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A unitary executive function predicts intelligence in children

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ABSTRACT

Executive functions (EF) and intelligence are of critical importance to success in many everyday tasks. Working memory, or updating, which is one latent variable identified in confirmatory factor analytic models of executive functions, predicts intelligence (both fluid and crystallised) in adults, but inhibition and shifting do not (Friedman et al., 2006), suggesting that not all executive functions are related to intelligence. We aimed to test this hypothesis in a group of children where both intelligence and executive functioning are developing rapidly. The present study tested 215 children aged between 7 years 1 month and 9 years 11 months on measures of working memory, shifting, inhibition and intelligence (fluid and crystallised) to determine the associations between executive functions and intelligence in children of these age groups. A single factor model of executive functions provided the best fit to the data, and this factor was a strong predictor of both fluid and crystallised intelligence. While each construct (EF, fluid and crystallised intelligence) is dissociable in developing children, EF is essentially unitary and equally related to both kinds of intelligence.

1. Introduction

Executive functioning is an umbrella term used to describe cognitive processes that are associated with goal-directed behaviour (Miller & Cohen, 2001). The development of executive functions and intelligence are of fundamental importance, as processes related to these constructs often influence how successful an individual is when performing complex tasks (Miyake et al., 2000) and consequently, in academic achievement (St. Clair-Thompson & Gathercole, 2006), and success in life (Garavan, Ross, & Stein, 1999). There has been a focus on three specific executive functions, inhibition, shifting and updating (often termed 'working memory' in some models), since the seminal research of Miyake et al. (2000) which investigated the related, yet separable, nature of these functions — coined the unity and diversity of executive functions (Miyake & Friedman, 2012; Miyake et al., 2000). Given that both fluid intelligence and executive functioning have been associated with frontal lobe functions (Duncan & Owen, 2000), Friedman et al. (2006) extended the Miyake et al. (2000) model of executive functions to determine which, if any, predicted fluid and crystallised intelligence (gF and gC respectively). They found that only updating predicted intelligence but, interestingly given a stronger association between EF and gF, updating predicted both gF and gC equally.

Although there are other theories of the structure of executive functions (see Miyake & Shah, 1999), the Miyake et al. (2000) model is widely cited as the seminal model. Consequently, most research has focussed on the three EFs proposed by Miyake et al.: (1) inhibition, or the suppression of prepotent or interfering responses or stimuli, indicated by tasks such as the Stroop, stop-signal, and antisaccade tasks; (2) shifting, or the ability to switch between tasks or mental sets, indicated by tasks that, for example, require participants to alternate between adding and subtracting numbers, and (3) updating, a major component of working memory that is implicated in the manipulation of incoming information, indicated by keep track, tone monitoring, and letter memory

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tasks (Kane & Engle, 2003; Miyake et al., 2000; Monsell, 2003). The critical feature of these executive functions are that they are all lower-order processes considered to be involved in a range of other higher-order functions, and that multiple measures can tap each function (Miyake et al., 2000). Miyake et al. used confirmatory factor analysis (CFA) to create latent variables for each of the three executive functions and found that they were all related, yet separable. The unity between the constructs was evidenced by moderately strong correlations between each latent variable (range $r = .42$ to $r = .63$). The common variance of inhibition, shifting and updating provided evidence of a unifying mechanism that is shared by each of these executive functions. However, when alternative models of the data were tested, having three separate latent variables was the best fit for the data, which justified the claim for discriminant validity (diversity) of the three EFs.

One of the pertinent questions in the literature relates to the distinctiveness of intelligence from EFs (Dennis et al., 2009). To test this, Friedman et al. (2006) used the Miyake et al. (2000) model to examine associations between executive functions and fluid and crystallised intelligence in young adults. Fluid intelligence (gF) is considered to be the ability to solve unfamiliar problems, and crystallised intelligence (gC), is considered to be the repository of previously acquired knowledge (Cattell, 1963). Friedman et al. replicated the structure of executive functions initially found in Miyake et al., and used the resulting model to test which if any executive function was related to gF and gC. At the level of the measurement model, a CFA indicated that unity (a high degree of common variance) was evidenced by moderately strong correlations between most of the three executive functions and two intelligence constructs (range $r = .31$ to $r = .68$). But again, when alternative measurement models of the data were tested, having five separate variables was the best fit for the data, which indicated the discriminant validity of inhibition, shifting, updating, and gF and gC. Furthermore, Friedman et al. used structural equation modelling (SEM) to determine which of the three EFs predict gF and gC. SEM allows a test of whether any executive function uniquely predicts either of the intelligences, by calculating associations between EFs and intelligence while controlling for EF intercorrelations. Once controlling for the common variance amongst the executive functions, Friedman et al. reported that updating was the only significant unique predictor of both gF and gC. Hence, Friedman et al. concluded that not all executive functions are related to intelligence in young adults.

Despite the developmental nature of executive functions (Shing, Lindenberger, Diamond, Li, & Davidson, 2010), intelligence and indeed frontal functioning (Casey, Giedd, & Thomas, 2000), and despite several attempts to replicate the Miyake et al. model in children (e.g., Duan, Wei, Wang, & Shi, 2010; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Willoughby, Blair, Wirth, Greenberg, & The Family Life Project Investigators, 2012), no previous research has attempted to extend the Friedman et al. model of EFs and intelligence to children. This study was designed to investigate the unity and diversity of executive functions and its relationship to intelligence in 7 and 9 year-old children, and the associations between these executive functions and intelligence within and between these age groups. These age groups were chosen for two reasons: firstly, cognitive development occurs at a rapid rate during childhood, with a critical period beginning around the age of 7 years (Diamond, 2002), and secondly, the structure of executive functions is thought to become increasingly differentiated (that is, decreasing unity and increasing diversity) from about 7 years onwards (Shing et al., 2010).

There are many fewer investigations of the structure of executive functioning in typically developing children compared to adults. And while there is a plethora of research into the development of individual executive functions (for a review, see Best, Miller, & Jones, 2009) and studies that investigate their relationships with developmental disorders, fewer studies have attempted to replicate the Miyake et al. (2000) model of EFs in typical children (Duan et al., 2010; Lehto et al., 2003; McAuley & White, 2011; Rose, Feldman, & Jankowski, 2011; Wiebe, Espy, & Charak, 2008; Willoughby et al., 2012; Wu et al., 2011). Of these, only two tested the relationship between executive functions with intelligence (Duan et al., 2010; Lehto et al., 2003), and none have tested their association with both gF and gC.

