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Normative Data From the Cantab. I: Development of Executive Function Over the Lifespan

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ABSTRACT

The study of executive function within a developmental framework has proven integral to the advancement of knowledge concerning the acquisition and decline of higher skill processes. Still in its early stages, there exists a discontinuity in the literature between the exploration of executive capacity in young children and the elderly. Research of age-related differences utilising a lifespan approach has been restricted by the lack of assessment tools for the measurement of executive skills that are applicable across all age levels. This paper addresses these issues using the computer-based Cambridge Neuropsychological Test Automated Battery (CANTAB) to identify periods of development in executive capacities using a normative sample of 194 participants ranging in age from 8 to 64 years. Findings of executive function in children as young as 8 years of age were extended, with functional gains found in the efficiency of working memory capacity, planning and problem-solving abilities, between the ages of 15 and 19 years and again at 20–29 years of age. Cognitive flexibility was assessed at adult-levels in even the youngest children. Declines in performance on all tasks were revealed for the 50–64 year old sample, providing support for the vulnerability of executive skills to normal aging.

Executive functions play a vital role in the ability of an individual to develop and coordinate an adaptive response to the environment. Such goal-directed, purposeful behaviour is purported to subsume a number of higher order parallel skills such as strategic planning, problem solving, organised search, abstract thinking, concept formation, inhibitory control, self-monitoring and cognitive flexibility (Anderson, 1998; Hughes, 1998; Temple, 1997; Weyandt & Willis, 1994).

Cerebral organisation and cognitive functioning models initially presented executive function as an adult capacity that reaches maturity around puberty, the time of Piaget's stage transition from concrete to formal operational thinking (Golden, 1981; Stuss, 1992; Travis, 1998). This resulted partly from a paucity of studies targeting the prepubertal years of life, and the absence of specifically developed measures sensitive to the range of immature executive skills available to the child (Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Kempton, Vance, Luk, Costin, & Pantelis, 1999). Recently, there has been a focus on the role of "executive dysfunction" in developmental disorders such as autism and attention deficit hyperactivity disorder, arguing the importance of developmentally-appropriate executive capacity even in very young children.

Research has now identified a stage-like sequence of executive function development characterised by 'spurts' in executive abilities beginning from as young as 12 months of age,

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with the majority of functions coming 'online' around the age of 8 (Ardila & Rosselli, 1994; Case, 1992; Luciana & Nelson, 1998). These improvements in executive performance (whether the result of improved strategic development, superior inhibitory control, mastery of temporal integration or processing efficiency) have been found to correlate with increased myelination and diffuse synaptogenesis of frontal brain regions, which occurs throughout development and well into the second decade of life (Espy, 1997; Kempton et al., 1999; Klingberg, Vaidya, Gabrieli, Moseley, & Hedehus, 1999; Ridderinkhof & van der Molen, 1997; Sowell & Jernigan, 1998; Stuss, 1992).

In contrast, gradual age-related decline in executive capacity from around 65 years of age is purportedly related to changes in frontal subcortical white matter (Brennan, Welsh, & Fisher, 1997; Espy, 1997; Klingberg et al., 1999; Parkin, 1996). Further age-related differences in cerebral activation of this area have been attributed to inefficient strategic operations during encoding and retrieval of information, leading to problems in planning and selective attention, including those skills that deal with novelty and information complexity (Levine, Stuss, & Milberg, 1997; Raz, Gunning-Dixon, Head, Dupuis, & Acker, 1998; Stuss, 1992).

The skills subsumed under the umbrella term of executive function are not homogeneous however, and have been found to dissociate with focal brain injury (Anderson, 1998; Lehto, 1996; Parkin, 1996; Stuss & Benson, 1987; Stuss et al., 2000). A number of studies have successfully isolated discrete functions and defined the variable acquisition of skills (Levin et al., 1991; Welsh & Pennington, 1988). Simple planning, attentional set-shifting and hypothesis testing are reportedly available to the child at an earlier stage than other abilities, including temporal ordering and complex strategy formation (Chelune & Baer, 1986; Espy, 1997; Luciana & Nelson, 1998; Stuss, 1992). Research which looks to extend this dialectic to the possible differential decline of executive capacities in later life is scarce.

