The Development of Executive Functions: Evidence from Behavioural and
Electrophysiological Perspectives

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Abstract

**Background:** Executive functions are cognitive processes associated with higher-order levels of behaviour. Previous research has suggested that between the ages of 7 and 11 years, executive functions change from a unitary structure, where specific abilities are indistinguishable from each other, to displaying ‘unity and diversity’, where specific executive functions are separate constructs, yet related to each other. During the same developmental period, large-scale neural changes also occur within the brain. This thesis tests the hypothesis that electrophysiological development occurs before, and is related to, the development of behavioural abilities specific to single executive functions. It is further hypothesised that this development of executive functions through mid- to late-childhood may be a sequential process – neural changes occurring during this time are known to affect the amplitude and latency of event-related potential (ERP) peaks, which may then lead to the development of behavioural abilities specific to single executive functions. This process changes the structure of executive functions from unitary to displaying both unity and diversity.

**Methods:** In chapter 2 of this thesis (published in *Intelligence*; Brydges, Reid, Fox, & Anderson, 2012), latent variable analyses were reported in order to determine the structure of executive functions in children aged 7-9 years ($N = 215$). A range of psychometric tasks designed to measure shifting, working memory, and inhibition were administered to attempt to replicate the ‘unity and diversity’ model of executive functions. In chapter 3, 14 young adults were administered a hybrid Go/Nogo flanker task whilst EEG data were recorded, in order to examine the manifestation of the N2 difference waveform elicited during two inhibitory subprocesses of cognitive control: response inhibition and interference suppression (published in *PLoS ONE*; Brydges, Clunies-Ross et al., 2012). The same task was administered to both children aged 8-11
years and young adults (both groups \( n = 13 \)) to examine changes in the manifestation of the N2 difference waveform between childhood and adulthood (chapter 4, published in *PLoS ONE*; Brydges, Anderson, Reid, & Fox, 2013). Chapter 5 (published in *Frontiers in Human Neuroscience*; Brydges, Fox, Reid, & Anderson, 2014) expanded upon the findings of the preceding chapters by adding analysis of N2 and P3b ERP components, electrophysiological correlates of cognitive control/inhibition and updating of working memory, respectively, extracted from a modified flanker task. These components were added as predictors of the executive function model reported in chapter 2.

**Results:** As reported in chapter 2, performance on all executive function measures between the ages of 7 and 9 years increased. Measurement invariance in the structure of executive functions was also observed between these two groups, and a unitary executive function factor was the best fit of the data. Differences in the manifestation of the N2 difference waveform, in terms of topography and peak latency, when response inhibition and interference suppression were required were reported in chapter 3. Furthermore, the results reported in chapter 4 show different developmental trajectories of the N2 peaks associated with these two cognitive control subprocesses. Specifically, site, latency, and amplitude differences in the N2 difference waveform elicited during response inhibition were reported between children and adults, and no significant interference suppression N2 was observed in the children. Structural equation modelling in chapter 5 showed that the mean amplitudes of the N2 difference waveform and the P3b ERP deflection were both significantly predictive of the unitary executive function factor.

**Conclusions:** The measurement invariance and subsequent unitary executive function factor observed in chapter 2 implies that executive functions are indistinguishable until at least the age of 9 years, and that a general executive ability is developing during this
time period, whereas specific executive function abilities have not developed to an observable degree. The ERP deflections commonly associated with cognitive control/inhibition and updating of working memory were observed, even though the behavioural manifestations were not distinguishable from other executive functions. However, amplitude, latency, and topography differences between children and adults clearly showed that much neural development occurs between childhood and adulthood, with respect to these ERP components. Nonetheless, the results are consistent with maturation of these electrophysiological indices waveform leading to the development of specific executive functions, which result in the increased differentiation of inhibition from other executive functions.
Publications Arising from this Thesis

Articles


Abstracts


Contribution of the Candidate to Publications

In regard to Regulation 33 (points 1 and 2) from the Regulations governing Higher Research Degrees of the Postgraduate Research School of the University of Western Australia, the following outlines the contribution by the candidate to each publication:

1. The candidate extracted records from the unit archives, checked scoring of protocols, conducted the analysis, wrote, submitted, prepared revisions of, and resubmitted the manuscript.

2. The candidate recruited and tested all participants in conjunction with the co-authors, conducted the analysis, wrote a draft of, submitted, prepared revisions of, and resubmitted the manuscript.

3. The candidate recruited and tested all participants in conjunction with co-authors and individuals acknowledged in the manuscript, conducted the analysis, wrote, and submitted the manuscript.
4. The candidate extracted records from the unit archives, checked scoring of protocols, conducted the analysis, wrote, submitted, and prepared revisions of the manuscript.

In regard to regulation 1.3.1.33(2)(a) and (b), the signatures of the co-authors of the above manuscripts are contained below, certifying that the above descriptions accurately detail the work of the candidate to the publications, and that they agree to the inclusion of these manuscripts in this thesis.

______________________________
Christopher R. Brydges (Candidate)

Signed Approval of the Co-Authors for the Above Manuscripts to be Included in the Thesis

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An Nguyen
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## Contents

*Abstract* ............................................................................................................................ 2  

*Publications Arising from this Thesis* ........................................................................... 5  

Articles ............................................................................................................................. 5  

Abstracts .......................................................................................................................... 5  

*Acknowledgements* ........................................................................................................ 7  

*Contents* ........................................................................................................................ 8  

*Tables and Figures* ....................................................................................................... 11  

Tables ............................................................................................................................. 11  

Figures ........................................................................................................................... 13  

*Abbreviations* .............................................................................................................. 15  

Chapter 1 – An Overview of Executive Functions ..................................................... 16  

Defining EFs .................................................................................................................. 17  

Measurement of EFs ..................................................................................................... 19  

EF as a construct – the Miyake et al. (2000) model ...................................................... 21  

Behavioural development of EFs ................................................................................ 22  

Electrophysiology of EFs ............................................................................................. 28  

The current thesis ........................................................................................................ 30  

References .................................................................................................................... 32  

Chapter 2 – A Unitary Executive Function Predicts Intelligence in Children .......... 45  

Method .......................................................................................................................... 52  

Participants ................................................................................................................... 52  

Materials ......................................................................................................................... 52  

Procedure ....................................................................................................................... 56  

Transformation and Outlier Analysis .......................................................................... 56  

Statistical Analysis ....................................................................................................... 58  

Results ............................................................................................................................. 58  

Descriptive Statistics ................................................................................................... 58  

Age-Related Changes in Executive Functions .............................................................. 63  

The Structure of Executive Functions in Children ...................................................... 63  

Intelligence in Children ................................................................................................. 66  

Associations between Executive Functions and Intelligence in Children .............. 66  

Discussion ...................................................................................................................... 69  

References ..................................................................................................................... 75
Tables and Figures

Tables

Table 1. Descriptive statistics of executive function and intelligence measures before transformations for 7 year-olds (N=120), 9 year-olds (N=95), and all participants (N=215) used in the analyses, and p values of independent-samples t-tests conducted between age groups .............................................................. 59

Table 2. Correlations between measures of executive functioning and intelligence in 7 year-olds (N=120) ........................................................................................................................................ 60

Table 3. Correlations between measures of executive functioning and intelligence in 9 year-olds (N=95) .................................................................................................................................. 61

Table 4. Correlations between measures of executive functioning and intelligence (N=215) ........................................................................................................................................ 62

Table 5. Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models of Executive Functions (N=215) .......................................................................................... 64

Table 6. Fit Indices for the Full Two-Factor and One Factor Confirmatory Factor Analysis Models of Intelligence (N=215) ..................................................................................................... 66

Table 7. Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models of Executive Functioning and Intelligence (N=215) ............................................................................. 68

Table 8. N2 Amplitude and Latency Summary Statistics (Means, with Standard Deviations in Parentheses) .............................................................................................................................. 91

Table 9. Descriptive statistics of behavioural measures between groups (means, with standard deviations in parentheses) .................................................................................................................. 111

Table 10. N2 amplitude and latency summary statistics between groups (means, with standard deviations in parentheses) .......................................................................................................... 115
Table 11. Descriptive statistics of executive functions and ERP measures before transformation \((N=215)\). ............................................................................................... 142

Table 12. Correlations between measures of executive functioning and ERPs \((N=215)\). 143

Table 13. Inter-factor correlations extracted from the CFA ............................................... 144
Figures

Figure 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. 

