential behavioral effects of frontal lobe disease. *Neuropsychologia*, **6**: 53–60, 1968.
  45. PARKER, D. M. and CRAWFORD, J. R.: Assessment of frontal lobe dysfunction. In: J. R. Crawford, D. M. Parker and W. W. McKinlay (editors) *A handbook of neuropsychological assessment* (Hove, UK: Lawrence Erlbaum Associates Ltd), pp. 267–294, 1992.
  46. WALSH, K. W.: *Understanding brain damage: A primer of neuropsychological evaluation* (New York: Churchill Livingstone), 1985.
  47. WELSH, M. C. and PENNINGTON, B. F.: Assessing frontal lobe functioning in children: views from developmental psychology. *Development Neuropsychology*, **4**: 199–230, 1988.
  48. ALBERT, M. S. and KAPLAN, E. F.: Organic implications of neuropsychological deficits in the elderly. In: L. W. Poon, J. Fozard, L. Cermak *et al.* (editors) *New directions in memory and ageing: Proceedings of the George A. Talland Memorial Conference* (Hillside, NJ: Lawrence Erlbaum Associates Inc.), pp. 403–432, 1980.
  49. BELL, M. A. and FOX, N. A.: The relations between frontal brain electrical activity and cognitive development during infancy. *Child Development*, **63**: 1142–1163, 1992.
  50. THATCHER, R. W.: Maturation of the human frontal lobes. Physiological evidence for staging. *Developmental Neuropsychology*, **7**: 397–419, 1991.
  51. THATCHER, R. W.: Cyclical cortical reorganization during early childhood. *Brain and Cognition*, **20**: 25–50, 1992.
  52. GADDES, W. H. and CROCKETT, D. J.: The Spreen Benton Aphasia Tests: normative data as a measure of normal language development. *Brain and Language*, **2**: 257–279, 1975.
  53. HALPERIN, J. M., HEALEY, J. M., ZEITCHIK, E. *et al.*: Developmental aspects of linguistic and mnemonic abilities in normal children. *Journal of Clinical and Experimental Neuropsychology*, **11**: 518–528, 1989.
  54. MCKAY, K. E., HALPERIN, J. M., SCHWARTZ, S. T. *et al.*: Developmental analysis of three aspects of information processing: sustained attention, selective attention, and response organization. *Developmental Neuropsychology*, **10**: 121–132, 1994.
  55. MILLER, P. H. and WEISS, M. G.: Children's attentional allocation, understanding of attention, and performance on the incidental learning task. *Child Development*, **52**: 1183–1190, 1981.
  56. ANDERSON, V., LAJOIE, G. and BELL, R.: *Neuropsychological assessment of the school-aged child* (Australia: Department of Psychology, University of Melbourne), 1995.
  57. HOWARD, L. and POLICH, J.: P300 latency and memory span development. *Developmental Psychology*, **21**: 283–289, 1985.
  58. BADDELEY, A.: *Working memory* (Oxford: Oxford University Press), 1986.
  59. CASE, R.: *Intellectual development: Birth to adulthood* (Orlando, FL: Academic Press), 1985.
  60. PARIS, S. G. and LINDAUER, B. K.: The role of inference in children's comprehension and memory for sentences. *Cognitive Psychology*, **8**: 217–227, 1976.
  61. SIMON, H. A.: The functional equivalence of problem solving skills. *Cognitive Psychology*, **7**: 268–288, 1975.
  62. CAESER, P.: Old and new facts about perinatal brain development. *Journal of Child Psychology and Psychiatry*, **34**: 101–109, 1993.
  63. ORZHEKHOVSKAYA, N. S.: Fronto-striatal relationships in primate ontogeny. *Neuroscience and Behavioural Physiology*, **11**: 379–385, 1981.
  64. YAKOVLEV, P. I.: Morphological criteria of growth and maturation of the nervous system in man. *Research Publications Association for Research in Nervous and Mental Disease*, **39**: 3–46, 1962.
  65. FUSTER, F.: Frontal lobes. *Current Opinion in Neurobiology*, **3**: 160–165, 1993.
  66. JERNIGAN, T. L. and TALLAL, P.: Late childhood changes in brain morphology observable with MRI. *Developmental Medicine and Child Neurology*, **32**: 379–385, 1990.
  67. KOLB, B. and FANTIE, B.: Development of the child's brain and behaviour. In: C. Reynolds and E. Fletcher-Janzen (editors)



- Handbook of clinical child neuropsychology* (New York: Plenum), pp. 17–39, 1989.