Propelled by the new sensitivity to childhood executive capacity, and the immature exploration of gender and lifespan issues within the executive area, this study aimed to address the question of developmental trajectories for discrete executive functions across the lifespan (Espy, 1997; Parkin, 1996). Extending previous investigations on the executive development of young children (Chelune & Baer, 1986; Levin et al., 1991; Luciana & Nelson, 1998; Welsh & Pennington, 1988), the Cambridge Neuropsychological Test Automated Battery (CANTAB) was used to plot the maturational pathway of working memory, strategic planning, organisation of goal-directed behaviour and attentional set-shifting from middle childhood to late adulthood (8–64 years of age). Performance of 194 individuals between the age-bands of 8–10, 11–14, 15–19, 20–29, 30–49 and 50–64, was compared to investigate when these skills come 'on-line', stabilise and decline. We predicted on the basis of recent findings on brain development that progressive improvement in these abilities would occur until around the ages of 12–15 years of age and plateau in early adulthood, remaining stable to around 65 years of age.

METHOD

Participants

The sample comprised of 194 normal participants, ranging in age from 8 to 64 years (Table 1). These participants were recruited from hospital ancillary staff, normal classes of three metropolitan primary schools and one secondary school, and through advertisement. Entry into the sample followed strict criteria of: English as a first language, normal or corrected vision and hearing, no learning disability, no record of psychiatric or serious medical conditions, no family history of psychiatric illness, no history of significant head injury, seizures, or neurological disease, no substance abuse or dependence. Written informed consent was provided by each participant and his/her guardian (for participants under 18 years of age) before administration of the battery. Some of the data reported in this paper was obtained as part of a larger study undertaken at the Mental Health Research Institute (MHRI). The assessment for all participants was completed individually in one session of approximately 60 min. The majority of participants were seen by CRDL with additional testing performed by JAB, TMP and KM. This study was approved by the Behavioural and Social Sciences Human Ethics subcommittee at the University of Melbourne.

Table 1. Demographics of the Sample Population.

Age group	N	Mean age	Predicted IQ	Gender ratio Male:female
8 to 10	29	9.73 ± 0.08	103.00 ± 1.90	13:16
11 to 14	29	12.91 ± 1.31	93.41 ± 1.48	13:16
15 to 19	39	17.74 ± 141	99.70 ± 1.55	21:18
20 to 29	39	24.42 ± 2.91	104.97 ± 1.70	19:20
30 to 49	39	38.80 ± 6.02	106.27 ± 1.76	21:18
50 to 64	19	55.91 ± 5.25	106.89 ± 2.36	6:13

Materials and Procedure

The National Adult Reading Test (NART; Nelson & Willison, 1991) was completed by each adult participant to provide an index of global cognitive ability (Crawford, Stewart, Cochrane, Parker, & Besson, 1999). The Schonell Graded Word Reading Test (Schonell, 1942) was employed for children under 12.6 years of age. Scores on the NART were converted to prorated intelligence quotients for analysis (Nelson & Willison, 1991), using the Wechsler Adult Intelligence Scale – Revised (WAIS–R; Wechsler, 1981). Reading age levels obtained on the Schonell were employed to provide prorated intelligence quotients using transformations from the Wide Range Achievement Test – Revised (WRAT–R; Jastak & Wilkinson, 1984).

Four cognitive tasks were selected from the Cambridge Neuropsychological Test Automated Battery (CANTAB; Owen, Downes, Sahakian, Polkey, & Robbins, 1990). A short motor screening task was performed to ensure participants were unimpaired in their ability to respond to the stimuli, and to familiarise them with the computerised procedure.

Spatial Span

This computerised version of the Corsi Block Tapping Test (Milner, 1971) assessed a participant's spatial short-term memory capacity. Visuo-spatial span was defined as the highest level (maximum = 9) at which the individual successfully remembered at least one sequence of squares.

Spatial Working Memory (SWM)

This task assesses the ability of a person to hold, manipulate and update information to direct moment-to-moment behaviour. Participants were required to search through an increasing number of boxes (3, 4, 6 and 8) to locate hidden tokens. Each box housed only one token per sequence, and searching any particular box more than once during a sequence resulted in a 'within search error,' while returning to search an already emptied box incurred a 'between search error.' A 'strategy' score, ranging from 1 (best) to 37 (worst), calculated for the more difficult six and eight box levels, reflected the extent to which the participant successfully adopted a systematic search.

Tower of London (TOL)

This computerised variation of the 'Tower of London' task developed by Shallice and McCarthy (Shallice, 1982) assesses the ability to organise goal-directed behaviour. Participants are required to plan and execute a set of movements to replicate a goal arrangement of balls provided on the screen. Scores reflected the ability to develop and monitor a problem-solving strategy at various levels of difficulty. Performance was measured as the percentage of trials completed in the minimum number of moves possible, and the percentage of problems solved within the maximum number of moves allowed.