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

Figure 3. The six stimuli used in the present experiment. 

Figure 4. Stimulus-locked ERP waveforms, difference waveforms, and scalp topographic maps. Left-hand panel: Grand-averaged ERP in response to congruous (blue), incongruous (red), and Nogo (green) stimuli with the amplitude ($\mu$V) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset. Middle panel: Grand-averaged difference waveforms computed as the incongruous – congruous waveform (red) and Nogo – congruous (green). Right-hand panel: Topographic distribution of amplitude at the peak latency of the N2 identified in the difference waveforms (incongruous – congruous is shown in the upper map, and Nogo – congruous is shown in the lower map). 

Figure 5. The six stimuli used in the present experiment (taken from Brydges, Clunies-Ross, et al., 2012). 

Figure 6. Stimulus-locked grand average ERP waveforms in response to congruous (blue), incongruous (green), and Nogo (red) stimuli with the amplitude ($\mu$V) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset. 

Figure 7. Grand-averaged difference waveforms computed as the incongruous – congruous waveform (green) and Nogo – congruous (green) with the amplitude ($\mu$V) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset.
Figure 8. Source localisation analyses for (a) Nogo – congruous and (b) incongruous –
congruous N2 effects in the adult group. ................................................................. 116

Figure 9. The six flanker task stimuli used in the current experiment..................... 135

Figure 10. Stimulus-locked ERP waveforms and difference waveforms. Panel (A):
Grand-averaged ERP in response to congruous (blue), incongruous (green), and
reversed (red) stimuli with the amplitude (μV) as the y-axis and time (ms) as the x-axis.
Time 0 represents stimulus onset. Panel (B): Grand-averaged difference waveforms
computed as the incongruous – congruous waveform (green) and reversed – congruous
(red). .............................................................................................................................. 144

Figure 11. Structural equation model predicting executive functioning with the N2
difference waveform amplitude, P3b ERP amplitude, and P3b latency. Single-headed
arrows have standardized factor loadings next to them. The numbers on the right are the
squared multiple correlations for each variable. The dotted regression weight between
the P3b latency and Executive Function factors is nonsignificant. All other coefficients
are significant to $p < .05$ ................................................................................................ 145
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confirmatory factor analysis</td>
<td>CFA</td>
</tr>
<tr>
<td>Crystallised intelligence</td>
<td>gC</td>
</tr>
<tr>
<td>Electroencephalogram</td>
<td>EEG</td>
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<tr>
<td>Event-related potential</td>
<td>ERP</td>
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<tr>
<td>Executive function</td>
<td>EF</td>
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<tr>
<td>Exploratory factor analysis</td>
<td>EFA</td>
</tr>
<tr>
<td>Fluid intelligence</td>
<td>gF</td>
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<tr>
<td>Magnetic resonance imaging</td>
<td>MRI</td>
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<tr>
<td>Reaction time</td>
<td>RT</td>
</tr>
<tr>
<td>Structural equation modelling</td>
<td>SEM</td>
</tr>
</tbody>
</table>
Chapter 1 – An Overview of Executive Functions

Executive functions (EFs) are higher order cognitive processes that allow for and control goal-directed behaviour (Miller & Cohen, 2001), and are thought to be associated with neural activation of the prefrontal cortex (Duncan, Johnson, Swales, & Freer, 1997). These processes are extremely important, as they are essential for academic achievement (St Clair-Thompson & Gathercole, 2006) and successful living (Garavan, Ross, & Stein, 1999). Hence, it is crucial that EFs develop fully during childhood and adolescence. This development occurs at a rapid rate during childhood, with a critical period between the ages of 7 and 11 years (Diamond, 2002). With this critical period in mind, this thesis will focus on the development of EFs during this period and through to adulthood. The thesis will present a series of studies that investigate the development of EFs in children from both behavioural and electrophysiological perspectives, highlighting differences between children and adults from both of these viewpoints, and providing some initial evidence for the sequential development of the electrophysiological correlates of EFs, before the behaviours themselves are apparent.

Before presenting the studies, however, an overview of executive functioning and development is required. In particular, the question of whether EFs can be considered unitary or composed of multiple and independently developing components is the question that the rest of the thesis is predicated on. Although the childhood development of EFs has recently been reviewed by Best and colleagues (Best & Miller, 2010; Best, Miller, & Jones, 2009), these previous reviews largely focus on the development of individual EFs. Although this will be briefly discussed (from both behavioural and neural perspectives), the primary aim of the current paper is to review
associations between EFs during childhood development, as well as highlight issues with the research methodology of the study of EFs.

**Defining EFs**

As mentioned above, EFs are higher-order cognitive processes that allow for goal-directed behaviours (Miller & Cohen, 2001) that are associated with the activation of the dorsolateral prefrontal cortex (Duncan et al., 1997). Lezak (2004) conceptualised EFs as having four components: the ability to form goals, planning, carrying out goal-directed plans, and effective performance. Importantly, a person who has incurred substantial cognitive loss can continue to function in a relatively unimpaired and independent manner, assuming that the EFs (and, most likely, the dorsolateral prefrontal cortex) are intact, highlighting the higher-order nature of EFs.

Although there is some disagreement over a formal definition of EFs, there is a general consensus on the role that EFs play in everyday cognition (Miyake & Friedman, 2012). EFs allow us to shift our mind set quickly and adapt to dynamic and diverse situations, whilst at the same time allowing us to coordinate multiple tasks simultaneously, inhibit inappropriate behaviours, and suppress interfering distractions (Jurado & Roselli, 2007). As such, several different processes have been postulated as EFs, the most commonly investigated being task switching, response inhibition, and updating/working memory (Miyake & Friedman, 2012; Miyake et al., 2000).

Task switching is the ability to rapidly and repeatedly shift between multiple tasks, operations, or mental sets (henceforth referred to as “shifting”; Monsell, 2003). Both neuropsychological and neuroimaging studies provide evidence of the importance of frontal lobe integrity with regards to shifting. Rogers et al. (1998) reported significantly impaired performance on a letter-naming/digit-naming switching task in patients with frontal lesions, when compared to age- and IQ-matched controls. From a
neuroimaging perspective, Kim, Cilles, Johnson, and Gold (2012) conducted a meta-
analysis of 36 studies of shifting, and found that the dorsolateral prefrontal cortex
displayed increased activation on trials requiring shifting than on control trials.

Updating of working memory refers to the ability to monitor and manipulate
incoming information, and remove older, irrelevant information from working memory
(referred to as “updating” from here onwards; Ecker, Lewandowsky, Oberauer, & Chee,
2010; Lehto, 1996). Again, there is evidence from both neuropsychological and
neuroimaging perspectives of updating being an important executive function, and
being associated with frontal regions of the brain. Hanten et al. (2013) reported that
patients who suffered from a mild traumatic brain injury and a frontal lesion performed
significantly worse on a keep track task (a common measure of updating) than mild
traumatic brain injury patients who did not also suffer from a frontal lesion.
Additionally, Owen, McMillan, Laird, and Bullmore (2005) conducted a meta-analysis
of 24 normative functional neuroimaging studies that used the n-back task (a common
updating measure), and also found that the dorsolateral prefrontal cortex is part of a
frontoparietal network associated with the behavioural manifestations of working
memory.

