Intelligence 47 (2014) 34–43

Contents lists available at ScienceDirect

Intelligence

The differentiation of executive functions in middle and late childhood: A longitudinal latent-variable analysis

Christopher R. Brydges [a,b,*], Allison M. Fox [b], Corinne L. Reid [a], Mike Anderson [a,b]

[a] School of Psychology and Exercise Science, Murdoch University, Murdoch WA 6150, Australia
[b] Neurocognitive Development Unit, School of Psychology, University of Western Australia, Crawley WA 6009, Australia

ARTICLE INFO

Article history:
Received 9 June 2014
Received in revised form 28 August 2014
Accepted 29 August 2014
Available online 26 September 2014

Keywords:
Children
Executive function
Shifting
Working memory
Inhibition

ABSTRACT

Executive functions are cognitive processes that are associated with goal-directed behaviour. Although these functions are commonly thought to be related yet separable in young adults, attempts to replicate this finding in children have been mixed, as executive functions are indistinguishable in children up to 9 years of age but are related yet separable by 10–11 years. We aimed to provide longitudinal evidence of the differentiation of executive functions in this age range. The present study tested 135 children on a range of inhibition, working memory, and shifting measures twice over a two year period (mean age = 8 years 3 months and 10 years 3 months) to determine if any changes in the structure of executive function occur in this age range. Longitudinal factor analyses showed that the structure of executive functions significantly differed between testing periods, and that the factor structure of executive functions changed from a one-factor (i.e. unitary) model to a two-factor model where working memory was separable yet related to an inhibition/shifting factor. Further structural equation models showed that the unitary factor from testing period 1 was highly, but not entirely, predictive of the two factors yielded from testing period 2. The results provide evidence for the development and differentiation of executive functions, and the distinction between general and specific executive abilities.

Executive functions are higher-order cognitive processes that allow for and control goal-directed behaviours (Miller & Cohen, 2001). The development of these functions is of critical importance, as they are commonly associated with performance on complex tasks (Miyake et al., 2000) and academic outcomes (St Clair-Thompson & Gathercole, 2006). One commonly accepted model of executive functions is the 'unity and diversity' model proposed by Miyake et al. (2000). Miyake et al. tested 137 young adults on multiple measures of three commonly theorised executive functions (prepotent response inhibition, updating of working memory, and task shifting), and extracted latent variables for each of these three constructs by using confirmatory factor analysis (CFA). The resultant model provided evidence of these constructs being related yet distinct from each other, as evidenced by moderately strong inter-factor correlations (range $r = .42$ to $r = .63$). This model proposes that there is a general, domain-free ability underlying all executive processes, as well as several independent abilities specific to each single executive function (Miyake & Friedman, 2012). The general, common ability causes each single executive function to correlate with each other, whereas the specific abilities cause each function to be separable from each other.

Although the Miyake et al. (2000) model is generally considered the seminal model of executive functions, attempts to replicate it in children have been mixed. Specifically, the structure of executive functions though early to mid-childhood, up to around the age of 9 years, appears to be unitary (i.e. a one-factor model of executive functioning is the best fit of the data). Wiebe, Espy, and Charak (2008) administered a range of

* Corresponding author at: Murdoch University, 90 South St, Murdoch, WA 6150, Australia. Tel.: +61 8 9360 6741; fax: +61 8 9360 6492.
E-mail address: c.brydges@murdoch.edu.au (C.R. Brydges).

http://dx.doi.org/10.1016/j.intell.2014.08.010
0160-2896/

inhibition and working memory tasks to 243 typically developing children aged between 2.3 and 6 years. The unitary model of executive functioning was found to be the best and most parsimonious fit of the data. Furthermore, invariance testing between the younger (2 years 4 months – 3 years 11 months) and older (4 years 0 months – 6 years 0 months) children found no structural differences in executive functioning between these two groups. That is, the unitary model was as good a fit in the younger children as it was in the older children. More recently, Lynn (1992) tested 228 young children (mean age 3.01 years) on a battery of working memory and inhibition tasks, and found that the best and most parsimonious fit for the data was also a one factor model of executive functioning. Willoughby, Wirth, Blair, and Greenberg (2012) found the same pattern of results when testing a sample of 5 year olds ($N =$ 1036) on a range of executive function measures. Once more, a unitary executive function factor was found to be the best and most parsimonious fit. A two factor model, where working memory was a separate factor to inhibition/shifting, was also tested; however, given that the model fit statistics were no better for this model than the unitary model, and that the correlation between the two factors was extremely high ($r =$ .89), it was concluded that executive functions are unitary in this age group. Finally, Brydges, Reid, Fox, and Anderson (2012) tested 215 typically developing children aged 7 and 9 years on a range of inhibition, working memory, and shifting measures. Although behavioural performance significantly improved between the two age groups, relations between measures was reported to be invariant (i.e. there were no differences in the underlying structure of executive functions between the ages of 7 and 9 years). Furthermore, when the Miyake et al. model of executive functions was tested in this sample, it was found that a single factor model of executive functions was the best fit for the data. That is, executive functions were reported to be unitary in typical children up to the age of 9 years.

At some point after the age of 9 years, the individual executive functions differentiate themselves from each other, so that by the age of 10–11 years, the Miyake et al. (2000) model of executive functions is observed (i.e. children display 'unity and diversity'). Wu et al. (2011) tested 185 children (mean age of 10.08 years) on measures of working memory, inhibition, and shifting, and reported that a full three factor model (i.e. a model with three factors that all significantly correlate with each other) was the best fit for the data in this sample. Lehto, Juujärvi, Kooistra, and Pulkkinen (2003) tested 108 8–13 year old children (with a mean age of 10.5 years) on several measures of inhibition, working memory, and shifting, and reported that the full three factor model was also the best fit of the data. Duan, Wei, Wang, and Shi (2010) also tested the structure of executive functions in 11 and 12 year old children (mean age of 11.88 years), and found similar results. Specifically, the three executive function factors were separate, but moderately correlated with each other. Lastly, Shing, Lindenberger, Diamond, Li, and Davidson (2010) tested the differentiation of inhibitory control and memory maintenance (similar to updating of working memory) in 263 children aged 4–14 years. Latent variable analyses found that the two youngest age groups (4–7 and 7–9.5 years) did not produce separate factors for the two constructs, but the oldest children (9.5–14 years) did show two distinct factors, again providing further support for the differentiation of executive functions during childhood. In short, the previous studies described provide consistent support for unity (i.e. a general executive ability) and diversity (abilities specific to each executive function) being evident in children around the age of 10 years and above.