68. RISSER, A. H. and EDGELL, D.: Neuropsychology of the developing brain: implications for neuropsychological assessment. In: M. G. Tramontana and S. R. Hooper (editors) *Assessment issues in child neuropsychology* (New York: Plenum), pp. 41–60, 1988.
  69. GOLDEN, C. J.: The Luria–Nebraska Children’s Battery: theory and formulation. In: G. W. Hynd and J. E. Obrzut (editors) *Neuropsychological assessment of the school-aged child* (New York: Grune & Stratton), pp. 277–302, 1981.
  70. CHUGANI, H. T., PHELPS, M. E. and MAZZIOTTA, J. C.: Positron emission tomography study of human brain functional development. *Annals of Neurology*, **22**: 287–297, 1987.
  71. BARBAS, H.: Architecture and cortical connections of prefrontal cortex in the rhesus monkey. In: P. Chauvel and A. Delgado-Escueta (editors) *Advances in neurology* (New York: Raven Press), pp. 91–115, 1992.
  72. HUDSPETH, W. and PRIBRAM, K.: Stages of brain and cognitive maturation. *Journal of Educational Psychology*, **82**: 881–884, 1990.
  73. STAUDT, M., SCHROPP, C., STAUDT, F. *et al.*: Myelination of the brain in MRI: a staging system. *Pediatric Radiology*, **23**: 169–176, 1993.
  74. CAESAR, P. and LAGAE, L.: Age specific approach to neurological assessment in the first year of life. *Acta Paediatrica Japonica*, **33**: 125–138, 1991.
  75. UEMURA, E. and HARTMAN, H. A.: RNA content and volume of nerve cell bodies in human brain: I. Prefrontal cortex in aging normal and demented patients. *Journal of Neuropathology and Experimental Neurology*, **37**: 487–496, 1978.
  76. KENNEDY, C., SAKURADA, O., SHINOHARA, M. *et al.*: Local cerebral glucose utilization in the newborn macaque monkey. *Annals of Neurology*, **12**: 333–340, 1982.
  77. RAKIC, P., BOURGEOIS, J.-P., ECKENHOFF, *et al.*: Concurrent overproduction of synapses in diverse regions of the primate cerebral cortex. *Science*, **232**: 232–235, 1986.
  78. LIDOW, M. and GOLDMAN-RAKIC, P. S.: Synchronised overproduction of neurotransmitter receptors in diverse regions of the primate cerebral cortex. *Proceedings of the National Academy of Science*, **88**: 10218–10221, 1991.
  79. GIBSON, K. R.: Myelination and behaviour development: a comparative perspective on questions of neoteny, altriciality, and intelligence. In: K. R. Gibson and A. C. Petersen (editors) *Brain maturation and cognitive development: Comparative and cross-cultural perspectives* (New York: Aldine De Grueter), pp. 29–64, 1991.
  80. PIAGET, J.: *The origins of intelligence in children* (New York: W. W. Norton), 1963.
  81. FLAVELL, J. H.: Cognitive development: past, present, and future. *Developmental Psychology*, **28**: 998–1005, 1992.
  82. DIAMOND, A.: Differences between adult and infant cognition: is the crucial variable presence or absence of language? In: L. Weiskrantz (editor) *Thought without language* (New York: Oxford University Press), pp. 337–370, 1988.
  83. DIAMOND, A. and GOLDMAN-RAKIC, P. S.: Evidence for involvement of prefrontal cortex in cognitive changes during the first year of life: comparison of human infants and rhesus monkeys on a detour task with transparent barrier. *Neurosciences Abstracts (Pt. II)*, **11**: 832, 1985.
  84. BECKER, M. G., ISAAC, W. and HYND, G.: Neuropsychology development of non-verbal behaviours attributed to the frontal lobes. *Developmental Neuropsychology*, **3**: 275–298, 1987.
  85. CHELUNE, G. J. and BAER, R. A.: Developmental norms for the Wisconsin Card Sorting Test. *Journal of Clinical and Experimental Neuropsychology*, **8**: 219–228, 1986.
  86. BERG, E. A.: A simple objective treatment for measuring flexibility in thinking. *Journal of General Psychology*, **39**: 15–22, 1948.
  87. HEATON, R. K.: *Wisconsin Card Sorting Test (WCST)* (Odessa, FL: Psychological Assessment Resources), 1981.
  88. REY, A.: *L’examen clinique en psychologie* (Paris: Presses Universitaires de France), 1964.
  89. HYND, G. W., SNOW, J. and BECKER, M. G.: Neuropsychological assessment in clinical child psychology. In: B. B. Lahey and A. E. Kazden (editors) *Advance in Clinical Child Psychology*, Volume 9 (New York: Plenum Press), pp. 35–86, 1986.