Response inhibition is the ability to suppress actions that are inappropriate or no
longer required (Verbruggen & Logan, 2008). From a neuropsychological perspective,
patients suffering from frontal lesions have been found to display significantly impaired
performance on a Go/Nogo task when compared to a control group (Picton et al., 2006).
Simmonds, Pekar, and Mostofsky (2008) conducted a meta-analysis of 10 functional
neuroimaging studies that used a Go/Nogo task, and found that response inhibition was
related to activation of the dorsolateral prefrontal cortex. It should be noted, however,
that much research also links the right inferior frontal cortex to performance on tasks
requiring response inhibition (for reviews, see Aron, 2007, and Chambers, Garavan, & Bellgrove, 2009), indicating that a network of brain regions is recruited for a response to be successfully inhibited, of which the dorsolateral prefrontal cortex is a major part.

It should be noted that other processes, such as planning and dual-tasking, are also often included under the umbrella term “EF”. However, task switching, response inhibition, and updating/working memory are much simpler, lower-level constructs than these processes, hence can be assigned an operational definition with relative ease (Miyake et al., 2000). Additionally, the more complex processes such as planning and dual-tasking may in fact implicate two or more of these ‘basic’ EFs (Miyake & Friedman, 2012).

**Measurement of EFs**

Many previous studies of EFs typically used a correlation-based approach to examining associations between different EFs (e.g., Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Welsh, Pennington, & Grossier, 1991). However, the correlations between different EF measures are typically reported to be weak (i.e. \( r < .40 \); Miyake et al., 2000). Due to this apparently weak association between different EFs, it has been argued that EFs are fractionated (Lehto, 1996).

However, there are flaws with using a correlational method to study EFs. Firstly, an inherent problem with the measurement of EFs is task impurity (Burgess, 1997; Rabbitt, 1997). Put simply, all tasks that are theorised to tap into an EF also require non-EF processes in order to be completed (e.g., language or motor coordination). From this, it cannot be assumed that a low score on one single measure of EF indicates a deficit in that EF. Similarly, low or non-significant correlations between EF measures may be due to non-executive processes that differ between tasks (Miyake & Shah, 1999).
A second issue with the measurement of EFs is that many measures have relatively low internal and/or test-retest reliability (Rabbitt, 1997). It is possible that this is due to the novelty of the task being diminished when the participant attempts it repeatedly. The participant’s increased familiarity with the task may result in fewer cognitive resources being allocated to the completion of the task, resulting in the task not reliably measuring the EF it was supposed to measure (Rabbitt, 1997). These low reliabilities generally lead to low correlations between these measures (Miyake et al., 2000), which provides potentially spurious evidence of the independence of EFs.

To address these problems, Miyake et al. (2000) used a latent variable approach to determine the structure of EFs. Specifically, confirmatory factor analysis (CFA) was conducted, using several measures of EFs. CFA is advantageous for several reasons. First, latent variables (also referred to as factors) are considered to be better measures of a construct as task impurity is removed within a ‘measurement model’. Multiple tasks hypothesised to measure a construct are used, and the variance common between the tasks is extracted to form the latent variable. In addition, CFA is a theoretically driven form of latent variable extraction, as the tasks used are theorised, a priori, to measure a specific construct. Assuming that the theory is sound, this makes CFA a more robust statistical method than exploratory factor analysis (EFA), which creates factors based entirely on the data obtained from the administered measures, rather than any theory.

An additional advantage of CFA is that the ‘goodness of fit’ of the measurement model can be calculated, indicating to what extent the data differ from that predicted by the model. An extension of this is that alternative nested models can be tested and directly compared to each other. For example, in a three-factor model, correlations between any two factors can be constrained to 1.0 (i.e. a perfect correlation, whereby the two constructs are hypothesised to be the same), and model fit statistics can be
compared between the original and alternative models. If the more parsimonious model is no worse a fit than more complex models, it is chosen as the theoretical model that best represents the data.

**EF as a construct – the Miyake et al. (2000) model**

Although originally proposed by Teuber (1972) and more recently by Duncan et al. (1997), the notion of ‘unity and diversity’ of EFs has largely gained widespread acceptance due to the seminal work of Miyake et al. (2000). The idea of unity and diversity stems from previous research that postulates that different EFs are related yet distinct constructs. Evidence supporting this theory has come from both behavioural (Miyake et al., 2000) and neural (Duncan & Owen, 2000) perspectives. Specifically, Miyake et al. administered a battery of EF measures to 137 young adults, and used CFA to determine associations between inhibition, updating of working memory, and shifting. Inhibition (the ability to deliberately inhibit a prepotent response) was measured by the antisaccade task (Hallett, 1978), the Stroop task (Stroop, 1935), and the stop signal task (Logan, 1994). Updating (the monitoring and updating of working memory representations) was measured by the keep track task (Yntema, 1963), the letter memory task (Morris & Jones, 1990), and the tone monitoring task. Thirdly, shifting (the ability to switch between multiple tasks) was measured by the plus-minus task (Jersild, 1927), the number-letter task (Rogers & Monsell, 1995), and the local-global task. As alluded to previously, the CFA produced correlations between factors ranging from $r = .42$ to $r = .63$. Additionally, and of critical importance, when alternative models were tested, the full three-factor model statistically provided the best fit of the data. By testing alternative models, including a model of EFs being unitary and another of the three factors being completely independent, Miyake et al. provided strong
evidence of inhibition, updating, and shifting being related, yet separable, components of EF.

Neuroimaging evidence also supports the Miyake et al. (2000) model of ‘unity and diversity’ of EFs. A recent meta-analysis of 193 fMRI studies (Niendam et al., 2012) examined the neural activation associated with a range of EFs, including inhibition, working memory, and flexibility (synonymous with shifting), which revealed a high degree of common activation between these constructs in the dorsolateral prefrontal cortex, frontopolar cortex orbitofrontal cortex, and anterior cingulate cortex. From this, it was concluded that EFs are associated with a larger cognitive control network (Botvinick, Braver, Barch, Carter, & Cohen, 2001; MacDonald, Cohen, Stenger, & Carter, 2000). Whilst this provides strong support for the unity of EFs, it is also argued that different subdivisions of this large network are differentially activated for different task requirements (Chambers et al., 2007; Dosenbach et al. 2006; Miller & Cohen, 2001), providing evidence for some separability of specific EFs.

**Behavioural development of EFs**

There is a paucity of research into the development of individual EFs throughout childhood and adolescence (for a comprehensive review, see Best et al., 2009). The three EFs examined by Miyake et al. (2000) – inhibition, updating, and shifting – can be observed in children younger than five years (Anderson, 1998), although there is debate about when development of each EF is complete. The general consensus leans toward maturity of EFs occurring during late childhood or early adolescence (Huizinga & van der Molen, 2007; Luciana, Conklin, Hooper, & Yarger, 2005; Romine & Reynolds, 2005) although some other studies (Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Huizinga, Dolan, & van der Molen, 2006; Luciana & Nelson, 1998) provide evidence that performance on some tasks measuring inhibition and working memory
(WM), of which updating is a major component (Ecker, Lewandowsky, & Oberauer, 2013), continues to improve through adolescence.

Research testing the Miyake et al. (2000) model in children has generally converged upon the notion of a unitary structure of EFs in young children. That is, individual EFs cannot be distinguished from each other until at least the age of 7 years. Wiebe, Espy, and Charak (2008) tested 243 typically developing children aged 2.3 - 6 years, on several different measures of working memory and inhibition. The unitary model of executive functioning was again found to be the best and most parsimonious fit. 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.

Wiebe et al. (2011) tested 228 young children (mean age 3.01 years) on a battery of working memory and inhibition tasks (however, no measures of shifting were administered). They found that the best and most parsimonious fit for the data was a one factor model of executive functioning. Additionally, when the working memory and inhibition factors were separated, the correlation between these two factors was very high ($r = .76$), providing further support for a unitary EF in children of this age.

Willoughby, Wirth, Blair, Greenberg and The Family Life Project Investigators (2012) found the same pattern of results when testing a sample of 5 year olds ($N = 1036$) on a range of EF measures. Once more, a unitary EF 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 EFs are unitary in this age group.