Wiebe et al. (2008) assessed different explanatory models of executive control in preschool children. Working memory and inhibition were the two EFs investigated in these children, and as such, two separable yet correlated factors were expected. These factors were created using tasks including a Digit Span task as an indicator of working memory and the Tower of Hanoi as an indicator of inhibition. A very high correlation was found between these two factors, with the authors concluding that a single general executive control factor was the best fit for the data (that is, unity and no diversity). Additionally, this general executive factor was age invariant when considering children aged 2 years 4 months to 3 years 11 months, and 4 years to 6 years. These results suggest that working memory and inhibition are not distinguishable in children up to the age of 6 years. Similarly, Shing et al. (2010) found that working memory (indicated by two abstract shapes tasks) and inhibition (indicated by two dots task, a Simon task, and an arrows task) were not differentiated in children aged 4–7 years. This relationship was also found in children aged 7 years to 9 years 6 months, however, these executive functions formed two distinct factors in children aged 9 years 6 months to 14 years 6 months. These studies suggest the possible differentiation of at least working memory and inhibition from mid-childhood.

In a direct replication of Miyake et al. (2000) with 108 children aged between 8 and 13 years (mean age of 10 years 6 months), Lehto et al. (2003) found similar relationships between inhibition, working memory, and shifting. Inhibition was measured by using the Tower of London and Matching Familiar Figures tasks as indicators; working memory was measured using Auditory Attention and Response, Spatial Span, Spatial Working Memory, and Mazes; shifting was measured using Word Fluency and the Trail-Making test. Lehto et al. replicated the results of Miyake et al., in that they found both unity and diversity, as evidenced by correlations (range $r = .63$ to $r = .65$) and model fit statistics.

Wu et al. (2011) also replicated the Miyake et al. (2000) model of EFs with 160 children aged 7–14 years (mean age of 10 years 1 month) by finding similar associations between shifting, inhibition, and working memory/updating. The Stroop task and Test of Everyday Attention for Children

(TEA-Ch) Sky Search task were indicators of inhibition; TEA-Ch Code Transmission was the indicator of working memory/updating; Creature Counting and Opposite World (both TEA-Ch subtests) and the Contingency Naming Test were used as indicators of shifting. Again, unity and diversity of EFs in children were reported, based on factor correlations (range $r = .38$ to $r = .82$) and model fit statistics.

Duan et al. (2010) replicated the Miyake et al. (2000) model of EFs in 61 slightly older children (aged 11–12 years, mean age of 11 years 11 months). Duan et al. used two 2-back tasks as indicators of updating, two go/no-go tasks as indicators of inhibition, and a digit shifting and a local–global task as indicators of shifting. Once more, unity and diversity of EFs in children were reported, based on factor correlations (range $r = .33$ to $r = .71$) and model fit statistics.

In short, the six critical papers that have attempted to replicate the Miyake et al. (2000) model of EFs in children have found that EFs appear to be unitary up to the age of 7 years (Shing et al., 2010; Wiebe et al., 2008; Willoughby et al., 2012). However, by the age of 10–11 years, these functions are distinguishable (Duan et al., 2010; Lehto et al., 2003; Wu et al., 2011).

Despite some research investigating the structure of executive functions in children, determining associations between executive functions and intelligence in children has been almost entirely neglected. The development of intelligence is itself characterised by increased differentiation with age. The two types of intelligence, gF and gC, are not distinguishable in early childhood (Cattell, 1967), but can clearly be distinguished by late childhood (Stankov, 1978). Early research in children investigated the association between a wider range of cognitive functions and gF (Welsh, Pennington, & Groisser, 1991). However, Welsh et al. (1991) found no significant correlations between any measure of executive function and gF. Since this initial work there has been little consideration of relationships between individual measures of executive functions and intelligence and no previous research has attempted to replicate the Friedman et al. (2006) model of executive functions and intelligence in children. Lehto et al. (2003) only used one composite measure of Intellectual Capacity, which was partialled out of correlations between the three EFs. They found no effect on the reported associations between inhibition, shifting and working memory, which supported their claim that intelligence was not related to these executive functions in children. More recently, Duan et al. (2010) found unity and diversity of executive functions in children in late childhood, and that Raven's Advanced Progressive Matrices (a commonly used measure of gF) was significantly predicted by updating and inhibition, but not shifting. In the case of both of these studies, however, the use of only single indicators of intelligence cannot distinguish gF and gC. In short, there is no study in children that has tested the Miyake et al. model of executive functions and concurrently tested the hypothetical relationship with gF and gC.

The aims of this study were to test the three latent trait Miyake et al. (2000) model of executive functions in a sample of children, and use the resulting model of executive functioning to determine the relationship between executive functioning and gF and gC. The age groups of 7 and 9 years were examined as this is a critical period for cognitive development, especially for executive functions (Diamond, 2002). Confirmatory factor analysis and structural equation modelling were conducted to investigate the relationships between inhibition, shifting, working memory and intelligence in children. In addition, we sought to test a number of specific hypotheses. Based on previous research it was hypothesised that development of executive functions and intelligence occurs with age (Anderson, Bucks, Bayliss, & Della Sala, 2011; Huizinga, Dolan, & van der Molen, 2006; Lehto et al., 2003; Shing et al., 2010); hence, older children will perform better than younger children on all tasks. It was hypothesised that the structural relations of executive functions and their relationship with intelligence would change between the ages of 7 and 9 years, as demonstrated with invariance testing of structural covariances between the two age groups. Specifically, it was predicted that 9 year olds will display increased differentiation of executive functions as evidenced by lower correlations between each of the indicators in the correlation matrix and more factors in the CFA than in comparison to 7 year olds. Furthermore, it was also hypothesised that inhibition, shifting and working memory would show a higher degree of unity than observed in young adults (Miyake et al., 2000), as evidenced by higher correlations between the latent traits, while still demonstrating a level of diversity, and that the diversity would be more apparent in 9 year olds than in 7 year olds. SEM also facilitated an examination of the unique predictive utility of executive functioning on intelligence in children. Given the rapid change in frontal functioning between seven and nine our final hypothesis was that while executive functioning would predict both gF and gC, we hypothesised that, in contrast to the Friedman et al. (2006) study with adults, executive functions would be more highly correlated with gF than gC.