This pattern of development could be due to contrasting developmental trajectories of the general executive ability and the specific abilities described by Miyake and Friedman (2012), and appears to be analogous to the differentiation hypothesis of intelligence (Garrett, 1946). Specifically, Garrett administered a range of intelligence subtests to children and adolescents, and reported stronger correlations between tasks in children. From this, he postulated that the structure of intelligence changes from a unified, general ability to more specific abilities through childhood development. More recent research (Deary et al., 1996; Detterman & Daniel, 1989; Legree, Pifer, & Grafton, 1996) have found stronger correlations between measures of cognitive abilities in lower IQ groups than in higher IQ groups, providing support for Garrett's differentiation hypothesis (Anderson & Nelson, 2005).

Considering the close associations between intelligence and executive functions from both behavioural (Ackerman, Beier, & Boyle, 2005; Friedman et al., 2006; Obonsawin et al., 2002) and neuroimaging perspectives (Duncan & Owen, 2000; Tsujimoto, 2008), it is possible that the differentiation hypothesis may also apply to the childhood development of executive functions. Although executive functions are known to develop rapidly throughout childhood (Best, Miller, & Jones, 2009), the unitary structure of executive functions observed repeatedly and the measurement invariance reported by Wiebe et al. (2008) and Brydges et al. (2012) in children aged up to 9 years suggests that the general ability ("unity") develops rapidly through early childhood in typical children, whereas the specific abilities ("diversity") appear to have not developed to an observable degree at this age. From around the age of 10 years, however, this shift from a unitary structure of executive functioning to distinguishable yet related constructs may be due to the differential development of abilities specific to each single executive function, possibly because the prefrontal cortex (a region of the brain that is commonly implicated in executive functioning, Niendam et al., 2012) has become functionally organised into fractionated systems by this age (Tsujimoto). Although this trend has been observed in the previous research described above, it has not been tested directly by using a longitudinal sample of children over this age range.

The aim of this study was to examine the longitudinal development of executive functions across this critical period when the structure of executive functions changes from unitary (up to about the age of 9 years) to displaying unity and diversity (from around the age of 10 years). Thus, it was hypothesised that executive functions develop with age (Best et al., 2009). It was predicted that performance would improve on all measures between testing periods. Furthermore, it was hypothesised that children in mid-childhood would display a unitary executive function (Brydges et al., 2012), whereas children in late childhood would display increased diversity of executive functions (Lehto et al., 2003). This was tested using factorial invariance testing, which is a statistical procedure that examines the relative contributions of each indicator onto a latent variable across time points. That is, if the loadings of each indicator do not change with time, it can be assumed that the underlying structure of the latent variable has not changed between the two time points. Conversely, if the loadings have significantly changed, then some structural change has occurred. It was predicted that factorial invariance of executive functions would not be observed between testing periods, and that the resultant CFA model of executive functioning in testing period 1 (referred to from now as T1) would be a one-factor model, whereas the CFA model from testing period 2 (T2) would display 2 or 3 related factors. From this, structural equation modelling (SEM) was conducted, with the T1 factor(s) predicting the T2 factor(s). Based on the assumption that the CFAs from T1 and T2 yielded one and two/three factors respectively, it was predicted that the T1 factor would be highly – but not completely – predictive of the T2 factors, due to the T2 factors comprising of general and specific executive abilities, whereas the T1 factor should be a general ability only.

1. Method

1.1. Participants

Participants were 135 typically developing children (66 females, 69 males). At T1, mean age was 8 years 3 months ($SD = 1$ year). At T2, mean age was 10 years 3 months ($SD = 1$ year). These children were recruited through Project K.I.D.S. (Kids' Intellectual Development Study) at the Neurocognitive Development Unit of the School of Psychology of the University of Western Australia, and were tested twice over a two year period (Anderson, Reid, & Nelson, 2001). Originally, advertisements were placed in newsletters of local schools, and interested parent/guardians were sent screening questionnaires to ensure the eligibility of their child. 228 children attended the first testing period (Brydges et al., 2012, tested the structure of executive functions in the 215 7- and 9-year olds in this sample). The measures used were part of a larger battery of tests designed to measure the cognitive, social, and emotional development of the children (Reid & Anderson, 2012). All participants were healthy at both times of testing, reported normal or corrected-to-normal vision and hearing, and had no reported history of neurological or psychiatric conditions. Their WISC-IV (Wechsler, 2003) IQ scores were within normal range at both T1 ($M = 107.35$, $SD = 12.89$) and T2 ($M = 109.49$, $SD = 11.20$).

1.2. Materials

All nine measures of executive function analysed by Brydges et al. (2012) were used in the current study, and are described in full detail in that paper.

Inhibition was measured using the Stroop task (Stroop, 1935), where the children were required to suppress the tendency to read the word, and name the colour of the ink that the word was printed in instead. In the neutral condition, the children were required to name the colour of a string of asterisks (dependent variable, or DV = naming time on incongruous trials – naming time on neutral trials). The Go/No-go task (Cragg, Fox, Nation, Reid, & Anderson, 2009) required the children to click a mouse button as quickly as possible when a soccer ball appeared on screen, but withhold their response when an Australian Rules football appeared (DV = proportion of correct no-go trials). A Compatibility Reaction Time task required participants to develop a prepotent response to two types of stimuli (if two lines were the same length, participants had to press the left button on a button box; if the two lines were different lengths, they pressed the right button). After four blocks of 26 trials each, the required button for a response were swapped for the fifth and final block of trials (DV = reaction time of block 5 – reaction time of blocks 1–4).

Working memory was measured using the Letter-Number Sequencing subtest of the WISC-IV (Wechsler, 2003), where children had to listen to a series of numbers and letters, and rearrange and repeat them in alphabetical and ascending order (DV = number of correct trials). WISC-IV Backward Digit Span (Wechsler, 2003) was also administered, where the children were required to listen to a series of digits and repeat them in the reverse order (DV = number of correct trials). The Sentence Repetition subtest of the NEPSY (Korkman, Kirk, & Kemp, 1997), where children are required to listen to sentences of increasing length, and repeat the sentences verbatim. Two points were awarded for a correct trial, and one point was awarded if one or two errors were made (DV = total number of points across trials).