At some point after the age of 7 years, the individual EFs differentiate themselves from each other, so that by the age of 10-11 years, the Miyake et al. (2000) model of EFs is observed (i.e. children display ‘unity and diversity’ of EFs). 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. Furthermore, Wu et al. found significant improvements in performance on all EF tasks between the ages of 7 and 11 years, providing evidence of the continued development of EFs through this period.

Lehto, Juujärvi, Kooistra, and Pulkkinen (2003) reported findings consistent with those of Wu et al. (2011). Having tested 108 8 – 13 year old children (with a mean age of 10.5 years) on several measures of EFs, the full three factor model was also reported to be the best fit of the data. Additionally, Lehto et al. also found that age correlated with most EF tasks that were administered, again providing support for the continued development of EFs through this age group.

Duan, Wei, Wang, and Shi (2010) also tested the structure of EFs in 11 and 12 year old children (mean age of 11.88 years), and found similar results. Specifically, the three EF factors were separate, but moderately correlated with each other. In short, the previous three studies described provide consistent support for unity and diversity being evident in children around the age of 10 – 11 years.

Additionally, two longitudinal studies have examined that changes in the structure of EFs as children age, and provide further support for this differentiation process occurring through childhood. Lee, Bull, and Ho (2013) examined the structure
of EFs, and whether it changed with age, in 688 children aged 6 - 15 years. They found that the structure of EFs showed increased differentiation with age. A two factor structure, where working memory was separable from inhibition and shifting, was the best fit for the data until the age of 12 years, from which point the full three factor model applied. It is possible, however, that this increased differentiation in young children (i.e. the fact that a two factor model was observed, rather than a one factor model) is due to the tasks administered in the study. Specifically, all the inhibition and shifting measures were timed, whereas the three working memory scores were all based on accuracy. Hence, it is possible that the model is, to some degree, influenced by method characteristics, which should be avoided if possible (Podsakoff, MacKenzie, Jeong-Yeon, & Podsakoff, 2003). Nonetheless, evidence of the differentiation of EFs is still apparent in this sample.

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 EFs during childhood.

It is also important to note the distinction between the development of EF abilities (as evidenced by levels of performance on measures of EFs), and changes in structure (i.e. the relationships between components of EFs). EF abilities develop rapidly throughout childhood (Best & Miller, 2010; Best et al., 2009), and potentially keep developing until as late as mid-adolescence (Huizinga et al., 2006; Luciana et al., 2005). Conversely, as previously mentioned, the structure of EFs remains constant and is effectively unitary until at least the age of 7 years (Wiebe et al., 2008; Wiebe et al.,
2011; Willoughby et al., 2012), before displaying unity and diversity by 10-11 years of age (Duan et al., 2010; Lehto et al., 2003; Wu et al., 2011). It is possible that two different, sequential stages of cognitive development can account for this: first, up to the age of 7 years, the general underlying component of EF, that Miyake et al. (2000) postulate is the cause of the ‘unitary’ part of their model, develops, but abilities specific to each EF do not, or only to a negligible degree. This would account for a global increase in performance on EF tasks, and would explain why the unitary structure of EFs remains constant through this period. Between the ages of 7-11 years, however, the specific EF processes may develop rapidly and on different developmental trajectories, explaining the continued increase in EF task performance, and the rapid differentiation of individual EFs.

This differentiation process 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. This is thought to be due to younger children being more reliant upon a general intellectual ability (commonly referred to as g; Spearman, 1904). From this, the structure of intelligence develops from a relatively general ability to multiple cognitively separable abilities. Cattell (1967) administered a wide range of fluid intelligence (gF; the ability to solve unfamiliar problems) and crystallised intelligence (gC; previously acquired knowledge; Cattell, 1963) measures to children aged 5-6 years, and reported that only one general factor could be plausibly extracted from the data. However, Stankov (1978) found that fluid and crystallised intelligence were separable (yet still significantly related; \( r = .63 \)) in children aged 11-12 years. Considering the high degree of association between EFs and intelligence from both behavioural (performance and differentiation) as well as neural perspectives (Ackerman, Beier, & Boyle, 2005; Ardila, Pineda, & Rosselli, 2000; Duncan & Owen, 2000;
Friedman et al., 2006; Roca et al., 2010; Tsujimoto, 2008), this similarity is perhaps unsurprising. Friedman et al. extended the Miyake et al. (2000) model of EFs by creating latent variables of gF and gC as well as inhibition, updating, and shifting. Structural equation modelling (SEM) showed that of the three EF latent variables, only updating significantly predicted gF and gC in young adults. Additionally, Friedman et al. reported that the relationship between gF and gC significantly decreased once updating was accounted for ($r = .62$ decreased to $r = .17$, though still significant), inferring that the process by which gF is converted into gC is partially mediated through updating. Both of these findings are interests of this thesis, and are tested in chapter 2.

Some neuroimaging studies show support for these two different developmental processes, in that the structural and functional development of the brain appears to occur on similar timescales to the behavioural development described previously. Magnetic resonance imaging (MRI) research has shown that, by about the age of 6 years, the typically developing brain has reached approximately 90% of the weight (Kretschmann, Kammradt, Krauthausen, Sauer, & Wingert, 1986) and volume (Giedd et al., 2009; Reiss, Abrams, Singer, Ross, & Denckla, 1996) of that of an adult. Despite only minimal brain growth after this period, however, the volume of white matter (myelinated neurons which allow for faster cognitive processing and greater neural connectivity; Giedd et al., 2009) generally increases throughout childhood and adolescence (Barnea-Goraly et al., 2005; Schmithorst, Wilke, Dardzinski, & Holland, 2005), and has been found to be associated with the development of cognitive functions during this time (Nagy, Westerberg, & Klingberg, 2004). Furthermore, at some point around mid-childhood, research has reported that neural activation during EF tasks (such as the Go/No-go task) begins to show marked changes. Specifically, children show more diffuse neural activation, which becomes increasingly focalised through late childhood and adolescence (Dosenbach et al., 2010; Durston et al., 2006; Fair et al.,
This process of increased neural localisation is commonly thought to be due to synaptic pruning, where the neural regions associated with behavioural performance on a particular construct become increasingly more efficient with development, so there is a gradual loss of synaptic connections during this time (Casey, Giedd, & Thomas, 2000). However, it should be acknowledged that many neuroimaging techniques are not feasible in young children (i.e. up to 6 years), when EF development is most rapid (for example, MRI can be quite claustrophobic, and requires participants to stay completely still for an extended period of time), limiting the quality of the data.

**Electrophysiology of EFs**

Much previous research has used electroencephalography (EEG) in order to examine EFs from a neural perspective. Specifically, event-related potentials (ERPs) have been extracted from the EEG, and distinct peaks/deflections in the ERP have been found to correlate with performance on psychometric measures of EFs.

The N2 peak is a frontally maximal negativity with a typical latency of approximately 150-400 ms, which has been associated with cognitive control (Carter & Krug, 2011; Folstein & van Petten, 2008). Previous research has repeatedly recorded EEG data whilst participants completed a Go/Nogo task, and reported an enhanced N2 amplitude at frontal electrode sites on Nogo trials (requiring response inhibition) in comparison to the go (control) trials (e.g., Bokura, Yamaguchi, & Kobayashi, 2001; Jodo & Kayama, 1992; Kok, 1999).

The P3b peak of the ERP is a positivity that is maximal at parietal scalp sites, and typically has a latency of approximately 300-500 ms in adults (Polich, 2007). The P3b has been theorised to be predictive of ‘context updating’ (Donchin, 1981), a process akin to that of updating of working memory – if a new stimulus is presented, the P3b
amplitude is enhanced due to the updating of the neural representation of the stimulus environment (i.e. a larger P3b peak is observed when working memory is updated with incoming information; Polich, 2007). Walhovd and Fjell (2002) reported a significant positive correlation between P3b peak amplitude and performance on a backward digit span task (a common measure of working memory), providing evidence for this link between updating and the P3b peak.