For each planning trial participants completed a yoked control condition to provide baseline motor initiation and executive times, independent of thinking latencies. Participants were instructed to follow the ball movements as quickly as possible to provide a control measure of sensorimotor speed for the copying phase, with each trial being an exact replication of their earlier planning moves.

Intradimensional/Extradimensional Set-Shifting (ID/ED)

This task assessed a participant's ability to maintain attention to different examples within a reinforced stimulus dimension (intradimensional shift) and to then shift attention to a previously irrelevant stimulus dimension (extradimensional shift). The task involved nine stages, with participants proceeding to the next stage once a criterion of six consecutive correct responses had been attained. Alternatively, termination of the task followed failure to reach criterion within 50 trials at a particular stage. The first stage requires simple discrimination and the second simple reversal for stimuli varying on one dimension (white lines). The third stage sees the introduction of a second dimension (irregular purple filled shapes), presented together with the line patterns. This phase tests compound discrimination with success defined by the ability to follow the previously enforced rule while ignoring the new distractors. At the next level, the lines are superimposed over the shapes to test compound reversal. Performance was measured as the highest stage reached by the participant, the trials required to reach criterion, and the number of errors incurred at each completed stage.

Statistical Analysis

Analyses were performed using SPSS (Version 10). Prorated intelligence scores (derived from performance on the reading tests) were analysed using a two-way analysis of variance (ANOVA) to assess differences in ability by age-group and gender. Two-way ANCOVAs were employed to compare gender and age-group performance on each of the measures, controlling for prorated IQ. The performance of different ages at the various levels of the SWM task and TOL was assessed using a group by task difficulty repeated-measures analysis of covariance (ANCOVA) within a multivariate ANOVA (MANOVA) design using Wilks' Λ.

Distributions of the data were reviewed prior to statistical analysis to check for violations of test assumptions. Extreme values on individual tasks were excluded where appropriate and have been noted in the results. Skewed distributions of scores were analysed using the nonparametric Kruskal–Wallis test. Follow-up comparisons of significant findings were performed using a two-independent samples test with groups whose difference in ranking was thought to warrant further analysis.

Alpha levels were set at 0.05, although analyses reaching significance were treated with caution in the context of multiple statistical tests performed on the data. A Bonferroni type adjustment was not applied to testing at this stage to maximise group differences in task performance. This was considered appropriate for an exploratory study interested in a large number of possible relationships and interactions between the variables, which were not explicitly expressed in the hypotheses. Follow-up comparisons were performed for significant main effects using a Bonferroni correction to account for inflated Type 1 error. All analyses included gender as a factor.

RESULTS

Sample Demographics

Intelligence scores were found to differ as a function of age, $F(5, 186) = 7.65$, $p < .001$. Average prorated IQs were reported for all age groups except the 11–14 year olds who were significantly lower in global intelligence than all other ages, with a mean IQ of 93.41. This finding is not unusual in Australian samples and appears to reflect a problem with standardisation within this age-range rather than a true deficit in IQ (Anderson, Smibert, Godber, Ekert, & Weiscop, 2000; Grimwood, Anderson, Anderson, Tan, & Nolan, 2000). Comparable performance for males and females was found within each individual age-group, and no age-group-by-gender interaction was noted. All analyses of the CANTAB data were covaried for IQ, which contributed a significant, albeit small, amount of variance to performance on the spatial span, and 'between search errors' measures. Importantly, the significance of age and gender effects was not altered by the inclusion of the IQ score.

Short-Term Memory Capacity & Sequencing Ability

Spatial span scores (Table 2) were found to differ significantly on group analysis, revealing a main effect of both age group, $F(5, 185) = 10.99$, $p < .001$, and gender, $F(1, 190) = 5.17$, $p = .024$, with males outperforming females. There was no age group-by-gender interaction.

Post hoc comparisons revealed that the 15–19 year olds, along with 20–29 year olds, displayed markedly longer memory spans than the 8–10, 30–49 and 50–64 age groups. The poor performance of the 50–64 year olds also fell significantly below that of the 11–14 age group.

Due to minimal 'within search errors' on the SWM task only a summary measure ('within search errors' across all five difficulty levels) was employed in the analysis (Table 2). The age group difference in error scores, $\chi^2(5) = 17.10$, $p = .004$, confirmed that the 50–64 age group performed significantly poorer than the 11–14, 15–19 and 20–29 year olds. The 8–10 and 30–49 age groups also made more errors than the 15–19 and 20–29 year olds, the latter of which were most proficient on this task.