2. Method

2.1. Participants

A total of 215 typically developing children aged between 7 years 1 month and 9 years 11 months (110 male and 105 female, $M = 8$ years 4 months, $SD = 1$ year 1 month) participated in the study. There were 120 children in the 7 year-old group (57 male and 63 female, $M = 7$ years 6 months, $SD = 3$ months), and 95 children in the 9 year-old group (53 males and 42 females, $M = 9$ years 6 months, $SD = 3$ months). Participants were recruited through Project K.I.D.S. (Kids' Intellectual Development Study), a child development research programme at the Neurocognitive Development Unit of the School of Psychology of the University of Western Australia. The measures used in this study were part of a larger battery of psychometric tests, computer tests and physiological measures administered to measure the cognitive, social, and emotional development of the children.

2.2. Materials

2.2.1. Inhibition

2.2.1.1. Stroop task (Stroop, 1935). A paper version of the Stroop task was used. The neutral condition of the task presented children with 30 strings of asterisks ranging between three and five in each string. The children had to name the colour of the ink as quickly as possible. The incongruent condition presented children with 30 colour words written in a different colour ink. The children had to state the colour of the ink, and suppress the prepotent response of saying the word (for example, if "BLUE" is presented in red ink, the children are required to say "Red"). The indicator of inhibition was the difference in time to complete the two conditions (incongruous–neutral).

2.2.1.2. Go/no-go. The task required the children to move their index finger from a left mouse button, press a right mouse button, and move back to the left button when a soccer ball appeared on screen (see Cragg, Fox, Nation, Reid, & Anderson, 2009, for a full description). A prepotent response was developed by having two blocks of 30 trials of this "go" condition, before two blocks of 100 trials each where a "no-go" stimulus (an Australian Rules football) was introduced on 25% of the trials. For these trials, children were required to keep their index finger on the left mouse button. The indicator of inhibition was the proportion of correct no-go trials (i.e. appropriate non-responses; partial inhibitions, where the children lifted their finger from the left mouse button but did not click the right button, were considered incorrect).

2.2.1.3. Compatibility reaction time. A computer-based two-choice reaction time task required children to make a simple judgement regarding the lengths of two lines. The stimuli were presented in the form of having to shoot aliens. Specifically, children had to press one of two buttons depending on whether the lengths of antennae on an alien were the same or different. Four blocks of 26 trials each built up a prepotent response for the buttons required for same and different lengths, after which a final block of 26 trials was administered, where the required button for a response were swapped. The indicator of inhibition was the difference between the mean reaction times of blocks 1–4 and block 5.

2.2.2. Working memory

2.2.2.1. Letter–number sequencing. Letter–number sequencing (LNS) is part of the Working Memory Index of the WISC-IV (Wechsler, 2003). The children were required to mentally sort series of letters and numbers into alphabetical and ascending order, and state this transformed sequence to the administrator. The indicator of working memory was the raw score from this measure, which is the total number of correct trials.

2.2.2.2. Backward digit span. Backward digit span is also a part of the Working Memory Index of the WISC-IV (Wechsler, 2003). The children were required to recall lists of numbers of increasing length in reverse order. The indicator of working memory was the raw score from this measure, which is the total number of correct trials.

2.2.2.3. Sentence repetition (NEPSY; Korkman, Kirk, & Kemp, 1997). A sentence is read by the administrator, with the child required to repeat the sentence verbatim. If the child repeats the sentence without error, two points are awarded for the trial. One point is awarded if one or two errors are made on the sentence. The indicator of working memory was the raw score from this measure, which is the total number of points across trials.

2.2.3. Shifting

2.2.3.1. Wisconsin Card Sorting Task (WCST; Heaton, Chelune, Talley, Kay, & Curtiss, 1993). Children were required to sort cards based on colour, form and number to one of four key cards. The children were not told how to categorise the cards, but receive immediate feedback on whether they have sorted the card correctly. The category changes after ten consecutive correct trials. The indicator of shifting used was the number of perseverative errors (when a participant does not change their categorisation strategy despite feedback indicating that it is incorrect).

2.2.3.2. Verbal fluency. Verbal fluency is a subtest of the British Abilities Scale (Elliott, Smith, & McCullouch, 1997). For 30 s, each child was required to generate names of animals, then to generate names of food as fast as possible. The indicator of shifting was the sum of correct words across the two categories.

2.2.3.3. Letter monitoring (Duncan, Emslie, Williams, Johnson, & Freer, 1996). Duncan et al.'s (1996) Letter monitoring task required children to read letters aloud from one side of a computer screen as they appeared, while ignoring letters on the opposite side and numbers. Near the end of each trial (twelve in total), a + or − symbol appeared, indicating that children should read letters from the right or left hand side of the screen respectively. Hence, on half of the trials, the child was required to switch their attention from one side of the screen to the other. The indicator of shifting was the number of correct switch trials.

2.2.4. Intelligence

In line with Friedman et al. (2006), intelligence was measured with two tasks for each of gF and gC respectively.

2.2.4.1. Cattell Culture Fair Intelligence Test (Scale 2, Cattell, 1973). The Cattell Culture Fair Intelligence Test (CCFIT) is a commonly used, nonverbal measure of gF. The task requires inductive reasoning about perceptual patterns, and consists of four timed subtests (series completion, odd-one-out, matrices, and topology), with items increasing in difficulty within each subtest. The CCFIT has been shown to load highly on a general factor (along with Raven's Progressive Matrices, another commonly used measure of gF) in psychometric studies of intelligence (Carroll, 1993). The indicator for gF was the raw score of this measure, which is the total number of correct items across all subtests.

2.2.4.2. Block design. Block design is a subtest from the Perceptual Reasoning Index of the WISC-IV (Wechsler, 2003). This task requires children to reconstruct patterns using blocks, with more points awarded in each trial for more accurate replications of the patterns. The indicator for gF was the raw score for this measure, which is the total number of points across trials.