From a developmental perspective, these ERP peaks show marked changes through childhood and adolescence. Both the N2 and P3b have been found to show decreased latency from the age of 6 years onwards (Polich, Ladish, & Burns, 1990; Rueda, Posner, Rothbart, & Davis-Stober, 2004), possibly due to myelination occurring during this period (Barnea-Gorlay et al., 2005; Geidd et al., 1999). Decreases in amplitude with age are also commonly reported for both the N2 (e.g., Johnstone, Pleffer, Barry, Clarke, & Smith, 2005; Rueda et al., 2004) and P3b peaks (e.g., Pfueller et al., 2011; Stige, Fjell, Smith, Lindgren, & Walhovd, 2007), possibly due to less cognitive effort being required to perform inhibition and updating tasks, respectively, as development occurs. Interestingly, whilst the topography of the P3b is relatively stable during childhood development (Pfueller et al., 2011), research from both ERP (Jonkman, 2006) and fMRI studies (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002) show that the neural regions associated with response inhibition become increasingly frontal with development, possibly because the frontal lobes are one of the last regions of the brain to fully mature (Fuster, 2002). Of interest is the similar marked development between childhood and adulthood of these ERP components and the EF behaviours (described above), which are the focus of this thesis.
The current thesis

This thesis addresses three main issues. First, the thesis investigates whether EFs are unitary or composed of different (yet related) components in mid-childhood. Second, the thesis examines behavioural changes of EFs (in terms of both performance on EF measures and structure between EFs) during this mid-childhood period, and what electrophysiological changes occur between childhood and adulthood. Third, the thesis investigates whether differences in EF relationships between younger and older children are observable at both behavioural and electrophysiological levels (i.e. behavioural and electrophysiological development of EFs occur simultaneously), or whether development occurs at one level before the other.

The following chapters will present four papers (three already published and one submitted for publication) that empirically investigate the questions of interest listed above. Chapter 2 examines the structure of EFs and intelligence in a group of children aged 7 years and a group aged 9 years, in order to determine whether differentiation has occurred to an observable degree by the age of 7 years, and to investigate any differentiation occurs between these ages. Specifically, CFA and invariance testing are used to create latent variable models of executive functioning, gF and gC, and test for any structural differences in these models between these two age groups. Additionally, SEM is used to test the predictive validity of EFs onto gF and gC, and to examine associations between gF and gC after EF has been accounted for. Chapter 3 examines the ERP profiles of two subtypes of inhibition (response inhibition and interference suppression) in an adult sample to provide an insight into potential differences between subtypes of specific EFs. Whilst fMRI studies have examined this area previously (Niendam et al., 2012), the use of ERPs is advantageous due to the high temporal resolution of the technique, which may provide insights into the timing of neural
activation between these two inhibitory subprocesses. Additionally, this adult sample provides a comparison for the ERP profiles of child samples. Chapter 4 extends this by investigating differences between children and adults with regards to these two inhibitory subprocesses, as well as asking if these process display different patterns of maturation. Chapter 5 tests associations between the behavioural manifestations of EFs and the ERP correlates of EFs in children to determine if the incomplete development of these constructs (EFs and ERP peaks) affects the relationship between the two, and to examine if one of the constructs has developed to an observably greater extent than the other. All four of these chapters are unchanged from the published/submitted versions of the papers. A final discussion chapter will attempt to draw general conclusions from the results of these empirical investigations for the questions of interest above, and will propose new hypotheses as to the development and differentiation of EFs (and their neural correlates) through childhood development.
References


Chapter 2 – A Unitary Executive Function Predicts Intelligence in Children

A version of this chapter has been published in Intelligence:


Executive functioning is an umbrella term used to describe cognitive processes that are associated with goal-directed behaviour (Miller & Cohen, 2001). The development of EFs 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 EFs, 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 EFs (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 EFs 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 EFs (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
tasks (Kane & Engle, 2003; Miyake et al., 2000; Monsell, 2003). The critical feature of
these EFs 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 EFs 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 EFs. 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 EFs 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 EFs initially found in Miyake et al., and used the resulting
model to test which if any EF 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 EFs 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 $g_F$ and $g_C$. Furthermore, Friedman et al. used structural equation modelling (SEM) to determine which of the three EFs predict $g_F$ and $g_C$. SEM allows a test of whether any EF uniquely predicts either of the intelligences, by calculating associations between EFs and intelligence whilst controlling for EF intercorrelations. Once controlling for the common variance amongst the EFs, Friedman et al. reported that updating was the only significant unique predictor of both $g_F$ and $g_C$. Hence, Friedman et al. concluded that not all EFs are related to intelligence in young adults.

Despite the developmental nature of EFs (Shing, Lindenberger, Diamond, Li, & Davidson, 2010), intelligence and indeed frontal functioning (Casey, Geidd, & 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 EFs and its relationship to intelligence in 7 and 9 year-old children, and the associations between these EFs 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 EFs 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 EFs (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 et al. 2011; Wiebe et al., 2008; Willoughby et al., 2012; Wu et al., 2011). Of these, only two tested the relationship between EFs 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 (Elliott, 1990) as an indicator of working memory and the Tower of Hanoi (Simon, 1975) 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 EFs 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 (Shallice, 1982) 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; Manly, Robertson, Anderson, & Nimmo-Smith, 1999) 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., 2011; Lehto et al., 2003; Wu et al., 2011).

Despite some research investigating the structure of EFs in children, determining associations between EFs 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 EF and gF. Since this initial work there has been little consideration of relationships between individual measures of EFs and intelligence and no previous research has attempted to replicate the Friedman et al. (2006) model of EFs 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 EFs in children. More recently, Duan et al. (2010) found unity and diversity of EFs 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 a single indicator of intelligence cannot distinguish gF and gC. In short, there is no study in
children that has tested the Miyake et al. model of EFs 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 EFs 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 EFs (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 EFs 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 EFs 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 EFs 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 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, EFs would be more highly correlated with gF than gC.

**Method**

**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, range 7.05 - 7.98 years), and 95 children in the 9 year-old group (53 males and 42 females, $M = 9$ years 6 months, $SD = 3$ months, range 9.00 - 9.98 years). Participants were recruited through Project K.I.D.S. (Kids’ Intellectual Development Study), a child development research program 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.

**Materials**

**Inhibition.**

**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).

**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).

**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.

**Working Memory.**

**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.

**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.

**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 total number of points across trials.

**Shifting.**

**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 10 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).

**Verbal Fluency:** Verbal Fluency is a subtest of the British Abilities Scale (Elliott, Smith, & McCullough, 1997). For 30 seconds, 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.
**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, whilst ignoring letters on the opposite side and numbers. Near the end of each trial (12 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.

**Intelligence.**

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

**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.

**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.
**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.

**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.

**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 two-week testing session occurred in the school holidays. All testing was presented in a child-friendly manner, and each testing session lasted 25 minutes. 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.

**Transformation and Outlier Analysis**

The distributions of the reaction time and proportion measures for the nine EF 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 13 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 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 χ²/df value is less than 2 (χ²/df = 1.36), arguing that the missing data is missing completely at random. These scores were estimated using the full information maximum likelihood method.

**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 χ²/df statistic was used, because models with larger sample sizes and/or more degrees of freedom often show significant χ² values, despite having only marginal differences between the model and the data. χ²/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 is 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, χ² 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).

**Results**

**Descriptive Statistics**

Descriptive statistics of the raw scores of the 13 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, 3, and 4.