Shifting was measured with the Wisconsin Card Sorting Test (WCST; Heaton, Chelune, Talley, Kay, & Curtiss, 1993), where participants were required to categorise cards based on colour, form and number to one of four key cards (DV = number of perseverative errors). The Verbal Fluency subtest of the British Abilities Scale (Elliott, Smith, & McCullouch, 1997) requires children to generate as many names of animals as possible in 30 s, then to generate names of food as fast as possible (DV = number of correct words). The Letter Monitoring task (Duncan, Emslie, Williams, Johnson, & Freer, 1996) 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 (DV = number of correct switch trials).

1.3. Procedure

For both of the testing periods, a maximum of 24 children attended Project K.I.D.S. for two consecutive days over a two week period. Parents delivered the children each morning at 8.30 am and collected them each day at 4.30 pm. This two-week testing session occurred in the school holidays. All testing was conducted in a child-friendly manner, and each testing session lasted 25 minutes. All tasks in the current study were administered individually, with the exceptions of Go/No-go, Compatibility Reaction Time, and Letter Monitoring, where up to six children completed these tasks in a group setting – there was a computer for each child to use at the same time, with trained administrators supervising the children and with computer screens oriented away from one another to prevent distraction. 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.

1.4. Statistical procedures

In order to achieve normality, we applied arcsine transformations to all proportion measures, as this method creates more dispersion in scores close to floor and ceiling levels (observed particularly in the WCST and Letter Monitoring tasks, respectively, in both testing periods), but has little effect on scores in the range of .20–.80 (Judd & McClelland, 1989). For the Compatibility Reaction Time task, only correct trials with reaction times 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. All measures achieved a satisfactory level of normality after trimming/transformation.

As CFA is sensitive to outliers, univariate and multivariate outlier analyses were conducted on the nine dependent variables. Specifically, a test score was considered a univariate outlier if it was greater than 3 *SDs* from the between-subjects variable mean, and was replaced with a value that was 3 *SDs* from the mean. This affected no more than 3% 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. Little's (1988) MCAR test was nonsignificant [$\chi^2(353) = 358.16$; $p = .41$], indicating that the missing data is missing completely at random. These scores were estimated using the expectation maximisation method.

Amos 20 (Arbuckle, 2011) 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. Three other fit indices recommended by (Hu & Bentler, 1998) were also used: Bentler's comparative fit index (CFI), the root-mean-square error of approximation (RMSEA), and the standardised root mean residual (SRMR). The criteria for excellent model fit based on these indices is greater than .95 for CFI, and less than .05 for RMSEA and SRMR, although greater than .90 and less than .08, respectively, are considered acceptable.

2. Results

Descriptive statistics of the raw measures (before any trimming or transformation procedures) are presented in Table 1, and correlations between measures after trimming and transformation are presented in Table 2.

2.1. Age-related changes in executive functions

The first hypothesis to be tested is that executive functions develop with age. Hence, a series of Bonferroni-corrected ($\alpha = .006$) paired-samples t-tests were conducted to determine whether performance improved between testing periods. It was found that performance significantly improved between testing periods on all measures with the exception of Compatibility Reaction Time, which did not reach the required alpha level ($p = .043$).

2.2. The structure of executive functions in children

The second hypothesis was that executive functions would show increased differentiation with development from mid- to late childhood. The analytic procedures conducted were adapted from those used previously by Hertzog and Schaie (1986) to test for longitudinal invariance in factor structure. Specifically, a two-factor model (with executive functioning at each time period being the two factors) was created with unconstrained factor loadings. To test for longitudinal invariance, an alternative model where factor loadings were constrained to be equal across time periods (for example, the Executive Functioning T1 – > Stroop T1 loading was constrained to be equal to the Executive Functioning T2 - > Stroop T2 loading) was created, and model fit statistics between these two

Table 1
Descriptive statistics of executive function measures before transformation for Time 1 and Time 2 used in the analyses (N = 135).

Task	Time 1		Time 2		Effect size of differences between testing periods (Cohen's *d*)
	M	*SD*	*M*	*SD*	
Inhibition					
Stroop[a]	27.07	14.45	15.83	9.65	0.93
Go/No-go[b]	.46	.22	.51	.20	0.24
Compatibility reaction time[c]	162.60	272.97	119.21	112.33	0.23
Working memory					
Letter-Number Sequencing[d] (/30)	14.50	4.50	17.52	3.11	0.79
Backward Digit Span[d] (/16)	6.24	1.48	6.93	1.57	0.45
Sentence Repetition[e] (/34)	21.36	3.70	24.17	3.60	0.77
Shifting					
Wisconsin Card Sorting Test[f]	26.91	20.65	11.45	6.91	1.12
Verbal Fluency[g]	20.80	5.17	24.01	5.25	0.62
Letter Monitoring[d] (/6)	3.32	2.05	4.87	1.42	0.89

Note. [a]Difference between incongruous and neutral conditions (sec). [b]Proportion correct. [c]Difference between block 5 and blocks 1–4 (ms). [d]Total trials correct. [e]Total points scored. [f]Number of perseverative errors. [g]Number of words. Values next to some tasks indicate maximum possible score.

Table 2
Correlations between measures of executive functioning between Times 1 and 2 (N = 135).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Stroop T1	-																	
2. Go/No-go T1	.08	-																
3. Compatibility Reaction Time T1	.20*	−.04	-															
4. Letter-Number Sequencing T1	.30**	−.01	.17*	-														
5. Backward Digit Span T1	.24**	.16	.10	.39**	-													
6. Sentence Repetition T1	.11	.12	.01	.34**	.26**	-												
7. WCST T1	.22*	.04	.15	.38**	.16	.14	-											
8. Verbal Fluency T1	.37**	.03	.20*	.40**	.33**	.29**	.25**	-										
9. Letter Monitoring T1	.26**	.04	.29**	.45**	.27**	.19*	.36**	.29**	-									
10. Stroop T2	.40**	.16	.29**	.37**	.32**	.17*	.33**	.47**	.39**	-								
11. Go/No-go T2	.19*	.44**	.17	.12	.34**	−.04	.17	.16	.23**	.19*	-							
12. Compatibility Reaction Time T2	.09	−.03	.07	.12	.02	.05	.24**	.21*	.29**	.16	−.05	-						
13. Letter-Number Sequencing T2	.10	.08	.09	.46**	.36**	.31**	.19*	.36**	.27**	.30**	.09	−.11	-					
14. Backward Digit Span T2	.14	.14	.08	.24**	.36**	.26**	.14	.20*	.10	.28**	.17*	.01	.26**	-				
15. Sentence Repetition T2	−.03	−.01	−.03	.29**	.25**	.68**	.15	.41**	.09	.12	−.03	.10	.30**	.34**	-			
16. WCST T2	.05	.14	.03	.24**	.15	.11	.39**	.13	.18*	.30**	.15	−.05	.14	.19*	.08	-		
17. Verbal Fluency T2	.27**	.10	−.07	.22*	.22*	.19*	.20*	.42**	.12	.38**	.23**	.21*	.06	.23**	.20*	.10	-	
18. Letter Monitoring T2	.25**	.02	.35**	.09	.11	−.04	.03	.22**	.18*	.22*	.01	−.10	.03	.12	−.11	.06	.14	-