Working Memory

Age and gender exerted significant influence in the total number of 'between search errors' performed on the spatial working memory task [Age: $F(5, 186) = 16.35$, $p < .001$; Gender:

Table 2. Means and Standard Deviations for the CANTAB Tasks Organised According to Age Group and Gender.

	Short-term memory capacity & sequencing ability	Working memory			Strategic planning & organisation of goal-directed behaviour			Attentional set-shifting
	Spatial Span	Spatial Working Memory			Tower of London			ID/ED
	Span	Within search errors	Between search errors	Strategy	% perfect solutions	Average excess moves per trial	% completed in max moves	Level completed
8 to 10								
Male	5.71 ± 0.91	2.46 ± 3.13	44.38 ± 13.05	16.85 ± 3.08	64.06 ± 10.36	1.30 ± 0.40	85.23 ± 8.04	8.50 ± 1.09
Female	5.56 ± 1.09	1.31 ± 1.62	43.88 ± 10.12	17.75 ± 2.32	59.17 ± 8.47	1.24 ± 0.39	88.33 ± 6.19	8.69 ± 0.87
Total	5.63 ± 0.10	1.83 ± 2.44	44.10 ± 11.31	17.34 ± 2.68	61.34 ± 9.50	1.26 ± 0.39	87.02 ± 7.05	8.60 ± 0.97
11 to 14								
Male	6.46 ± 1.51	1.31 ± 1.60	26.92 ± 16.98	15.92 ± 4.11	72.16 ± 12.92	0.97 ± 0.58	90.34 ± 10.22	8.46 ± 1.20
Female	6.00 ± 1.20	1.06 ± 1.00	38.94 ± 15.34	16.25 ± 4.19	60.27 ± 13.56	1.40 ± 0.47	87.50 ± 6.93	8.19 ± 0.98
Total	6.21 ± 1.29	1.17 ± 1.28	33.55 ± 16.93	16.10 ± 4.08	65.50 ± 14.33	1.21 ± 0.55	88.75 ± 8.46	8.31 ± 1.07
15 to 19								
Male	7.76 ± 1.34	0.81 ± 1.66	14.14 ± 11.53	14.19 ± 3.68	81.53 ± 12.57	0.69 ± 0.52	93.45 ± 6.98	8.73 ± 0.94
Female	6.63 ± 1.50	1.17 ± 1.42	26.61 ± 18.47	15.50 ± 4.83	78.47 ± 12.17	0.77 ± 0.37	92.65 ± 7.73	8.63 ± 0.76
Total	7.23 ± 1.51	0.97 ± 1.55	19.90 ± 16.19	14.79 ± 4.24	80.16 ± 12.33	0.72 ± 0.45	93.09 ± 7.23	8.68 ± 0.85
20 to 29								
Male	7.05 ± 1.19	0.74 ± 1.52	8.05 ± 7.63	10.63 ± 5.52	81.56 ± 15.37	0.57 ± 0.53	95.72 ± 5.91	8.42 ± 1.47
Female	7.05 ± 1.64	1.05 ± 1.54	19.60 ± 14.55	15.75 ± 3.27	75.66 ± 11.95	0.84 ± 0.46	91.45 ± 7.30	8.75 ± 0.79
Total	7.05 ± 1.41	0.90 ± 1.52	13.97 ± 12.94	13.26 ± 5.15	78.69 ± 13.95	0.70 ± 0.51	93.59 ± 6.89	8.59 ± 1.16
30 to 49								
Male	6.41 ± 1.40	1.38 ± 1.99	20.19 ± 18.93	14.10 ± 4.27	76.70 ± 14.71	0.80 ± 0.52	92.85 ± 8.90	8.86 ± 0.64
Female	5.63 ± 1.07	2.53 ± 2.43	28.29 ± 21.98	15.29 ± 5.41	69.74 ± 13.05	1.03 ± 0.53	89.58 ± 6.78	8.84 ± 0.50
Total	6.05 ± 1.30	1.89 ± 2.24	23.82 ± 20.48	14.63 ± 4.78	73.48 ± 14.24	0.91 ± 0.53	91.35 ± 8.06	8.85 ± 0.57
50 to 64								
Male	5.33 ± 0.52	2.83 ± 1.72	32.83 ± 9.62	16.50 ± 3.62	71.25 ± 20.06	1.03 ± 0.50	91.25 ± 7.13	8.33 ± 0.82
Female	4.92 ± 0.95	3.00 ± 3.98	37.31 ± 17.06	17.62 ± 3.62	69.27 ± 15.18	1.06 ± 0.60	90.63 ± 8.64	8.23 ± 1.30
Total	5.05 ± 0.85	2.95 ± 3.37	35.89 ± 14.97	17.26 ± 3.56	69.85 ± 16.12	1.05 ± 0.55	90.81 ± 8.00	8.26 ± 1.15