Table 1
Descriptive statistics of executive function and intelligence measures before transformation for 7 year-olds (N = 120), 9 year-olds (N = 95), and all participants (N = 215) used in the analyses.

Task	7 year-olds		9 year-olds		All participants	
	M	*SD*	*M*	*SD*	*M*	*SD*
Inhibition						
Stroop[a]	31.84	15.57	18.12	8.36	25.72	14.55
Go/no-go[b]	.47	.22	.42	.21	.45	.22
Compatibility reaction time[c,*]	193.07	300.80	108.08	148.73	155.99	249.37
Working memory						
Letter–number sequencing[d]	13.58	4.30	17.26	3.27	15.18	4.29
Backward digit span[d]	5.85	1.46	6.66	1.52	6.21	1.54
Sentence repetition[e]	20.68	3.77	22.96	4.01	21.67	4.03
Shifting						
Wisconsin Card Sorting Test[f]	29.69	20.70	21.03	15.79	25.87	19.14
Verbal fluency[g]	19.66	4.89	23.82	5.21	21.50	5.44
Letter monitoring[d]	2.80	1.90	3.98	1.90	3.34	1.98
Fluid intelligence						
Cattell Culture Fair Intelligence Test[h]	26.46	6.41	31.84	7.00	28.82	7.18
Block design[d]	21.69	9.17	34.83	10.88	27.51	11.90
Crystallised intelligence						
Vocabulary[d]	24.14	5.45	33.23	7.62	28.19	7.92
Information[d]	13.55	2.85	17.75	2.85	15.38	3.53

Note.
[a] Difference between incongruous and neutral conditions (secs).
[b] Proportion correct.
[c] Difference between block 5 and blocks 1–4 (ms).
[d] Total trials correct.
[e] Total points scored.
[f] Number of words.
[g] Total items correct.
[*] We note that the SDs for Compatibility reaction time are quite high, but decrease after trimming and transformation to: 7 year-olds = −189.20 ms (SD = 240.70), 9 year-olds = −109.94 ms (SD = 146.39), all participants = −154.79 ms (SD = 208.46).

2.2.4.3. Vocabulary. The Vocabulary subtest from the Verbal Comprehension Index of the WISC-IV (Wechsler, 2003) was used as a measure of gC as it assesses previously acquired knowledge. For this task, participants are required to name pictures or provide definitions for words, with more points in each trial awarded for correct and clear definitions. The indicator of gC was the raw score of this measure, which is the total number of points across trials.

2.2.4.4. Information. Information is also a subtest from the Verbal Comprehension Index of the WISC-IV (Wechsler, 2003) that was used as a measure of gC. This task also assesses previously acquired knowledge, by requiring participants to answer questions about general factual knowledge, with more points awarded for correctness and clarity. The indicator of gC was the raw score of this measure, which is the total number of points across trials.

2.3. Procedure

A maximum of 24 children at a time attended Project K.I.D.S. for two consecutive days over a two week period. This

Table 2
Correlations between measures of executive functioning and intelligence in 7 year-olds (N = 120).

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Stroop	–												
2. Go/no-go	.16	–											
3. Compatibility reaction time	.07	.10	–										
4. Letter–number sequencing	.08	.01	.08	–									
5. Backward digit span	.15	.30**	.00	.34**	–								
6. Sentence repetition	−.01	.14	−.07	.25**	.24*	–							
7. Wisconsin Card Sorting Test	.13	.13	.07	.36**	.20*	.12	–						
8. Verbal fluency	.22*	.10	.13	.23*	.20*	.11	.21*	–					
9. Letter monitoring	.13	.09	.16	.28**	.16	−.09	.24*	.16	–				
10. Cattell Culture Fair Intelligence Test	.08	.10	.11	.47**	.38**	.21*	.42**	.33**	.42**	–			
11. Block design	.09	.14	.09	.26**	.29**	.20*	.31**	.23*	.27**	.53**	–		
12. Vocabulary	−.06	.03	−.08	.30**	.21*	.51**	.26**	.17	.15	.32**	.26**	–	
13. Information	−.10	−.01	−.02	.45**	.26**	.39**	.26**	.26**	.14	.38**	.22*	.68**	–

Note. 7 year-olds are above the diagonal, 9 year-olds are below.
[*] $p < .05$.
[**] $p < .01$.

Table 3
Correlations between measures of executive functioning and intelligence in 9 year-olds (N = 95).

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Stroop	–												
2. Go/no-go	.01	–											
3. Compatibility reaction time	−.03	.07	–										
4. Letter–number sequencing	.37**	.06	.14	–									
5. Backward digit span	.20	.02	.09	.23*	–								
6. Sentence repetition	−.01	.00	.18	.35**	.08	–							
7. Wisconsin Card Sorting Test	.18	−.01	.14	.23*	.07	.10	–						
8. Verbal fluency	.34**	.05	.13	.37**	.25*	.30**	.07	–					
9. Letter monitoring	.27*	−.05	.14	.38**	.27*	.19	.18	.15	–				
10. Cattell Culture Fair Intelligence Test	.24*	.06	.12	.27*	.07	.09	.29**	.23*	.27*	–			
11. Block design	.26*	−.09	.09	.34**	.14	.22*	.36**	.27*	.34**	.48**	–		
12. Vocabulary	.14	−.10	.19	.30**	.06	.66**	.19	.30**	.17	.19	.34**	–	
13. Information	.23*	−.05	.18	.40**	.25*	.55**	.18	.41**	.32**	.21*	.35**	.70**	–

Note.
* $p<.05$.
** $p<.01$.

two-week testing session occurred in the school holidays. All testing was presented in a child-friendly manner, and each testing session lasted 25 min. When not in testing sessions, meals and activities (such as games and arts) were scheduled to ensure the participants enjoyed themselves and did not become fatigued. At the conclusion of each two day testing period, all participants were given a Project K.I.D.S. t-shirt as a memento of their participation.