Table 1
Descriptive statistics of executive function and intelligence measures before transformations for 7 year-olds (N=120), 9 year-olds (N=95), and all participants (N=215) used in the analyses, and p values of independent-samples t-tests conducted between age groups

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<th>All participants</th>
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*Note.* <sup>a</sup> Difference between incongruous and neutral conditions (secs). <sup>b</sup> Proportion correct. <sup>c</sup> Difference between block 5 and blocks 1-4 (ms). <sup>d</sup> Total trials correct. <sup>e</sup> Total points scored. <sup>f</sup> Number of words. <sup>g</sup> Total items correct. *p* values represent significance levels of independent-samples t-tests conducted between age groups (one-tailed). *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).
### Table 2

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

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*Note.* *p < .05; **p < .01.*
Table 3

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

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*Note.* *p < .05; **p < .01.
Table 4

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

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<td>.31**</td>
<td>.40**</td>
<td>.30**</td>
<td>.40**</td>
<td>.52**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Information</td>
<td>.28**</td>
<td>-.10</td>
<td>.14</td>
<td>.56**</td>
<td>.35**</td>
<td>.52**</td>
<td>.32**</td>
<td>.48**</td>
<td>.36**</td>
<td>.45**</td>
<td>.52**</td>
<td>.79**</td>
<td></td>
</tr>
</tbody>
</table>

Note. *p < .05; **p < .01.
**Age-Related Changes in Executive Functions**

The first hypothesis to be tested is that EFs and intelligence develop with age. Hence, a series of Bonferroni-corrected ($\alpha = .004$) independent-samples t-tests were conducted to determine whether older children performed significantly better on measures of EFs 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 EFs 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.

**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.

Table 5

<p>| Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models of Executive Functions (N=215) |</p>
<table>
<thead>
<tr>
<th>Model</th>
<th>(\chi^2)</th>
<th>df</th>
<th>(P)</th>
<th>(\chi^2/df)</th>
<th>CFI</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Full three-factor</td>
<td>Not positive definite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-factor models</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Inhibition + (Shifting = Working Memory)</td>
<td>20.11</td>
<td>19</td>
<td>.39</td>
<td>1.06</td>
<td>1.00</td>
<td>.02</td>
</tr>
<tr>
<td>3. Working Memory + (Shifting = Inhibition)</td>
<td>18.03</td>
<td>19</td>
<td>.52</td>
<td>0.94</td>
<td>1.00</td>
<td>.00</td>
</tr>
<tr>
<td>4. Shifting + (Inhibition = Working Memory)</td>
<td>Not positive definite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Independent three factors</td>
<td>Not positive definite</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. One-factor</td>
<td>20.11</td>
<td>20</td>
<td>.45</td>
<td>1.01</td>
<td>1.00</td>
<td>.01</td>
</tr>
</tbody>
</table>

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

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

*Figure 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.
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.

Table 6

Fit Indices for the Full Two-Factor and One Factor Confirmatory Factor Analysis Models of Intelligence (N=215)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>df</th>
<th>$p$</th>
<th>$\chi^2$/df</th>
<th>CFI</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Full two-factor</td>
<td>1.68</td>
<td>1</td>
<td>.20</td>
<td>1.68</td>
<td>1.00</td>
<td>.06</td>
</tr>
<tr>
<td>2. One-factor</td>
<td>41.43</td>
<td>2</td>
<td>&lt;.01</td>
<td>20.71</td>
<td>0.89</td>
<td>.30</td>
</tr>
</tbody>
</table>

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

Associations between Executive Functions and Intelligence in Children

To test the hypothesis that EFs would be related to both gF and gC, a third measurement model was created to examine associations between a unitary EF, gF, and gC. The two executive function-intelligence correlations were both very high (EF-gF $r = .89$, and EF-gC $r = .83$). However, the 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 $\chi^2$ 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 EF-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 EF 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 EFs, 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 EF, and then a more differentiated two-factor EF 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 EF (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 EFs 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.
Table 7

Fit Indices for the Full Confirmatory Factor Analysis Model and Reduced Models of Executive Functioning and Intelligence (N=215)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>df</th>
<th>p</th>
<th>$\chi^2$/df</th>
<th>CFI</th>
<th>RMSEA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Full three-factor</td>
<td>108.31</td>
<td>51</td>
<td>&lt; .01</td>
<td>2.12</td>
<td>0.93</td>
<td>.07</td>
</tr>
<tr>
<td>2. One-factor</td>
<td>174.98</td>
<td>54</td>
<td>&lt; .01</td>
<td>3.24</td>
<td>0.85</td>
<td>.10</td>
</tr>
<tr>
<td>Two-factor models</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. gC + (EF = gF)</td>
<td>119.02</td>
<td>53</td>
<td>&lt; .01</td>
<td>2.25</td>
<td>0.92</td>
<td>.08</td>
</tr>
<tr>
<td>4. gF + (EF = gC)</td>
<td>152.07</td>
<td>53</td>
<td>&lt; .01</td>
<td>2.87</td>
<td>0.88</td>
<td>.09</td>
</tr>
<tr>
<td>5. EF + (gF = gC)</td>
<td>170.12</td>
<td>53</td>
<td>&lt; .01</td>
<td>3.21</td>
<td>0.86</td>
<td>.10</td>
</tr>
</tbody>
</table>

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

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 Figure 2 for complete SEM). Hence, the commonality between gF and gC is completely predicted by executive functioning$.^2$.
Figure 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 $p < .05$.

**Discussion**

The aims of this study were to test the three latent trait Miyake et al. (2000) model of EFs 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 EFs 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 EFs 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 EFs 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 EFs were indistinguishable in this sample, the two intelligence constructs clearly formed two factors. In a 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 EFs, but become distinguishable at an earlier stage than EFs.

Previous research examining associations between EFs 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 EFs and intelligence. However, prior to our study, no previous research had attempted to replicate the Friedman et al. (2006) model of EFs 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 EFs that have not been measured in our study, or processes that are not thought of as EFs, contribute to intelligence.

We conclude that the differentiation of the two types of intelligence occurs earlier than that of differentiated EFs. This difference between EFs and intelligence in differentiation processes might be explained from a neuropsychological perspective: the three EFs 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 EFs, 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 EFs are frontal, then it seems that incomplete frontal development affects all EF processes equally at this stage of development. The earlier differentiation of intelligence compared with the differentiation of EFs 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 EFs 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 EFs 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 EFs 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 EFs 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 EFs and intelligence throughout the lifespan. Previous research has found that deterioration of the frontal lobes as a result of aging causes is associated with decreased performance on tasks measuring EFs (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 EFs 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 EFs not measured by us (but we would argue we have a broad sample of EFs) 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 EFs 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 EFs are ignored. Although it could be argued that this is less of a problem in younger children (because as we have shown EFs 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 EFs 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.
References


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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, $p = .43$).

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.
Cognitive control refers to the ability to selectively attend and respond to task-relevant events while resisting interference from distracting stimuli or prepotent automatic responses (Michel & Anderson, 2009; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). Interest in the study of inhibitory processes has increased in the past two decades (Dempster, 1991), reflecting the importance of inhibition in everyday cognition, and, “ultimately, for successful living” (Garavan, Ross, & Stein, 1999, p. 8301). More recently, associations between inhibition and other EFs, particularly updating and shifting have been studied in more depth (Friedman et al., 2006; Miyake et al., 2000). Despite a growing amount of research interest in the area (Dagenbach & Carr, 1994; Friedman & Miyake, 2004), there is still considerable debate as to the separability of the subprocesses of inhibition. Several theorists have proposed that, from a behavioural perspective, inhibition should be viewed as a group of separable, yet related, subprocesses (Dempster, 1993; Harnishfeger, 1995; Nigg, 2000).

Nigg (2000) proposed that there are four types of inhibition in cognitive psychology; however, the present study focuses on only two of these: response inhibition, which involves the suppression of prepotent behavioural responses (as is required in a Go/Nogo task), and interference suppression, which is the active prevention of interference due to stimulus competition (such as that observed in a flanker task). Van Boxtel, van der Molen, Jennings, and Brunia (2001) proposed an...
alternate, but not necessarily conflicting theory of inhibitory processing, where inhibition is classified as selective (i.e. an event in which a response has to be made, but is not prepotent) or nonselective, when no response is required. This theory may be considered parallel to Nigg’s taxonomy, as many tasks thought to measure response inhibition (such as Go/Nogo and stop-signal tasks) require nonselective inhibition, whereas tasks requiring interference suppression (such as Stroop and flanker tasks) require selective inhibition. However, a key difference between these processes is the time required for each process to be completed, as it is reasoned that selective inhibition takes longer due to it requiring discrimination; that is, on a forced-choice task, a choice still has to be made (Logan & Burkell, 1986). Although other prominent theories of inhibition (Dempster, 1993; Harnishfeger, 1995) use different terminology, they each converge upon the theory that inhibition refers to several related yet distinct processes, as opposed to a unitary construct.