Note. $^{*}p < .05$; $^{**}p < .01$.

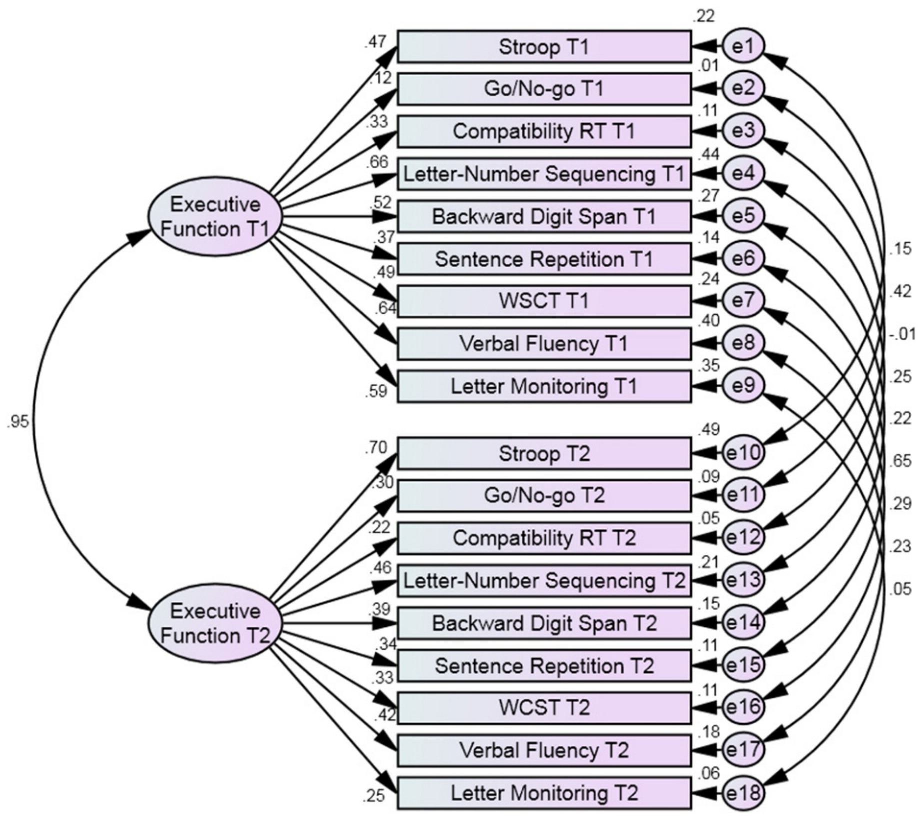

Fig. 1. Unconstrained model of executive function factor structure. Standardised values shown. Numbers next to curved lines with double-headed arrows are correlations. Numbers next to straight lines from factors to tasks are factor loadings. Numbers to the right of tasks are squared multiple correlations.

models were compared. The rationale for this is that if invariance is observed, then each measure of executive functioning contributes equally to the structure of executive functioning across the two time periods. Conversely, if the constrained model has significantly worse fit than the unconstrained model, then it can be inferred that some structural changes have taken place in executive functioning between the two testing periods. Additionally, the error variances of each measure of executive functioning were allowed to correlate across time in both models (see Hertzog & Schaie, 1986). As we were testing changes in executive functioning across time, any factor loadings that were nonsignificant were kept in all CFA models in order to analyse any changes between the task and the executive functioning factor.

The unconstrained model of executive functions is shown in Fig. 1. The model fit statistics for this model were generally acceptable, $\chi^2(125) = 215.48$, $p < .001$, $\chi^2/\text{df} = 1.72$, CFI = .83, RMSEA = .073, SRMR = .08. In the next stage of the analysis, the parameter restrictions described above were imposed in order to test the longitudinal invariance of the structure of executive functions. This constrained model was a significantly worse fit for the data than the unconstrained model ($\Delta\chi^2 = 58.64$, $\Delta\text{df} = 9$, $p < .001$), implying that the factorial structure of executive functions changed between testing periods.

Given this, separate analyses were conducted on the structure of executive functions within each testing period. These analyses followed the same procedure as Miyake et al. (2000). First, a three-factor model was created, with correlations between factors all free to vary. From this, a series of nested models were tested by applying a series of constraints to the inter-factor correlations (e.g., fixing a correlation to 1 in order to test the model fit statistics of a two-factor model). In T1, a one-factor model of executive functioning was the best and most parsimonious fit for the data, although two two-factor models also provided adequate solutions. chi-Square difference tests showed that the one-factor model did not have significantly worse fit than these two two-factor models ($\Delta\chi^2 = 0.92$, $\Delta\text{df} = 1$, $p = .34$ and $\Delta\chi^2 = 2.45$, $\Delta\text{df} = 1$, $p = .12$ respectively). Analysis conducted on the full three-factor model reported a non-positive definite covariance matrix, implying model misspecification (see Table 3 for all model fit statistics, and Fig. 2, Panel A for the final one-factor measurement model). In T2, a two-factor model where working memory was related ($r = .56$, $p < .001$) but separable from an inhibition/shifting factor was the best fit for the data and had mostly acceptable model fit statistics, although the CFI value was low. A one-factor model was also an acceptable solution, but had significantly worse fit ($\Delta\chi^2 = 13.49$, $\Delta\text{df} = 1$, $p < .001$). Consistent with T1, the full three-factor model had a non-positive definite covariance matrix, implying model misspecification (see Table 4 for all model fit statistics, and Fig. 2, Panel B for the final two-factor model).