2.4. Transformation and outlier analysis

The distributions of the reaction time and proportion measures for the nine executive function measures and four intelligence measures were skewed and/or kurtotic. Hence, transformations were conducted to achieve normality. For all data, we followed the same procedures used by Miyake et al. (2000). Arcsine transformation was applied to all proportion measures (Go/no-go, Letter–number sequencing, Digit span backwards, Sentence repetition, WCST, Letter monitoring, and all intelligence measures), as this method creates more dispersion in scores close to floor and ceiling levels, but has little effect on scores in the range of .20–.80 (Judd & McClelland, 1989). For the Compatibility Reaction Time task, only correct trials longer than 200 ms were analysed, and a two-stage trimming procedure was conducted. First, between-subjects reaction time (RT) distributions were calculated separately for each condition (i.e. trials with and without inhibition respectively), and any extreme outliers were replaced with RTs that were 3 standard deviations (*SDs*) from the respective mean. Next, the within-subject RT distributions (again calculated separately for each condition) were examined for any RTs that were more than 3 *SDs* from the individual's mean RT, and these observations were replaced with RTs 3 *SDs* from the mean. As reaction times for individual trials within the Stroop task could not be recorded, trimming occurred by examining the entire between-subjects distribution and replacing any individual times for each block that were greater than 3 *SDs* from the mean with a value that was 3 *SDs* from the mean. All measures achieved a satisfactory level of normality after trimming/transformation.

As CFA and SEM are very sensitive to outliers, univariate and multivariate outlier analyses were conducted on the thirteen dependent variables. Specifically, a test score was considered a univariate outlier if it was greater than 3 *SDs*

Table 4
Correlations between measures of executive functioning and intelligence (N = 215).

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Stroop	–												
2. Go/no-go	.03	–											
3. Compatibility reaction time	.13	.06	–										
4. Letter–number sequencing	.32**	−.03	.17*	–									
5. Backward digit span	.26**	.13	.07	.36**	–								
6. Sentence repetition	.14	.03	.06	.36**	.22**	–							
7. Wisconsin Card Sorting Test	.23**	.05	.13	.38**	.20**	.17*	–						
8. Verbal fluency	.39**	.02	.18**	.40**	.31**	.29**	.22**	–					
9. Letter monitoring	.29**	−.01	.20**	.40**	.28**	.13	.28**	.26**	–				
10. Cattell Culture Fair Intelligence Test	.29**	.03	.19**	.48**	.31**	.24**	.41**	.38**	.43**	–			
11. Block design	.37**	−.04	.18**	.45**	.32**	.32**	.39**	.41**	.42**	.59**	–		
12. Vocabulary	.28**	−.10	.12	.45**	.25**	.63**	.31**	.40**	.30**	.40**	.52**	–	
13. Information	.28**	−.10	.14	.56**	.35**	.52**	.32**	.48**	.36**	.45**	.52**	.79**	–

Note.
* $p<.05$.
** $p<.01$.

Table 5
Fit indices for the full confirmatory factor analysis model and reduced models of executive functions (N = 215).

Model	χ^2	df	p	χ^2/df	CFI	RMSEA
1. Full three-factor	Not positive definite					
Two-factor models						
2. Inhibition + (Shifting = Working Memory)	20.11	19	.39	1.06	1.00	.02
3. Working Memory + (Shifting = Inhibition)	18.03	19	.52	0.94	1.00	.00
4. Shifting + (Inhibition = Working Memory)	Not positive definite					
5. Independent three factors	Not positive definite					
6. One-factor	**20.11**	**20**	**.45**	**1.01**	**1.00**	**.01**

Note. The endorsed model is indicated in bold. CFI, Bentler's Comparative Fit Index; RMSEA, Root-Mean-Square Error of Approximation.

from the between-subjects variable mean, and was replaced with a value that was 3 *SD*s from the mean. This affected no more than 1.9% of the observations for each task. No multivariate outliers were identified when using a Cook's *D* value of >1 (Cook & Weisberg, 1982). Finally, scores on all RT measures and WCST were multiplied by −1 so that a higher score indicated better performance. Thirty-two participants had missing data for one or more tasks. Although Little's (1988) MCAR test was significant [$\chi^2(156) = 211.72$; $p = .002$], this is most likely due to the large number of degrees of freedom. The χ^2/df value is less than 2 ($\chi^2/\mathrm{df} = 1.36$), arguing that the missing data is missing completely at random. These scores were estimated using the full information maximum likelihood method.

2.5. Statistical analysis

Amos 18 (Arbuckle, 2009) was used to estimate latent variable models with missing data. In both CFA and SEM, several fit indices were used to evaluate the fit of each model to the data. The χ^2/df statistic was used, because models with larger sample sizes and/or more degrees of freedom often show significant χ^2 values, despite having only marginal differences between the model and the data. χ^2/df being less than two is considered an indication of good model fit. Two other fit indices recommended by Hu and Bentler (1998) were also used: Bentler's comparative fit index (CFI), and the root-mean-square error of approximation (RMSEA). The criteria for excellent model fit based on these indices are greater than .95 and less than .05 respectively. However, models are acceptable with respective values of .90 and .10 (Blunch, 2008). Significance of correlation and path coefficients was determined in the same manner as Friedman et al. (2006). That is, χ^2 difference tests were conducted when removing an individual regression parameter. If the difference in model fit was significant, it indicated that the regression path makes a significant contribution to model fit. This method is more reliable than using test statistics that are based upon comparing standard errors of parameters (Gonzalez & Griffin, 2001).

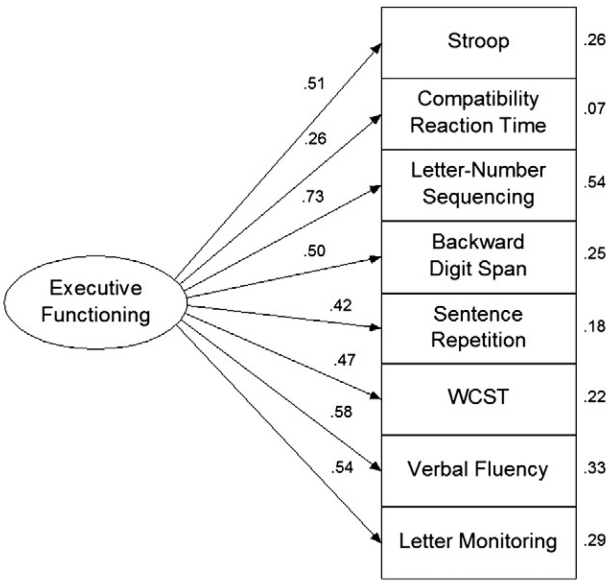

Fig. 1. The estimated one-factor model. Single-headed arrows have standardised factor loadings next to them. All factor loadings are significant to p<.01. The numbers on the right are the squared multiple correlations for each measurement variable.