$F(1, 190) = 10.96$, $p = .001$]. IQ also contributed a small amount of variance in performance on this task, $F(1, 190) = 8.62$, $p = .004$]. Males recorded substantially fewer errors than females. Post hoc comparisons revealed 20–29 year olds made significantly fewer errors than all other ages, except for the 15–19 age group, who themselves displayed superior performance to the 8–10 and 50–64 age groups. The youngest group made the greatest number of between search errors on this task with their performance falling significantly below that of the 11–14 and 30–49 year olds.

Analysis of 'between search errors' at each level demonstrated a main effect of task difficulty, Wilk's $\Lambda = 0.86$, $F(3, 188) = 9.39$, $p < .001$, an age group-by-difficulty interaction, Wilk's $\Lambda = 0.62$, $F(15, 176) = 6.20$, $p < .001$, an IQ-by-difficulty interaction, Wilk's $\Lambda = 0.95$, $F(3, 188) = 3.33$, $p = .021$, and a gender-by-difficulty interaction, Wilk's $\Lambda = 0.94$, $F(3, 188) = 3.62$, $p = .014$] (Fig. 1).

Significant age group differences were only evident for the 6- and 8-box trials where task demands on working memory were sufficiently taxing [6-box level: $F(5, 186) = 12.13$, $p < .001$; 8-box level: $F(5, 186) = 14.68$, $p < .001$]. Errors became more pronounced with greater task difficulty, and while the gender distinction arose for the 20–29 age group on both the 6-box and 8-box level with males revealing an 'on-line' advantage in processing of extended sequences, 11–14 and 15–19 year old males only showed this advantage at the more difficult 8-box level. Separate post hoc analyses at the two difficulty levels confirmed that the 15–19 and 20–29 age groups performed better on both the 6- and 8-box trials than 8–10 and 50–64 year olds. The 8–10 age group showed almost four times the errors made by the 20–29 group whose low scores were also significantly better than the 11–14 year olds.

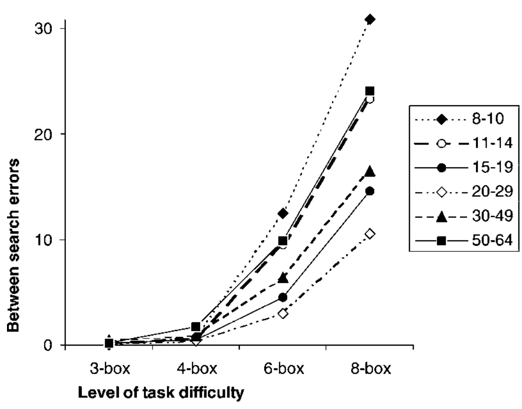

Fig. 1. Spatial Working Memory task. Number of 'between search errors' for each age group at each level of task difficulty.

Strategic Planning and Organisation of Goal-Directed Behaviour

Analysis of strategy scores showed a main effect of age group, $F(5, 186) = 4.10$, $p = .002$, and of gender, $F(1, 190) = 8.88$, $p = .003$, but no interaction. Males were found to be more effective in employing a search strategy than females, while the 20–29 age group were significantly better than the 8–10 and 50–64 year olds.

Two measures of planning ability from the TOL task were compared across groups at each level of task difficulty. The first accounted for the percentage of perfect solutions (trials completed in the minimum number of moves) obtained by the participant. A main effect of age group, $F(5, 175) = 8.66$, $p < .001$, and a main effect of gender, $F(1, 179) = 9.52$, $p = .002$, were revealed, but no significant age group-by-gender interaction. Although a main effect of task difficulty was not observed for minimum move solutions at each level, a significant age group-by-difficulty interaction, Wilk's $\Lambda = 0.803$, $F(15, 165) = 2.61$, $p = .001$, and a gender-by-difficulty interaction, Wilk's $\Lambda = 0.944$, $F(1, 179) = 3.40$, $p = .019$, indicated that differences in performance between the ages and genders increased as a function of greater organisational demands (Fig. 2).