To further examine developmental changes in executive functions between these age groups, SEM was conducted with the unitary 'executive functioning at T1' factor predicting the two factors extracted from the CFA of T2. The advantage of using SEM in this instance is that we can examine associations between the two dependent variables after the variance explained by the independent variables has been accounted for. Specifically, if the residual variances of the inhibition/shifting and working memory factors do not significantly correlate, it can be assumed that the variance shared between these factors has been completely accounted for by the T1 factor and, more broadly, the variance associated with a general executive ability in T2 is accounted for, and only specific abilities remain unaccounted for (i.e. that the residual variance of the Working Memory T2 factor is the specific working memory ability, and the residual variance of the Inhibition/Shifting factor are abilities specific to inhibition/shifting). From this, if the independent variable does not account for *all* of the variance in the two dependent variables, then it can be argued that some specific abilities have developed between testing periods, as the variance of the general executive factor is not accounting for it.

First, an unconstrained SEM was conducted, where the unitary T1 factor predicted the two factors from T2, and the residuals of these two factors were free to correlate (the residuals of each measure e.g. the Stroop task at each testing period were also free to correlate with each other). Model fit was acceptable, although the CFA was slightly low again [$\chi^2(123) = 208.71$, $p < .001$, $\chi^2/\text{df} = 1.70$, CFI = .84, RMSEA = .072, SRMR = .08]. The correlation between the two residuals was found to be non-significant ($r = -.19$, $p = .60$). Hence, the commonality between the inhibition/shifting and working memory factors is completely predicted by executive functioning at T1.

Next, constraints were placed on the paths from the unitary T1 factor to each of the T2 factors, one at a time. Specifically, each of these regression weights was constrained to 1 to determine if the T1 factor accounted for all the variance in either or both of the T2 factors. In both cases, model fit became significantly worse ($\Delta\chi^2 = 5.81$, $\Delta\text{df} = 1$, $p = .02$ and $\Delta\chi^2 = 504.48$, $\Delta\text{df} = 1$, $p < .001$), indicating that the T1 factor does not account for all the variance in either of the T2 factors. Fig. 3 shows this SEM (correlations between residuals of measures

Table 3
Fit indices for the Full Confirmatory Factor Analysis Model and Reduced Models of Executive Functions at Testing Period 1 (N = 135).

Model	χ^2	df	p	χ^2/df	CFI	RMSEA	SRMR
1. Full three-factor	Not positive definite						
Two-factor models							
2. Inhibition + (Shifting = Working Memory)	25.01	26	.52	0.96	1.00	.00	.05
3. Working Memory + (Shifting = Inhibition)	23.48	26	.61	0.90	1.00	.00	.05
4. Shifting + (Inhibition = Working Memory)	Not positive definite						
5. Independent three factors	Not positive definite						
6. One-factor	**25.93**	**27**	**.52**	**0.96**	**1.00**	**.00**	**.05**

Note. The endorsed model is indicated in bold. CFI, Bentler's Comparative Fit Index; RMSEA, root-mean-square error of approximation; SRMR, standardised root mean residual.

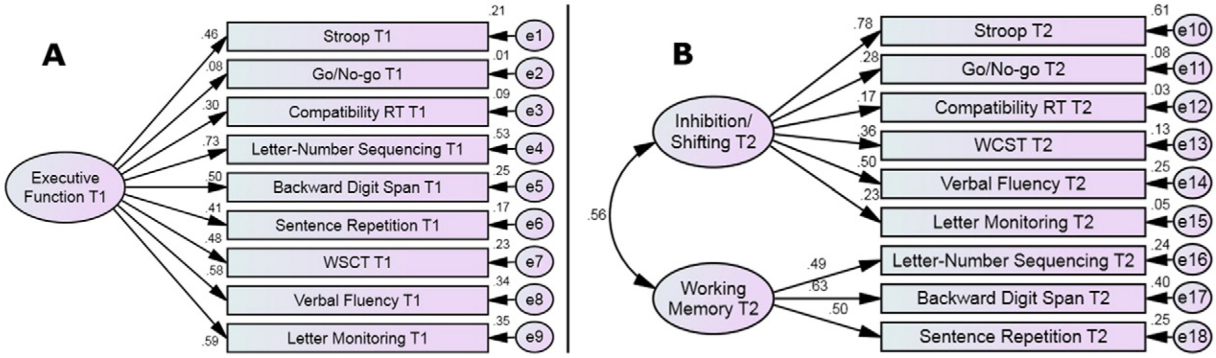

Fig. 2. The best fitting models of executive functioning from each testing period. Panel A: The estimated one-factor model from testing period 1. Panel B: The estimated two-factor model, where working memory is distinguishable from inhibition/shifting, from testing period 2.

have been removed for clarity. A figure including these is available upon request from the authors).

3. Discussion

The aim of this study was to examine the longitudinal development of executive functions from mid- to late childhood. It was hypothesised that executive functioning develops throughout childhood (Best et al., 2009); hence, performance would improve as children age. Previous research has shown rapid improvements in cognitive functions, including working memory, inhibition, and task switching between the ages of 7 and 11 years (Diamond, 2002). With the exception of the Compatibility Reaction Time task, the results supported this hypothesis. It should be noted that a proportion of these improvements may be due to practice/retest effects (Calamia, Markon, & Tranel, 2012), however, there is also a large body of cross-sectional research (Best et al., 2009) that suggests that childhood development is a major driver of these improvements in performance.

It was hypothesised that the structure of executive functions would change, and become more differentiated, between the ages of 9 and 10 years. Factorial invariance testing showed that there were structural differences in executive functioning between testing periods, and subsequent CFA testing showed that the structure of executive functions changed from a one-factor model to a two-factor model where working memory was distinguishable from inhibition and shifting. Furthermore, SEM analyses showed that the unitary factor observed at T1 was highly, but not entirely, predictive of the two factors observed at T2, and that the residual variances of the two T2 factors were not associated with any tasks measuring other executive functions, providing evidence of some development of abilities specific to each executive function. Previous research has shown that specific executive functions are indistinguishable from each other in typically developing children until around the age of 9 years (Brydges et al., 2012; Hughes, Ensor, Wilson, & Graham, 2009; Shing et al., 2010; Wiebe et al., 2008, 2011; Willoughby et al., 2012), but are separable yet related by the age of 10–11 years (Duan et al., 2010; Lehto et al., 2003; Wu et al., 2011). The findings of the current study confirm this general trend observed in the previous research.