Table 6
Fit indices for the full two-factor and one factor confirmatory factor analysis models of intelligence (N = 215).

Model	χ^2	df	p	χ^2/df	CFI	RMSEA
1. Full two-factor	**1.68**	**1**	**.20**	**1.68**	**1.00**	**.06**
2. One-factor	41.43	2	<.01	20.71	0.89	.30

Note. The endorsed model is indicated in bold. CFI, Bentler's Comparative Fit Index; RMSEA, Root-Mean-Square Error of Approximation.

3. Results

3.1. Descriptive statistics

Descriptive statistics of the raw scores of the thirteen measures before transformation are presented in Table 1, and the correlations between the measures being studied after transformation, outlier analysis and missing data estimation are presented in Tables 2–4.

3.2. Age-related changes in executive functions

The first hypothesis to be tested is that executive functions and intelligence develop with age. Hence, a series of Bonferroni-corrected ($\alpha = .004$) independent-sample t-tests were conducted to determine whether older children performed significantly better on measures of executive functions and intelligence than younger children. It was found that the 9 year old group performed significantly better on all measures than 7 year olds, with the exception of Go/no-go.

The second hypothesis was that the structure of executive functions and intelligence would change between 7 and 9 year olds. Measurement invariance between the two groups was tested. This is done by constraining covariances between measurement variable to be invariant between groups, and performing a chi-square difference test between this model and an unconstrained model. If the constrained model is not a significantly worse fit, it can be concluded that the associations between measurement variables do not differ between groups, and that the groups may be considered as one. It was found that the constrained model did not have a significantly worse fit [$\chi^2(182) = 189.29$; $p = .34$, $\chi^2/df = 1.04$]. Hence, analyses from this point forward are conducted on the complete sample group. However, the two age groups will be compared in some specific cases of interest.

Table 7
Fit indices for the full confirmatory factor analysis model and reduced models of executive functioning and intelligence (N = 215).

Model	χ^2	df	p	χ^2/df	CFI	RMSEA
1. Full three-factor	**108.31**	**51**	**<.01**	**2.12**	**0.93**	**.07**
2. One-factor	174.98	54	<.01	3.24	0.85	.10
Two-factor models						
3. gC + (EF = gF)	119.02	53	<.01	2.25	0.92	.08
4. gF + (EF = gC)	152.07	53	<.01	2.87	0.88	.09
5. EF + (gF = gC)	170.12	53	<.01	3.21	0.86	.10

Note. The endorsed model is indicated in bold. CFI, Bentler's Comparative Fit Index; RMSEA, Root-Mean-Square Error of Approximation.

3.3. The structure of executive functions in children

The current study followed the same procedure as Miyake et al. (2000) when testing CFA models. First, a full three-factor model was created, with correlations between latent variables all free to vary. However, this solution proved not admissible, as the covariance matrix was not positive definite. This was also the case for three of the alternative models that Miyake et al. also tested (models 1, 4, and 5 in Table 5). Based on these nonpositive definite matrices and the admissible models, it is apparent that a model displaying more unity than the original full three-factor model was the best fit of the data (see Table 5). When testing all models, Go/no-go (which was the only measure not to show a significant age difference) did not significantly load onto any latent variable in any model, so was subsequently removed from all analyses.

Although the three admissible models all reported excellent model fit indices, χ^2 difference tests found the unitary one-factor model to be no worse than the admissible two-factor models ($\Delta\chi^2 = 0$, $\Delta df = 1$, $p = 1.00$, and $\Delta\chi^2 = 2.08$, $\Delta df = 1$, $p = .15$ respectively). As the one-factor model is more parsimonious with no significant loss of fit, it is chosen as the best model (see Fig. 1)[1].

3.4. Intelligence in children

The same CFA procedure was applied to gF and gC. First, a full-two factor model was created, and then tested against a one-factor model. As the model fit statistics in Table 6 show, the one factor model was a significantly worse fit ($\Delta\chi^2 = 39.75$, $\Delta df = 1$, $p < .001$). While the gF–gC correlation of $r = .69$ ($p < .001$) is high, it is not large enough to warrant unity between gF and gC, as shown by the model fit statistics. The full two-factor model was also the best fit in the case of both the 7 year old group ($\Delta\chi^2 = 25.44$, $\Delta df = 1$, $p < .001$) and the 9 year old group ($\Delta\chi^2 = 17.77$, $\Delta df = 1$, $p < .001$) when analysed separately.

3.5. Associations between executive functions and intelligence in children

To test the hypothesis that executive functions would be related to both gF and gC, a third measurement model was created to examine associations between a unitary executive function, gF, and gC. The two executive function–intelligence correlations were both very high (executive function-gF $r = .89$, and executive function-gC $r = .83$). However, the

[1] Although the test of measurement invariance did not suggest any difference between the two groups, for completeness the preferred model was then tested on these age groups separately. Of the two models that produced admissible solutions in the 7 year old group, the one-factor model was the best fit to the data ($\chi^2 = 17.96$, $df = 20$, $p = .59$). However, it should be noted that the two factor model where inhibition = shifting (model 3 in Table 5) was also an excellent fit, although not significantly better ($\Delta\chi^2 = 3.31$, $\Delta df = 1$, $p = .07$). In the 9 year old group, the one-factor model had excellent fit, and was the only model that reported an admissible solution ($\chi^2 = 20.45$, $df = 20$, $p = .43$).