Evidence from a variety of perspectives has been put forward in support of a unitary view of inhibition. From a behavioural perspective, Friedman and Miyake (2004) created latent variables of prepotent response inhibition and resistance to distracter interference and reported that that model fit was not significantly worse when the two variables were collapsed into one. Verbruggen, Liefooghe, and Vandierendonck (2004) used a combined flanker/stop-signal task to determine whether there was overlap between the processes of response inhibition and interference suppression. They found that the stop-signal reaction time was longer for incongruous flanker trials than for congruous trials, suggesting a functional dependence between response inhibition and interference suppression. These results, together with the results from the confirmatory factor analysis (Friedman & Miyake, 2004), raise the possibility that a common inhibitory mechanism could be involved in both types of tasks (Verbruggen & Logan, 2009).
Neuroimaging studies have associated successful inhibition with activation of regions of the prefrontal cortex and the right inferior frontal gyrus (IFG; Aron, Robbins, & Poldrack, 2004; Chambers, Garavan, & Bellgrove, 2009; Mostofsky & Simmonds, 2008). Many studies using the event-related potential (ERP) have regarded the processes of response inhibition and interference suppression as similar constructs, reporting an enhanced anteriorly distributed negativity following presentation of stimuli that require inhibition of responses (Cragg, Fox, Nation, Reid, & Anderson, 2009; Folstein & van Petten, 2008; Kramer, Knight, & Münte, 2011) or the suppression of conflicting information in flanker tasks (Carter & van Veen, 2007; Forster, Carter, Cohen, & Cho, 2010; Tillman & Wiens, 2011; van Veen & Carter, 2002), although the amplitude and latency of the component varies across tasks (Fox, Michie, Wynne, & Maybery, 2000; Roche, Garavan, Foxe, & O'Mara, 2005). Bunge, Dudukovic, Thomason, Vaidya and Gabrieli (2002) examined the neural basis of response inhibition and interference suppression in adults and children with a hybrid Go/Nogo flanker task. By incorporating the Go/Nogo stimuli into the flanker task, they reduced the potential effects of motivational differences and other non-specific task differences. The task was completed whilst functional magnetic resonance imaging (fMRI) was conducted, to determine unique patterns of neural activation associated with these two fundamental processes of cognitive control. The efficiency of interference suppression in adults (measured as the reaction time cost for incongruous trials relative to neutral trials) was associated with increased activation of the IFG/insula and the anterior portion of the middle frontal gyrus in the right hemisphere. Despite robust activation of the prefrontal, cingulate, and parietal cortices associated with the Nogo trials, none of these regions were significantly correlated with the efficiency of response inhibition (measured as the accuracy cost for Nogo trials relative to neutral trials). They attributed this result to the lack of variability in both behavioural performance and activation levels across
individuals. One potential difficulty with the hybrid task developed by Bunge et al. is that the flankers provided the cue to inhibit responses and therefore required participants to consciously attend to these elements of the stimuli, rather than strategically suppress processing of these elements (Eriksen & Eriksen, 1974; Gehring, Gratton, Coles, & Donchin, 1992). This factor may have changed the way participants processed the incongruous stimuli, a conclusion that is supported by the low error rates observed following presentation of incongruous stimuli. Another potential difficulty is the lack of variability in behavioural and neural indices of response inhibition. Falkenstein, Hoormann and Hohnsbein (1999) reported that participants who performed worse on a Go/Nogo task had significantly smaller N2 amplitudes than those who performed well, suggesting that this neural index of inhibitory processing shows sufficient between-subject variability and could provide a more sensitive measure of online inhibitory processing.

The present study examined the dissociability of the two fundamental components of cognitive control, namely response inhibition and interference suppression, by recording the brain’s electrical response to stimuli presented in a hybrid Nogo/flanker task. Two hypotheses were made: first, given that previous fMRI studies have reported differences in the regions of neural activation associated with response inhibition and interference suppression (Blasi et al., 2006; Bunge et al., 2002), it was hypothesised that the amplitude of the N2 elicited in response to incongruous stimuli would be maximal at different scalp sites to that of the Nogo stimuli. Second, it was hypothesised that the latency of the N2 elicited in response to incongruous stimuli would be significantly longer than the latency of the N2 elicited in response to Nogo stimuli.
Method

Participants

Fourteen third-year psychology students studying at the University of Western Australia completed the experiment, and data from two participants were excluded as their performance on the incongruous flanker stimuli did not exceed chance. The mean age of the final sample was 21.3 years ($SD = 2.1$; range = 19-26).

![Figure 3. The six stimuli used in the present experiment.](image)

Materials

A modified visual flanker task was used (Richardson, Anderson, Reid, & Fox, 2011; Rueda, Posner, Rothbart, & Davis-Stober, 2004). Although this version is considered child-friendly, Rueda et al. found that this task produces results similar to the original flanker task (Eriksen & Eriksen, 1974) in adults. Each stimulus consisted of five fish presented on a blue background. An arrow on the body of the fish indicated direction and the target was the central fish. Participants were instructed to press a response button on a keyboard (red felt patches on the ‘Z’ and ‘/’ keys) corresponding to the direction of the central fish. There were three conditions: in the congruent condition (.5 probability), the fish were green and all facing the same direction. In the incongruent condition (.25 probability), the fish were also green, however the flankers faced the opposite direction to the target. In the Nogo condition (.25 probability), the fish all faced the same direction but were all red, the participant was required to not respond. Each fish subtended $0.9^\circ$ horizontally and $0.6^\circ$ vertically, with $0.2^\circ$ separating each
fish (see Figure 8). Stimuli were presented in random order for 300 ms with a 2,000 ms inter-stimulus interval. The task was presented as a game in which the participants had to feed the hungry central fish. Speed and accuracy were equally emphasized. A practice block of eight trials was administered to ensure the participants understood the task requirements. A total of 176 trials were presented in one block.

**Electrophysiological Acquisition**

The EEG was continuously recorded using an Easy-Cap™. Electrodes were placed at 33 sites (Fp1, Fp2, F3, F4, F7, F8, Fz, FC1, FC2, FC5, FC6, FCz, FT9, FT10, C3, C4, Cz, T7, T8, CP1, CP2, CP5, CP6, P3, P4, P7, P8, Pz, PO9, PO10, O1, O2, Iz). Eye movements were measured with bipolar leads placed above and below the left eye. The EEG was amplified with a NuAmps 40-channel amplifier, and digitized at a sampling rate of 250 Hz. During recording, the ground lead was located at AFz and the right mastoid was set as reference, and an averaged reference was calculated offline. Prior to recording, impedances were below 5 kΩ. The ERP processing was conducted offline using Scan 4.3 software. Offline, the EEG recording was digitally filtered with a 1-30 Hz zero phase shift band-pass filter (12 dB down). The vertical ocular electrodes enabled offline blink reduction according to a standard algorithm (Semlitsch, Anderer, Schuster, & Presslich, 1986).