One possible interpretation of these results is that the differentiation hypothesis of intelligence also applies to the development of executive functions (Garrett, 1946). As Miyake et al. (2000) state, executive functions comprise of a general executive ability that is common to all executive functions (and is why they correlate with each other), and abilities specific to each individual executive function (which is why executive functions are separable from late childhood). In young children, a unitary factor of executive functioning is implies that individual executive functions are indistinguishable until the age of 9 years, therefore, specific executive abilities have not begun developing at this point (or have only developed a negligible amount) and children are reliant upon their general executive ability, which rapidly develops through childhood, as evidenced by significant improvements in task performance with age. The specific abilities appear to begin developing, or reach a point where they have developed enough to make individual executive functions distinguishable from each other,

Table 4
Fit indices for the Full Confirmatory Factor Analysis Model and Reduced Models of Executive Functions at Testing Period 2 (N = 135).

Model	χ^2	df	*p*	χ^2/df	CFI	RMSEA	SRMR
1. Full three-factor	Not positive definite						
Two-factor models							
2. Inhibition + (Shifting = Working Memory)	54.37	26	.001	2.09	0.73	.09	.08
3. Working Memory + (Shifting = Inhibition)	**41.07**	**26**	**.03**	**1.58**	**0.85**	**.07**	**.07**
4. Shifting + (Inhibition = Working Memory)	Not positive definite						
5. Independent three factors	Not positive definite						
6. One-factor	54.56	27	.001	2.02	0.73	.09	.08

Note. The endorsed model is indicated in bold. CFI, Bentler's Comparative Fit Index; RMSEA, root-mean-square error of approximation; SRMR, standardised root mean residual.

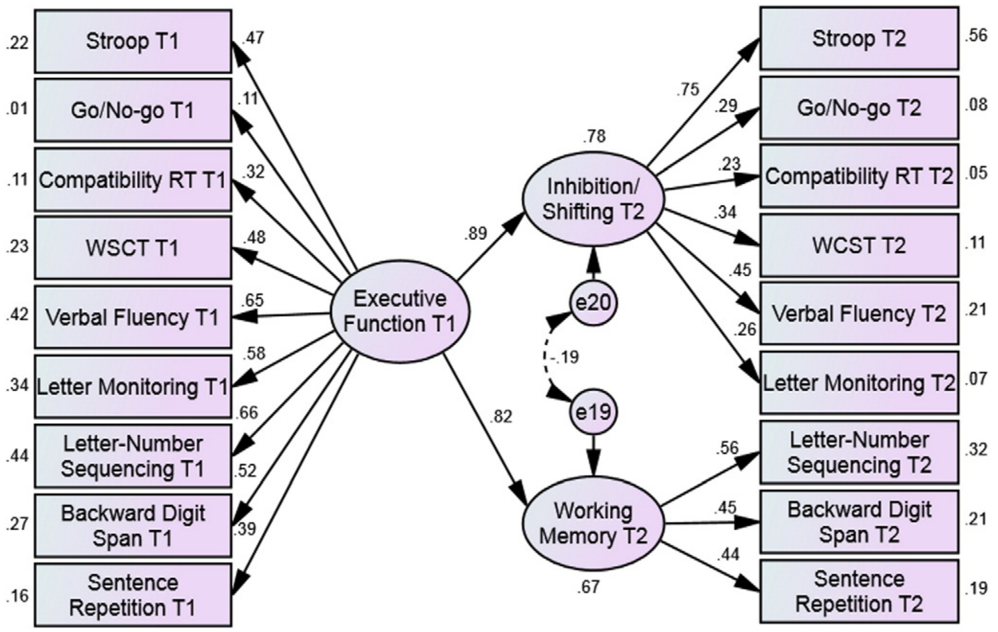

Fig. 3. Structural equation model predicting the two testing period 2 factors with executive functioning at testing period 1. The dotted correlation between the residuals of the two testing period 2 factors and the Go/No-go T1 factor loading are nonsignificant, but left in for completeness. All other coefficients are significant to $p < .05$.

at the age of 10 years. Hence, the current study has provided evidence of independent developmental trajectories of general and specific executive processes.

The results of the current study are also supported by developmental neuroimaging studies. Previous research has reported parallels in maturation of executive functions with neural development through childhood and adolescence (Amso & Casey, 2006; Durston et al., 2006). Specifically, whilst behavioural performance increases and executive functions become increasingly more distinguishable, decreases in neural activation (possibly due to less cognitive effort being needed with increasing development) and increases in focalisation are observed (Brydges, Anderson, Reid, & Fox, 2013; Casey, Giedd, & Thomas, 2000; Kelly et al., 2009; Tsujimoto, 2008). It may be of interest to conduct a longitudinal neuroimaging study across childhood and adolescence to observe at what point of development the neural correlates of single executive functions become distinguishable from each other, as this could provide insight into whether neural and behavioural development are parallel processes, or whether neural development is a precursor to behavioural development.

The results of the current study have implications for developmental theories of intelligence. Although working memory/updating has often been found to be a predictor of intelligence in adults (Ackerman et al., 2005; Friedman et al., 2006), Demetriou et al. (2014) proposed a cyclic theory of the development of intelligence, where working memory and processing speed alternate as major predictors of intelligence through childhood development (the major difference between Demetriou et al.'s theory and the current study being that we examined the development of several executive functions simultaneously, whereas Demetriou et al. studied working memory and processing speed). It could be that the general executive ability, rather than a specific working memory ability, is predictive of intelligence at ages 4–6 years, but the specific working memory ability is predictive of intelligence at ages 8–11 years (however, when examining several executive functions simultaneously, the specific ability has not developed enough to be distinguishable). Longitudinal research examining the development of multiple executive functions, processing speed, and intelligence would provide a clear picture of the differential development trajectories of these processes, and their associations with each other.

More broadly, as Brydges et al. (2012) and Friedman et al. (2006) discuss, many theories of intelligence include executive functions to some degree (e.g., Anderson, 1992, 2001; Demetriou et al., 2014; Dempster, 1991), yet many intelligence batteries only include measures of working memory, whilst neglecting other executive functions. Up to around the age of 9 years, this may not matter (as executive functions are indistinguishable from one another), but from this age onwards it could be argued that intelligence batteries are often missing commonly theorised associates of intelligence (Friedman et al., 2006).