Post hoc comparisons revealed significant differences in the total perfect solutions obtained by the 8–10 and 11–14 age groups in comparison to the 15–19 and 20–29 year olds, who were most efficient in their goal-directed behaviour. The youngest children also completed fewer trials in the minimum number of moves than the 30–39 age group. Further individual analysis of these data revealed that these significant differences in age group performance were only evident at the 3- and 5-move levels.

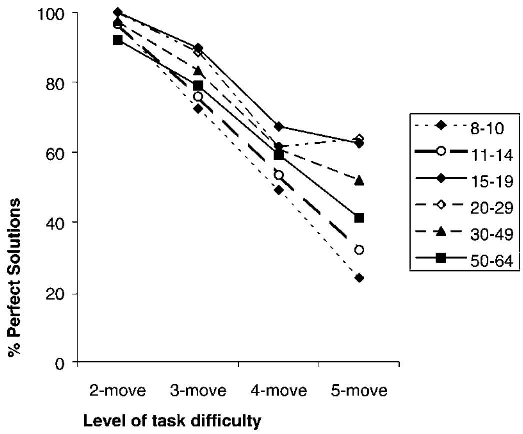

Fig. 2. Tower of London task. The percentage of 'perfect solutions' obtained by each age group at each level of task difficulty.

The second measure for the TOL task calculated the percentage of trials completed in the maximum number of moves allowed. This score provided a measure of the individual's ability to effectively complete the problems. A significant main effect of age group, $F(5, 175) = 3.53$, $p = .005$, and an age group-by-difficulty interaction, Wilk's $\Lambda = 0.828$, $F(15, 165) = 2.17$, $p = .007$, were again evident (Fig. 3). Post hoc comparisons indicated that the 8–10 year olds solved significantly fewer TOL problems than the

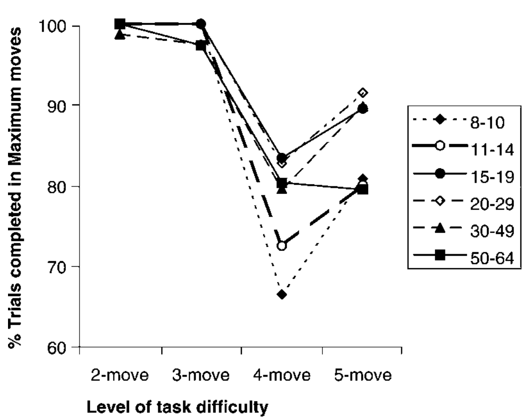

Fig. 3. Tower of London task. The percentage of trials completed by each age group within the 'maximum moves' allowed at each level of task difficulty.

more proficient 15–19 and 20–29 age groups. This age-defined difference in performance only occurred on the more taxing 4- and 5-move trials.

Attentional Set-Shifting

Performance on this task was assessed using the maximum stage reached by each participant. Analysis revealed a significant age-group difference in level attainment, $\chi^2(5) = 11.74$, $p = .038$. Ranking of group performance showed that significantly fewer of the 50–64 year olds were reaching the final level. However, it is important to note that the majority of individuals from each age-group progressed beyond the extradimensional shift-stage to complete the ID/ED task.

DISCUSSION

In this study, we have demonstrated that strategic planning and the organisation of goal-directed behaviour is at its height between the ages of 20 and 29 years. This improvement may in part be due to the achievement and maintenance of maximal short-term memory capacity in the 15–19 age range, since maturation of this 'capacity resource' contributes to a greater ability to define and order a strategic plan (Hitch, Towse, & Hutton, 2001). However, the absence of 'within search errors' for most participants on the SWM task suggest that the maturation of these skills is not reliant solely on the increase in span witnessed postpuberty.

The comparably poor working memory competence of the youngest and eldest participants is suspected to implicate distinct deficits in executive processing as suggested by previous investigations in this area (Belleville, Peretz, & Malenfant, 1996; Cabeza et al., 1996; Cabeza, McIntosh, Tulving, Nyberg, & Grady, 1997; Grady et al., 1995; Raz et al., 1998). Unfortunately, we were unable to analyse the data to identify the critical components, that is, strategic versus mnemonic aspects of working memory, contributing to poor performance, mainly due to the lack of variance in span capacity for the 50–64 year age group. A substantially larger sample is required for adequate variance to provide meaningful correlations between the skills investigated.