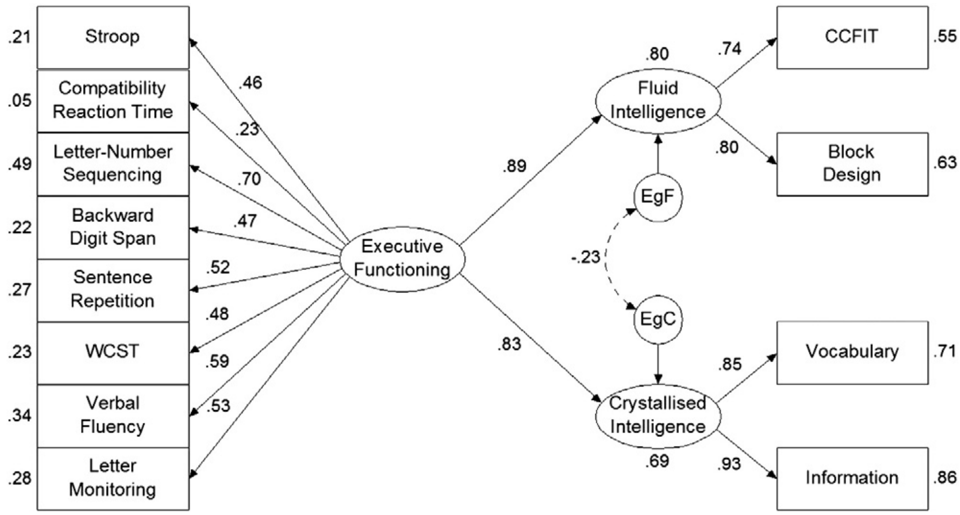

Fig. 2. Structural equation model predicting fluid intelligence (gF) and crystallised intelligence (gC) with executive functioning (EF). The dotted correlation between the residuals of gF and gC is nonsignificant. All other coefficients are significant to $p<.05$.

respective model fit indices show that the three constructs are distinguishable (see Table 7). Moreover, while the alternative model where executive functioning and gF are considered as a single construct does have acceptable fit indices, a χ^2 difference test indicated that a full three-factor model was a significantly better fit to the data ($\Delta\chi^2=10.71$, $\Delta df=2$, $p<.01$). Following Friedman et al. (2006), the two executive function–intelligence correlations were constrained to be equal and this did not significantly worsen model fit ($\Delta\chi^2=1.10$, $\Delta df=1$, $p=.29$). This argues that in the measurement model, executive functioning is equally related to gF and gC and suggests that a unitary executive function would be equally predictive of gF and gC in an SEM. However, the procedure used by Friedman et al. (2006) allows us to test statistically whether there is any differential relationship between potentially different executive functions, bearing in mind that while the unitary model has the best fit, the two factor model still had acceptable fit. So, in the SEM, we will attempt to predict gF and gC with a unitary executive function, and then a more differentiated two-factor executive function model more akin to Friedman et al.. There are two advantages of using SEM instead of simply relying upon the correlations in CFA models in this case: first, SEM allows the unique contribution of each executive function (in the second model) to be calculated. This could provide insight into the unique contributions of working memory and inhibition/shifting, or inhibition and working memory/shifting, which would be theoretically informative and therefore justify the use of the non-parsimonious model. Secondly, the residual associations between gF and gC can be considered after variance due to executive functions has been accounted for. That is, if there is a large difference between the reported values of the gF–gC correlation in the CFA and the correlation between the residual variances of gF and gC in the SEM, this would mean that executive functioning accounts for much of what is common between gF and gC.

In the CFA, executive functioning, gF and gC all correlated significantly. However, when SEM was conducted, executive functioning strongly predicted both gF and gC, but the correlation between the residuals of gF and gC became nonsignificant ($r=-.23$, $p=.28$; see Fig. 2 for complete SEM). Hence, the commonality between gF and gC is completely predicted by executive functioning.[2]

4. Discussion

The aims of this study were to test the three latent trait Miyake et al. (2000) model of executive functions in a sample of children, and use the resulting model of executive functioning to determine the relationship between executive functioning and gF and gC. The first hypothesis made was that development of executive functions and intelligence occurs with age (Anderson et al., 2011; Huizinga et al., 2006); hence, older children would perform better than younger children on all tasks. Previous research has found that there are rapid changes in cognitive development between 7 and 11 years of age (Best et al., 2009; Cattell, 1967), such as marked improvements in speed of processing, use of strategies, working memory, inhibition, and task switching (Diamond, 2002). With the exception of the Go/no-go task, the results supported this hypothesis.

It was hypothesised that the structural relations of executive functions and their relationship with intelligence would change between the ages of 7 and 9 years. However, in our sample, invariance testing showed that there was no difference in the structure of executive functions and intelligence between 7 year olds and 9 year olds.

In our sample, the latent traits of inhibition, working memory and shifting were indistinguishable from each other. Interestingly, although the three hypothesised executive functions were indistinguishable in this sample, the two intelligence constructs clearly formed two factors. In a

[2] Further SEM analyses were attempted with the two-factor executive function models described in Table 5. However, the SEMs for each of these analyses reported solutions that were inadmissible, as at least one standardised regression weight in each model was greater than 1, indicative of a model being misspecified.

sample of children aged 5–6 years, Cattell (1967) reported that the two constructs formed one factor, whereas Stankov (1978) observed the two intelligence factors in children aged 11–12 years. This suggests that gF and gC are initially unitary in the same manner as executive functions, but become distinguishable at an earlier stage than executive functions.

Previous research examining associations between executive functions and intelligence has reported mixed results. Duan et al. (2010) reported that inhibition and updating both significantly predicted gF in children; however, Lehto et al. (2003) and Welsh et al. (1991) found no associations between any executive functions and intelligence. However, prior to our study, no previous research had attempted to replicate the Friedman et al. (2006) model of executive functions and intelligence in children, by creating latent variables of both gF and gC. We hypothesised that executive functioning would predict both gF and gC. The relationships with gF and gC were identical in both age groups: executive functioning is highly related to intelligence in children aged 7–9 years whether this is conceptualised as gF or gC. The CFAs and SEMs showed that gF and gC shared 80% and 69% of their variance with executive functioning respectively. Furthermore, when associations with executive functioning were controlled for in the SEM, the previously high correlation between gF and gC in the CFA dropped to nonsignificance (when comparing the correlation between the two latent variables in the CFA with the correlation between the residuals of the two constructs in the SEM), indicating that executive functioning accounts for the association between gF and gC. In comparison to the young adult sample tested by Friedman et al. (2006), the proportion of variance in gF and gC explained by executive functioning is much larger in children. Specifically, inhibition, updating and shifting explained 43% and 51% of the variance in gF and gC in young adults respectively. Although greater proportions of variance of gF and gC are explained in children, sizeable proportions that are unique to each construct are still unaccounted for (20% and 31% respectively). This suggests either that other executive functions that have not been measured in our study, or processes that are not thought of as executive functions, contribute to intelligence.