It should be noted, however, that the results of the current study report only two factors in the 10-year old group, whereas previous studies have reported three (i.e. an inhibition factor has been distinguishable from a shifting factor in other studies). It is possible that this is due to differences in the developmental trajectories of each of the specific executive abilities. That is, it may be the case that working memory-specific abilities begin developing slightly earlier than inhibition-specific and shifting-specific abilities. Alternatively, it could be that there are some executive abilities that are shared by inhibition and shifting, but not by working memory. By nature, both inhibition and shifting require a 'stop' process to some degree (though shifting also requires a 'change' as well, i.e. the participant has to change from the prepotent response, rather than simply inhibit any response), so it could be that some interference control processes are shared between these two processes (Friedman & Miyake, 2004). Following on from this, it is possible that differences in the measures used between studies may also cause some inconsistencies. For instance, Duan et al. (2010) administered two Go/No-go tasks (both simply requiring a complete 'stop', or shutdown of all responses) to create an inhibition factor, whereas the current study used a Go/No-go task, the Stroop task, and a Compatibility Reaction Time task, the latter two of which require 'stop' and 'change' processes. However, the fact that increased differentiation was still readily observed provides strong evidence of the development of executive function-specific processes occurring at this age (Garrett, 1946).

In conclusion, the current study has provided evidence of the development and differentiation of executive functions occurring in mid-childhood. Behavioural performance improved on measures of executive functioning, and the factor structure changed from a unitary model, to a two factor model where working memory was separable from (but still moderately related to) inhibition and shifting. Theories of developmental cognition would benefit from considering the distinction between and differing developmental trajectories of general and specific executive abilities throughout childhood and adolescence.

Acknowledgements

This research was supported by an Australian Research Council grant DP0665616 awarded to M.A., A.M.F., C.L.R., and Professor Dorothy V.M. Bishop. We wish to thank Aoibheann O'Brien, Catherine Campbell, and Kaitie MacNamara for their help with coordination of Project K.I.D.S.

References

Ackerman, P. L., Beier, M. E., & Boyle, M.O. (2005). Working memory and intelligence: The same or different constructs? *Psychological Bulletin*, *131*(1), 30–60. http://dx.doi.org/10.1037/0033-2909.131.1.30.

Amso, D., & Casey, B. (2006). Beyond what develops when neuroimaging may inform how cognition changes with development. *Current Directions in Psychological Science*, *15*(1), 24–29.

Anderson, M. (1992). *Intelligence and development: A cognitive theory.* Oxford, UK: Blackwell.

Anderson, M. (2001). Annotation: Conceptions of intelligence. *Journal of Child Psychology and Psychiatry*, *42*(3), 287–298. http://dx.doi.org/10.1111/1469-7610.00722.

Anderson, M., & Nelson, J. (2005). *Individual differences and cognitive models of the mind: using the differentiation hypothesis to distinguish general and specific cognitive processes.* Measuring the mind: Speed, control, and age, 89.

Anderson, M., Reid, C., & Nelson, J. (2001). Developmental changes in inspection time: What a difference a year makes. *Intelligence*, *29*(6), 475–486.

Arbuckle, J. L. (2011). *IBM SPSS Amos 20 user's guide.* Amos Development Corporation, SPSS Inc.

Best, J. R., Miller, P. H., & Jones, L. L. (2009). Executive functions after age 5: Changes and correlates. *Developmental Review*, *29*(3), 180–200. http://dx.doi.org/10.1016/j.dr.2009.05.002.

Brydges, C. R., Anderson, M., Reid, C. L., & Fox, A.M. (2013). Maturation of cognitive control: Delineating response inhibition and interference suppression. *PLoS ONE*, *8*(7), e69826. http://dx.doi.org/10.1371/journal.pone.0069826.

Brydges, C. R., Reid, C. L., Fox, A.M., & Anderson, M. (2012). A unitary executive function predicts intelligence in children. *Intelligence*, *40*(5), 458–469. http://dx.doi.org/10.1016/j.intell.2012.05.006.

Calamia, M., Markon, K., & Tranel, D. (2012). Scoring higher the second time around: Meta-analyses of practice effects in neuropsychological assessment. *The Clinical Neuropsychologist*, *26*(4), 543–570. http://dx.doi.org/10.1080/13854046.2012.680913.

Casey, B. J., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological Psychology*, *54*(1–3), 241–257. http://dx.doi.org/10.1016/s0301-0511(00)00058-2.

Cook, R. D., & Weisberg, S. (1982). *Residuals and influence in regression.* New York: Chapman & Hill.

Cragg, L., Fox, A., Nation, K., Reid, C., & Anderson, M. (2009). Neural correlates of successful and partial inhibitions in children: An ERP study. *Developmental Psychobiology*, *51*(7), 533–543. http://dx.doi.org/10.1002/dev.20391.

Deary, I. J., Egan, V., Gibson, G. J., Austin, E. J., Brand, C. R., & Kellaghan, T. (1996). Intelligence and the differentiation hypothesis. *Intelligence*, *23*(2), 105–132.

Demetriou, A., Spanoudis, G., Shayer, M., van der Ven, S., Brydges, C. R., Kroesbergen, E., et al. (2014). Relations between speed, working memory, and intelligence from preschool to adulthood: Structural equation modeling of 14 studies. *Intelligence*, *46*, 107–121. http://dx.doi.org/10.1016/j.intell.2014.05.013.

Dempster, F. N. (1991). Inhibitory processes: A neglected dimension of intelligence. *Intelligence*, *15*(2), 157–173. http://dx.doi.org/10.1016/0160-2896(91)90028-c.

Detterman, D. K., & Daniel, M. H. (1989). Correlations of mental tests with each other and with cognitive variables are highest for low IQ groups. *Intelligence*, *13*(4), 349–359.

Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss, & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466–503). New York: Oxford University Press.

Duan, X., Wei, S., Wang, G., & Shi, J. (2010). The relationship between executive functions and intelligence on 11- to 12-year-old children. *Psychological Test and Assessment Modeling*, *52*(4), 419–431.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology*, *30*(3), 257–303. http://dx.doi.org/10.1006/cogp.1996.0008.

Duncan, J., & Owen, A.M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences*, *23*(10), 475–483. http://dx.doi.org/10.1016/s0166-2236(00)01633-7.