The difference in performance of the monitoring and execution of a sequence selection (SWM) across the lifespan is strengthened by data from the TOL. Performance on this task followed a pattern of steady improvement with effective planning and problem-solving skills available to the 12 year old child. The documented slow developmental progression of these skills in the literature corresponds to the finding of gains in the 11–14 year old group, who required the same number of excess moves to complete a problem, but solved significantly more trials than their younger counterparts (Anderson, Anderson, & Lajoie, 1996; Anderson et al., 2001; Ardila & Rosselli, 1994; Krikorian, Bartok, & Gay, 1994). Further functions that were mastered only once an individual reached early adulthood were found to decline relatively early in the aging process. Difficulty for the 50–64 year olds on the 5-move trials has been ascribed to natural declines in memory capacity for temporal ordering and object location (Brennan et al., 1997; Raz et al., 1998). Conversely the youngest participants are considered cognitively immature in their ability to create and order an effective plan, leading to disorganisation in their responses and failure to complete tasks on the more complex trials.

Attentional set-shifting ability showed a much swifter maturational path than the strategic planning, organisation and problem-solving components of executive function. Performance on the ID/ED task did not differentiate any of the groups, confirming documented adult levels of set-shifting competence in 8 and 10 year olds (Anderson et al., 2001; Chelune & Baer, 1986; Luciana & Nelson, 1998). Investigation of decline in these monitoring skills has, however, failed to produce consistent findings. Some studies suggest a late onset of decline in cognitive flexibility past the age of 70, while others report deficits to present at an earlier age (Boone, 1999; Robbins et al., 1998). Our data would suggest that the ability to adjust responses to feedback, and shift this to new exemplars within a previously learned set, is an executive skill acquired early in development, suggesting that the purported neural circuitry subserving this ability in the lateral and orbital PFC is connected and activated earlier than other executive systems (Rezai et al., 1993; Roberts, Robbins, & Weiskrantz, 1998; Stuss & Benson, 1987).

The use of an endpoint score for this task may have obscured subtle differences in performance over the lifespan. Previous research would suggest that children do in fact make a greater number of errors to reach criterion at both the ID and ED stages, but do not discriminate in the number of trials necessary to advance at either level (Luciana & Nelson, 1998; Shanab & Yasin, 1979). Thus, they can competently complete such tasks by responding to the absolute properties of the stimuli without relevant understanding of the underlying contingency being tested. Adolescents and adults on the other hand are found to experience greater difficulty performing an ED shift due to a better understanding of the dimension characteristics of the task. Having learned the relevant dimension governing the response rule, their performance is potentially impeded as they are required to extinguish the original response set and transfer this learning to new exemplars at the ED stage (Owen et al., 1993; Whitney & White, 1993). This ‘flexibility’ to shift decreases in later life, where repetition errors are seen to increase as a result of defective inhibition in strategic processing (Belleville et al., 1996; Levine, Stuss, & Milberg, 1995). Detailed investigation is required to delineate the component cognitive processes contributing to set-shifting ability.

The varied developmental trajectories for these executive abilities were seen to differ as a function of gender, although only a small amount of variance in performance was actually accounted for by sex differences. There is some mention of gender differences for select components of executive function in the literature, possibly mediated by hormonal factors and by gender-related differences in brain structure (Kolb & Stewart, 1991). Anderson et al. (2001) and Ardila and Rosselli (1994) tentatively propose gender differences in higher order skill acquisition in normal children. Boys were found to excel on planning and organisation, attentional control and speed of processing tasks, while a gender crossover effect with increasing age has been observed for the latter two factors (Anderson, 1998).

Gender-related differences in cognitive decline are similarly tentative. Meinz and Salthouse (1998) found significant interactions only in the direction of greater age-related decline in perceptual speed and reasoning abilities among females than among males, of which both skills apparently display accelerated decline with increasing age (Verhaeghen & Salthouse, 1997). Conversely, Schaie's seminal work on the Seattle Longitudinal Study (1994) provides evidence of a systematic gender bias in inductive reasoning favouring women across the life span, and a linear trajectory for decline of the perceptual speed construct.

On a broader level the traditional gender distinction of superior spatial abilities for males and verbal skills for females is thought to be preserved in the geriatric population (Schaie, 1994; Willis & Schaie, 1988). Collectively however, age-gender-cognition interactions are not extensively explored. Presumably most research endeavours subscribe to the notion that gender-cognition relations at all ages remain virtually stable and ignore the possibility that gender contributes significantly to the amount and rate of decline witnessed in the aging community (Meinz & Salthouse, 1998). This is in stark contrast to animal experimentation which shows gender differences in brain structure and function, and in anatomical recovery and benefits from environmental stimulation following frontal ablation in perinatal rats (Kolb, Gibb, & Gorny, 2000).