  90. OBRZUT, J. E. and HYND, G. W.: *Child neuropsychology, Volume 2: Clinical practice* (New York: Academic Press), 1986.
  91. TRAMONTANA, M. G. and HOOPER, S. R. (editors) *Assessment issues in child neuropsychology* (New York: Plenum), 1988.
  92. TAYLOR, H. G. and FLETCHER, J. M.: Neuropsychological assessment in children. In: G. Goldstein and M. Herson (editors) *Handbook of psychological assessment*, 2nd edn (New York: Pergamon), pp. 228–255, 1990.
  93. TODD, J. A., ANDERSON, V. A. and LAWRENCE, J.: Planning skills in head injured adolescents and their peers. *Neuropsychological Rehabilitation*, **6**: 81–99, 1996.
  94. GYNS, J. A. and WILLIS, G. W.: Validation of executive function tasks with young children. *Developmental Psychology*, **7**: 487–501, 1991.
  95. READER, M. J., HARRIS, E. L., SCHUERHOLZ, L. J. *et al.*: Attention deficit hyperactivity disorder and executive dysfunction. *Developmental Neuropsychology*, **10**: 493–512, 1994.
  96. BARKLEY, R. A. and GRODZINSKY, G.: Are tests of frontal lobe functions useful in diagnosis of attention deficit disorder? *The Clinical Neuropsychologist*, **8**: 121–139, 1994.
  97. WEYANDT, I. L. and WILLIS, W. G.: Executive functions in school-aged children: potential efficacy of tasks in discriminating clinical groups. *Developmental Neuropsychology*, **10**: 27–38, 1994.
  98. GARTH, J., ANDERSON, V. and WRENNALL, J.: Executive functions following moderate to severe frontal lobe injury: impact of injury and age at injury. *Pediatric Rehabilitation*, **1**: 99–108, 1997.
  99. HARRIS, E. L., SCHUERHOLZ, L. H., SINGER, H. S. *et al.*: Executive function in children with Tourette syndrome and/or attention deficit hyperactivity disorder. *Journal of the International Neuropsychological Society*, **1**: 511–516, 1995.
  100. *Army Individual Test Battery: Manual of directions and scoring* (Washington, DC: War Department, Adjunct General’s Office), 1944.
  101. REITAN, R. M. and DAVISON, L. A. (editors): *Clinical neuropsychology: Current status and applications* (Washington DC: Winston), 1974.
  102. REITAN, R. M.: *Manual for administration of neuropsychological test batteries for adults and children* (Indianapolis, IN: Author), 1969.
  103. GOLDEN, C. J.: *Manual for the Luria–Nebraska Neuropsychological Battery: Children’s Revision* (Los Angeles, CA: WPS), 1986.
  104. WECHSLER, D.: *Manual for the Wechsler Scale of Children’s Intelligence—III* (New York: Psychological Corporation), 1991.
  105. WECHSLER, D.: *Manual for the Wechsler Preschool and Primary Scale of Intelligence—Revised* (New York: Psychological Corporation), 1989.
  106. MCCARTHY, D.: *McCarthy Scales of Children’s Abilities* (New York: Psychological Corporation), 1972.
  107. KAUFMAN, A. S. and KAUFMAN, N. L.: *The Kaufman assessment battery for children: Interpretive manual* (Circle Pines, MN: American Guidance Services), 1983.
  108. KOLB, B. and WISHAW, Q.: *Fundamentals of human neuropsychology*, 3rd edn (New York: W. H. Freeman), 1990.
  109. WABER, D. P. and HOLMES, J. M.: Assessing children’s copy productions of the Rey-Osterreith Complex Figure. *Journal of Clinical and Experimental Neuropsychology*, **7**: 264–280, 1985.
  110. ANDERSON, P., ANDERSON, V. and GARTH, J.: A process-oriented approach to scoring the Complex Figure of Rey, *The Clinical Neuropsychologist* (in press).
  111. WABER, D. P. and BERNSTEIN, J. H.: Performance of learning disabled and non-learning disabled children on the Rey-Osterreith Complex Figure. *Developmental Neuropsychology*, **11**: 237–252.

112. GRIMWOOD, K., ANDERSON, V. A., BOND, L. *et al.*: Adverse outcomes of bacterial meningitis in school-age survivors. *Pediatrics*, **95**: 646–656, 1995.
113. WABER, D. P., BERNSTEIN, J. H., KAMMERER, B. L. *et al.*: Neuropsychological diagnostic profiles of children who received CNS treatment for acute lymphoblastic leukemia: the systemic approach to assessment. *Developmental Neuropsychology*, **8**: 1–28, 1992.