Durston, S., Davidson, M. C., Tottenham, N., Galvan, A., Spicer, J., Fossella, J. A., et al. (2006). A shift from diffuse to focal cortical activity with development. *Developmental Science*, *9*(1), 1–8.

Elliott, C. D., Smith, P., & McCullouch, K. (1997). *British Abilities Scales II.* Windsor, UK: NFER-Nelson.

Friedman, N.P., & Miyake, A. (2004). The relations among inhibition and interference control functions: A latent-variable analysis. *Journal of Experimental Psychology: General*, *133*(1), 101–135. http://dx.doi.org/10.1037/0096-3445.133.1.101.

Friedman, N.P., Miyake, A., Corley, R. P., Young, S. E., DeFries, J. C., & Hewitt, J. K. (2006). Not all executive functions are related to intelligence. *Psychological Science*, *17*(2), 172–179. http://dx.doi.org/10.1111/j.1467-9280.2006.01681.x.

Garrett, H. E. (1946). A developmental theory of intelligence. *American Psychologist*, *1*(9), 372–378.

Heaton, R. K., Chelune, G. J., Talley, J. L., Kay, G. G., & Curtiss, G. (1993). *Wisconsin Card Sorting Test Manual: Revised and expanded.* Odessa, FL: Psychological Assessment Resources.

Hertzog, C., & Schaie, K. W. (1986). Stability and change in adult intelligence: I. Analysis of longitudinal covariance structures. *Psychology and Aging*, *1*(2), 159–171.

Hu, L. -T., & Bentler, P.M. (1998). Fit indices in covariance structure modeling: Sensitivity to underparameterized model misspecification. *Psychological Methods*, *3*(4), 424–453. http://dx.doi.org/10.1037/1082-989x.3.4.424.

Hughes, C., Ensor, R., Wilson, A., & Graham, A. (2009). Tracking executive function across the transition to school: A latent variable approach. *Developmental Neuropsychology*, *35*(1), 20–36. http://dx.doi.org/10.1080/87565640903325691.

Judd, C. M., & McClelland, G. H. (1989). *Data analysis: A model-comparison approach.* San Diego, CA: Harcourt Brace Jovanovich.

Kelly, A.M. C., Di Martino, A., Uddin, L. Q., Shehzad, Z., Gee, D.G., Reiss, P. T., et al. (2009). Development of anterior cingulate functional connectivity from late childhood to early adulthood. *Cerebral Cortex*, *19*(3), 640–657. http://dx.doi.org/10.1093/cercor/bhn117.

Korkman, M., Kirk, U., & Kemp, S. (1997). *NEPSY.* New York: Psychological Corporation.

Legree, P. J., Pifer, M. E., & Grafton, F. C. (1996). Correlations among cognitive abilities are lower for higher ability groups. *Intelligence*, *23*(1), 45–57.

Lehto, J., Juujärvi, P., Kooistra, L., & Pulkkinen, L. (2003). Dimensions of executive functioning: Evidence from children. *British Journal of Developmental Psychology*, *21*(1), 59–80. http://dx.doi.org/10.1348/026151003321164627.

Little, R. J. A. (1988). A Test of missing completely at random for multivariate data with missing values. *Journal of the American Statistical Association*, *83*(404), 1198–1202. http://dx.doi.org/10.1080/01621459.1988.10478722.

Lynn, R. (1992). Does Spearman's g decline at high IQ levels? Some evidence from Scotland. *The Journal of Genetic Psychology*, *153*(2), 229–230.

Miller, E. K., & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*(1), 167–202. http://dx.doi.org/10.1146/annurev.neuro.24.1.167.

Miyake, A., & Friedman, N.P. (2012). The nature and organization of individual differences in executive functions four general conclusions. *Current Directions in Psychological Science*, *21*(1), 8–14.

Miyake, A., Friedman, N.P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. http://dx.doi.org/10.1006/cogp.1999.0734.

Niendam, T. A., Laird, A.R., Ray, K. L., Dean, Y. M., Glahn, D. C., & Carter, C. S. (2012). Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective, & Behavioral Neuroscience*, *12*(2), 241–268.

Obonsawin, M. C., Crawford, J. R., Page, J., Chalmers, P., Cochrane, R., & Low, G. (2002). Performance on tests of frontal lobe function reflect general intellectual ability. *Neuropsychologia*, *40*(7), 970–977. http://dx.doi.org/10.1016/s0028-3932(01)00171-3.

Reid, C. L., & Anderson, M. (2012). Left-brain, right-brain, brain games and beanbags: neuromythsin education. In P. Adey, & J. Dillon (Eds.), *Bad education: Debunking myths in education*. Maidenhead, UK: McGraw-Hill Education.

Shing, Y. L., Lindenberger, U., Diamond, A., Li, S. -C., & Davidson, M. C. (2010). Memory maintenance and inhibitory control differentiate from early childhood to adolescence. *Developmental Neuropsychology*, *35*(6), 679–697. http://dx.doi.org/10.1080/87565641.2010.508546.

St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *The Quarterly Journal of Experimental Psychology*, *59*(4), 745–759. http://dx.doi.org/10.1080/17470210500162854.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology: General*, *18*, 643–662. http://dx.doi.org/10.1037/0096-3445.121.1.15.

Tsujimoto, S. (2008). The prefrontal cortex: Functional neural development during early childhood. *The Neuroscientist*, *14*(4), 345–358. http://dx.doi.org/10.1177/1073858408316002.

Wechsler, D. (2003). *Manual for the Wechsler Intelligence Scale for Children* (4th ed.). San Antonio, TX: The Psychological Corporation.

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology*, *44*(2), 575–587. http://dx.doi.org/10.1037/0012-1649.44.2.575.

Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A., Chevalier, N., & Espy, K. A. (2011). The structure of executive function in 3-year-olds. *Journal of Experimental Child Psychology*, *108*(3), 436–452.

Willoughby, M. T., Wirth, R. J., Blair, C. B., & Greenberg, M. (2012). The measurement of executive function at age 5: Psychometric properties and relationship to academic achievement. *Psychological Assessment*, *24*(1), 226–239.

Wu, K. K., Chan, S. K., Leung, P. W. L., Liu, W. -S., Leung, F. L. T., & Ng, R. (2011). Components and developmental differences of executive functioning for school-aged children. *Developmental Neuropsychology*, *36*(3), 319–337. http://dx.doi.org/10.1080/87565641.2010.549979.