We conclude that the differentiation of the two types of intelligence occurs earlier than that of differentiated executive functions. This difference between executive functions and intelligence in differentiation processes might be explained from a neuropsychological perspective: the three executive functions of interest are all commonly associated with activation of the prefrontal cortex (Duncan & Owen, 2000), and neuroimaging studies have found that activation of the prefrontal cortex is more diffuse in children than adults (Casey et al., 2000). Conversely, gF is also associated with the prefrontal cortex (Duncan, Burgess, & Emslie, 1995), but gC has previously been associated with activation of parietal regions of the brain (Geary, 2005). Perhaps these different areas of neural activation cause gF and gC to become separable earlier in development than executive functions, despite the fact that gC is usually considered a by-product of gF (Cattell, 1963). In other words, the differentiation of gF and gC may be caused by differences in development rates of frontal and non-frontal regions, whereas if all executive functions are frontal, then it seems that incomplete frontal development affects all executive function processes equally at this stage of development. The earlier differentiation of intelligence compared with the differentiation of executive functions has some support from previous research. Stankov (1978) reported a correlation between gF and gC of $r = .63$ in children aged 11–12 years, and Friedman et al. (2006) reported a correlation of $r = .62$ in young adults, suggesting that differentiation of intelligence occurs relatively early in development, and may reach adult levels in children as young as 11.

It is apparent that gF and gC are both highly associated with executive functioning, particularly so in childhood, and that executive functioning accounts for nearly all the association between the two, as evidenced by the nonsignificant correlation between the residuals of gF and gC in the SEM. This suggests that the process by which gF is converted into gC is mediated through executive functioning. By this we do not mean that the only common processes between gF and gC are themselves executive processes but rather we are claiming that if EF processes are engaged when children learn then this offers a mechanistic explanation for the association between gF and gC. This view of the relationship is consistent with the Friedman et al. (2006) data that showed that this residual correlation was significant in adults. This argues that the commonality between gF and gC is not the EF mechanisms themselves, but the process of engaging them which is more important for young children than adults where executive functions and intelligence become increasingly differentiated. Put another way, late in childhood, nonexecutive processes are becoming increasingly important in converting gF into gC.

The current study suggests several promising avenues of future research. First, using the Friedman et al. (2006) model of executive functions and intelligence in a longitudinal sample of children would provide a stronger test of the causal account between development (using age as a proxy measure) and change in the structure of executive functions and intelligence. Specifically, testing the same children twice or more over a period of several years allows for direct comparisons between age groups (assuming the same measures are used each time of testing), rigorously testing for the differentiation of executive functions and intelligence throughout childhood.

A second avenue is to apply the Friedman et al. (2006) model to an ageing population in order to ascertain a more complete picture of development of executive functions and intelligence throughout the lifespan. Previous research has found that deterioration of the frontal lobes as a result of ageing causes is associated with decreased performance on tasks measuring executive functions (Rodríguez-Aranda & Sundet, 2006). Additionally, Baltes, Cornelius, Spiro, Nesselroade, and Willis (1980) found that 'de-differentiation' occurs in intelligence in older adults. That is, as adults age, the gF–gC correlation increases, until the two constructs become unitary. Although Salthouse, Atkinson, and Berish (2003) examined the contributions of inhibition and updating to gF, using the Friedman et al. model would provide a more comprehensive depiction of lifespan development of executive functions and intelligence by including shifting and gC.

Another possible avenue for research involves attempting to uncover what else predicts intelligence. As mentioned previously, 20% and 31% of the variance in gF and gC respectively were not accounted for in our study. This means that either other executive functions not measured by us (but we would argue we have a broad sample of executive functions) or nonexecutive processes are associated with intelligence. Clearly processes influenced by sociocultural variables are a likely category of cognitive functions, while another might be other global processing properties such as speed of processing, which is related to, but can be distinguished from, executive processes (Fry & Hale, 1996, 2000; Kail & Salthouse, 1994).

Like Friedman et al. (2006), we would argue the current study has broader implications for intelligence research on two fronts. First, many cognitive theories of intelligence include executive functions in some form or other (e.g., Anderson, 1992, 2001; Dempster, 1991; Sternberg, 1988). For instance, Dempster (1991) argues that inhibitory processes are a major component of intelligent behaviour. Although different terms (such as mental or cognitive flexibility) are often used, shifting is also argued to be a core component of intelligence (Sternberg, 1988). However, while many common intelligence batteries include measures of working memory, other executive functions are ignored. Although it could be argued that this is less of a problem in younger children (because as we have shown executive functions are essentially unitary), it does imply that "traditional measures of intelligence are missing some fundamental supervisory functions" (Friedman et al., 2006, p. 178). Second, there is the potential that a theory of the development of executive functions may also explain a number of aspects of the developmental relationship between fluid and crystallised intelligence. We should acknowledge that the strength of an SEM approach is to test alternative models and the one we have chosen because of its influence in the field is the Miyake et al. (2000) model. However, SEM, at least in this form, is still essentially correlational and researchers are perfectly at liberty to reverse the paths themselves in our current model if theoretically motivated to do so. For example, the theoretical position of Karmiloff-Smith (1992) might suggest that fluid intelligence itself may emerge from crystallised processes rather than the other way round. And again it might be that the commonality we have found between intelligence and EF reflects working hypercognition in Demetriou's developmental framework (Demetriou & Valanides, 1998) rather than what we think of as the conventional processes considered to be components of executive functioning as outlined in the Miyake et al. (2000) model. It may be that developing SEM models inspired by other theoretical positions would be a fruitful path for future research.

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