114. PORTEUS, S. D.: *Porteus maze test: Fifty years' application* (New York: Psychological Corporation), 1965.
115. KRİKORIAN, R., BARTOK, J. and GAY, N.: Tower of London procedure: a standard method and developmental data. *Journal of Clinical and Experimental Neuropsychology*, **16**: 840–850, 1994.
116. LEVIN, H. S., MENDELSON, D., LILY, M. A. *et al.*: Tower of London performance in relation to magnetic resonance imaging following closed head injury in children. *Neuropsychology*, **8**: 171–179, 1994.
117. BASSETT, S. S. and SLATER, E. J.: Neuropsychological function in adolescents sustaining mild closed head injury. *Journal of Paediatric Psychology*, **15**: 225–236, 1990.
118. ANDERSON, V., GODBER, T., SMIBERT, E. *et al.*: Neurobehavioural sequelae following cranial irradiation and chemotherapy in children: an analysis of risk factors. *Pediatric Rehabilitation*, **1**: 63–76, 1997.
119. ANDERSON, V. and STANLEY, G. V.: Ability profiles of learning disabled children. *Australian Psychologist*, **27**: 48–51, 1992.
120. BEERS, S. R., GOLDSTEIN, G. and KATZ, L. J.: Neuropsychological differences between college students with learning disabilities and those with mild head injury. *Journal of Learning Disabilities*, **27**: 315–324, 1994.
121. DENNY, D. R. and DENNY, N. W.: The use of classification for problem solving: a comparison of middle and old age. *Development Psychology*, **9**: 275–278, 1973.
122. PENTLAND, L. and ANDERSON, V.: Attention skills in head injured adolescents and their peers. *Journal of the International Neuropsychological Society*, **1**: 330, 1995.
123. BOUCUGNANI, L. L. and JONES, R. W.: Behaviors analogous to frontal lobe dysfunction in children with attention deficit disorder. *Archives of Clinical Neuropsychology*, **4**: 161–173, 1989.
124. CHELUNE, G. J., FERGUSON, W., KOON, R. *et al.*: Frontal lobe disinhibition in attention deficit disorder. *Child Psychiatry and Human Development*, **16**: 221–234, 1986.
125. STROOP, J. R.: Studies of interference in serial verbal reaction. *Journal of Experimental Psychology*, **18**: 643–662, 1935.
126. GOLDEN, C. J.: *Stroop Color and Word Test* (Chicago, IL: Stoelting Co.), 1978.
127. CHADWICK, O., RUTTER, M., SHAFFER, D.: A prospective study of children with head injuries: IV. Specific cognitive deficits. *Journal of Clinical Neuropsychology*, **3**: 101–120, 1981.
128. SHALLICE, T. and BURGESS, P.: Deficits in strategy application following frontal lobe damage in man. *Brain*, **114**: 727–741, 1981.
129. LEVINE, B., STUSS, D. T. and MILBERG, W. P.: Concept generation: validation of a test of executive functioning in a normal aging population. *Journal of Clinical and Experimental Neuropsychology*, **17**: 740–758, 1995.
130. DENNIS, M. and BARNES, M. A.: Knowing the meaning, getting the point, bridging the gap, and carrying the message: aspects of discourse following closed head injury in childhood and adolescence. *Brain and Language*, **39**: 428–446, 1990.
131. HARTLEY, L. and JENSEN, P.: Three discourse profiles of closed-head-injury speakers: theoretical and clinical implications. *Brain Injury*, **6**: 271–282, 1991.
132. HAYES-ROTH, B. and HAYES-ROTH, F.: A cognitive model of planning. *Cognitive Science*, **3**: 275–310, 1979.
133. CHALMERS, D. and LAWRENCE, J. A.: Investigating the effects of planning aids on adults' and adolescents' organisation of a complex task. *International Journal of Behavioral Development*, **16**: 191–214, 1993.
134. CONDOR, A., ANDERSON, V. and SALING, M.: Do reading disabled children have planning problems? *Developmental Neuropsychology*, **11**: 485–502, 1996.
135. WANSART, W.: Learning to solve a problem: a microanalysis of the solution strategies of children with learning disabilities. *Journal of Learning Disabilities*, **23**: 164–170, 1990.
136. ANDERSON, V., BOND, L., CATROPPA, C. *et al.*: Childhood bacterial meningitis: impact of age at illness and medical complications on long term outcome. *Journal of the International Neuropsychological Society*, **3**: 147–158, 1997.
137. PIAGET, J.: *The construction of reality in the child* (New York: Basic Books), 1954.