This study failed to replicate findings of a gender crossover in selected executive functions (Anderson et al., 2001; Ardila & Rosselli, 1994). Males were consistently seen to outperform females, with a lack of any age-by-gender interaction signifying that skills come 'on-line' at the same time for both genders, and progress at equal rates. There is little explanation for this male bias in executive abilities, as it effectively contradicts expectations based on the earlier onset of puberty in females. A more detailed analysis of individual ages within this adolescent period would provide clearer interpretation of this male advantage. Unfortunately the small number of participants at each age point places this analysis beyond the scope of the present study, and calls on future projects to provide a closer look at development of executive function over pubertal onset. The superior performance of males in this study would most logically be attributed to the well documented visuo-spatial processing advantage enjoyed by this gender and exploited by the visually based CANTAB tasks (Hamilton, 1995; Gilger & Ho, 1989; Kirk, 1992).

The results of this study are consistent with developmental theories of the early acquisition of executive function. They confirm an immature executive system available to the child as young as 8–10 years of age that matures differentially for discrete functions. The heterogeneity of executive skills is upheld by discrepant age-related performance of the CANTAB tasks, suggesting that the psychological (and likely neural) "structures" regulating these skills and their underlying neural networks develop at different times and rates (Robbins et al., 1998; Stuss, 1992). Lesion studies support the idea that these functions are subsumed by discrete neural circuits with their base in the PFC (Owen et al., 1990; Robbins, 1998; Tate, 1999). Assuming the integrity of the cerebral regions, the efficiency of the executive system improves with age as cortico-cortical connections develop in the late teens, allowing these cognitive processes to become more comprehensive, abstract and flexible in early adulthood (Case, 1992; Levin et al., 1994; Travis, 1998). Fluctuations in performance between 11 and 14 years of age in the absence of significant improvement is thought to reflect the increasing capacity in neural circuitry during this time and the relative ignorance of the adolescent in how to implement and constrain their new found skills (Kirk, 1985; Klingberg et al., 1999).

Executive functions were seen to decline earlier than anticipated, with significant performance decrements recorded for the 50–64 year olds. Age-related cerebral atrophy of the neuronal circuitry is thought to compromise the system's capacity to cope with strategic and inhibitory processing, leading to deficits in working memory and general cognition (Brennan et al., 1997; Levine et al., 1997). A return to almost child-level performance by the age of 64 suggests that executive skills are particularly sensitive to cognitive decline.

There are however a number of limitations in interpreting these data and comparing these findings to the literature. Firstly this age-group had a smaller number of participants than the other age brackets and the gender distribution was biased in favour of females. Unfortunately, the number of participants older than 65 years was too few to allow meaningful analysis of the data and therefore this group had to be excluded, eliminating the upper end of the age spectrum and reducing our capacity to effectively cover the years where decline would be greatest. It should also be noted that the suggestion of such early decline may be an artifact of the test medium in both the use of a computer-based system unfamiliar to the older population and the visuospatial nature of the tasks. Of the studies on normal aging that do employ some form of visuospatial measure of executive function, this usually comprises tests from intelligence batteries which assess well established crystallised skills rather than fluid abilities. Therefore, a plausible reason for their findings of longevity in executive capacity could be the robustness of performance on ‘hold’ tests which assess skills that people typically have a lot of practice on (Mejia, Pineda, Alvarez, & Ardila, 1998; Verhaeghen & Salthouse, 1997).

Future studies would do well to look specifically at the level of executive abilities for each age rather than adopting the crude age-grouping of this study, which although necessary when comparing such an extensive range of ages, sacrifices a substantial amount of sensitivity in the interpretation of results. A more appropriate and well standardised intelligence measure for an Australian sample would potentially minimise discrepancies in IQ scores for adolescents and provide a more valid prorated intelligence estimate. A longitudinal design would also better demonstrate acquisition and decline in executive skills, as the literature warns of considerable variability in the locus and extent of both brain alterations and cognitive deficits between individuals (Zyzak, Otto, Eichenbaum, & Gallagher, 1995). Following individuals as they mature beyond the age of 65 years is of great interest and necessary for a thorough understanding of how and when deficits in executive performance arise and progress. Generalisation of the current findings to performance on other executive tasks may be problematic as relationships revealed between measures on the CANTAB are affected by a substantial amount of colinearity. Careful consideration of the tasks used to develop hypotheses of age-related practices in cognition is necessary to avoid misinterpretation of non-parallel pathways of executive abilities when compared across studies.

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