**Data Analysis**

Epochs encompassing an interval from 100 ms prior to the onset of the stimulus and extending to 1000 ms post-stimulus were extracted and baseline corrected around the pre-stimulus interval. Epochs containing artifacts larger than 150 μV or where an incorrect behavioural response was committed were excluded from the ERP average. The average number of trials included in each grand-averaged waveform was 84 trials for the congruous condition, 34 trials for the incongruous condition, and 41 trials for the
Nogo condition. Participants committed between 0 and 12 false alarm responses following Nogo stimuli ($M = 1.8, SD = 3.4$). One missed trial following a congruous stimulus was recorded, and no misses were observed following incongruous stimuli. Between 0 and 5 incorrect responses were recorded following congruous stimuli ($M = 1.8, SD = 1.9$) and between 2 and 13 incorrect responses were recorded following incongruous stimuli ($M = 8.6, SD = 3.6$). Difference waveforms were then calculated by subtracting the individual ERP average elicited following presentation of the congruent stimuli from the ERP average elicited following presentation of the incongruent stimuli and the Nogo stimuli. We calculated the interval over which the N2 inhibition effect was significant by comparing the amplitude of the difference waveforms at each time point from 0 - 450 ms against a mean value of zero. To control for the number of comparisons conducted, we required a successive sequence of 11 statistically significant values based on an autocorrelation of 0.9 and graphical threshold of 0.05, as detailed by Guthrie and Buchwald (1991). In the incongruous difference waveform, the N2 effect was significant over the interval 356 – 408 ms at Cz. In the Nogo waveform, the N2 effect was observed considerably earlier, over the latency 256 – 300 ms, and the amplitude differed from zero at the Fz site only. As it was not possible to identify a clear peak in the waveform at each of the sites, the scalp topography of the N2 effects within each condition were examined by computing the mean amplitudes over the 356 - 408 ms latency interval for the incongruous - congruous difference waveforms and over the 256 - 300 ms latency interval for the Nogo - congruous difference waveforms. ANOVA with scalp site (Fz, FCz, Cz) as a repeated measures factor was conducted on the mean amplitudes extracted. Latency and amplitude of the N2 effect were quantified for the peaks within a 248 – 408 ms latency window at the site of maximal amplitude only. This window was chosen to capture the intervals identified in difference
waveform analyses for both conditions and to ensure the maximum point was identified in each participant’s waveform.

Results

Behavioural Results

Relative to the congruous condition, performance was impaired in the incongruous condition in terms of both response time (congruous stimuli $M = 386$ ms, $SD = 20.9$; incongruous stimuli $M = 460$ ms $SD = 32.3$; $F(1, 11) = 131.9$, $p < .001$, $\eta_p^2 = .92$), and accuracy (congruous stimuli $M = 97.9\%$, $SD = 2.3$; incongruous $M = 80.5\%$, $SD = 8.2$; Nogo $M = 95.8\%$, $SD = 7.8$).

ERP Results

Figure 2 shows the stimulus-locked grand averaged waveforms for each condition and the difference waveforms computed by subtracting the ERPs elicited to congruous stimuli from each of the other two waveforms. The amplitudes and latencies of the N2 peak identified in the difference waveforms are summarized in Table 12.

Table 8

$N2$ Amplitude and Latency Summary Statistics (Means, with Standard Deviations in Parentheses).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Site</th>
<th>N2 mean amplitude</th>
<th>N2 peak amplitude</th>
<th>N2 peak latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incongruous – Congruous</td>
<td>Fz</td>
<td>-0.4 (1.6)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>FCz</td>
<td>-1.6 (1.9)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cz</td>
<td>-2.0 (1.7)</td>
<td>-3.3 (1.9)</td>
<td>379 (23)</td>
</tr>
<tr>
<td>Nogo – Congruous</td>
<td>Fz</td>
<td>-0.9 (0.9)</td>
<td>-1.9 (1.1)</td>
<td>288 (33)</td>
</tr>
<tr>
<td></td>
<td>FCz</td>
<td>0.1 (1.6)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Cz</td>
<td>0.8 (1.7)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 4. Stimulus-locked ERP waveforms, difference waveforms, and scalp topographic maps. Left-hand panel: Grand-averaged ERP in response to congruous (blue), incongruous (red), and Nogo (green) stimuli with the amplitude (μV) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset. Middle panel: Grand-averaged difference waveforms computed as the incongruous – congruous waveform (red) and Nogo – congruous (green). Right-hand panel: Topographic distribution of amplitude at the peak latency of the N2 identified in the difference waveforms (incongruous – congruous is shown in the upper map, and Nogo – congruous is shown in the lower map).

The negativity observed in the incongruous – congruous difference waveform over the 356 – 408 ms interval was centrally distributed (quadratic trend, $F(1, 11) = 6.5$, $p = .027$, $\eta_p^2 = .37; Cz > FCz > Fz$). In contrast, the negativity observed in the Nogo – congruous difference waveform over the 256 – 300 ms interval was frontally distributed (linear trend, $F(1, 11) = 17.0$, $p = .002$, $\eta_p^2 = .61, Fz > FCz > Cz$).
The negativity observed in the incongruous – congruous difference waveform peaked significantly later than the negativity observed in the Nogo – congruous difference waveform ($F(1, 11) = 75.2, p < .001, d = 2.6$).

**Discussion**

The results of this study showed that the topography and latency of the N2 were different following presentation of incongruous and Nogo stimuli. The N2 was found to be more frontal in the Nogo condition and more central in the incongruous condition, indicating that different neural generators are responsible for the two processes. Topographical differences between the response inhibition ERP effect and the interference suppression ERP effect suggest that these two processes originate in different neural regions, although source analysis would be required to verify this conclusion. While topographical differences do support a suggestion that non-equivalent cognitive processes are engaged, it is very possible that there is a common set of generators that differentially contribute to each process. Previous neuroimaging studies have suggested the dorsolateral prefrontal cortex is involved in response inhibition (Fassbender et al., 2004; Tanji & Hoshi, 2008), whereas the anterior cingulate cortex, located in a more central region, is implicated in the suppression of interference (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Swick & Jovanovic, 2002). These differences add to the experimental evidence examining whether these two aspects of inhibition reflect a unitary construct, or separable processes.

Latency was significantly longer in the incongruous condition than the Nogo condition, indicating that successful interference suppression required more time than successful response inhibition in our task. Although Friedman and Miyake (2004) speculated that interference suppression occurred before response inhibition, the current study found the opposite to be the case. Specifically, Friedman and Miyake reasoned
that interference suppression seems to refer to a stage of perceptual processing that occurs very quickly, and response inhibition is synonymous with a later stage of processing in which a motor response must be modified or withheld. However, results from the current study suggest that response inhibition occurs before interference suppression. One possible explanation for this is the differences between ‘stop’ and ‘change’ paradigms within inhibition (Logan & Burkell, 1986; van Boxtel et al., 2001). That is, response inhibition requires (in the case of the Nogo condition) the participant to inhibit all responses, whereas interference suppression requires participants to make a response despite interference from distractor stimuli. Conceptually, response inhibition can be viewed as a complete ‘shut-down’ of all responses, whereas interference suppression involves a more specific shut-down of processes, resulting in a more complex and intricate procedure, requiring more time to occur successfully. An alternate explanation for the differences in latency may be the use of colour as the distinguishing feature of the Nogo stimuli. Previous research suggests that colour processing occurs prior to the processing of form (Karayanidis & Michie, 1997). Given that in the current study the cue to inhibit the response was based on the colour of the stimuli whereas the interference suppression was cued by form, the initiation of response inhibition would occur before the interference suppression mechanism.

There is still some debate about the underlying mechanisms of the flanker task. An opposing explanation to the cognitive control account of the flanker task is the grouping effect (White, Ratcliff, & Starns, 2011), whereby feature similarity of several objects in an array is thought to cause all the objects to be grouped, such as in the congruous condition. This grouping effect may account for enhanced behavioural performance in the congruous condition compared to the incongruous condition, in which the target stimulus faces the opposite direction to the flankers, disrupting the grouping mechanism. However, the presence of the N2 difference waveform suggests
that there is some degree of interference suppression occurring in the incongruous condition (Falkenstein et al., 1999), supporting the role of cognitive control within the flanker task.

The results of this study could contribute to the development of new interventions in psychopathology. Previous research in children has found that Attention Deficit Hyperactivity Disorder is related to diminished response inhibition (Kooijmans, Scheres, & Oosterlaan, 2000), whereas interference suppression is reportedly unimpaired (van Mourik, Oosterlaan, & Sergeant, 2005). The opposite profile of inhibitory deficits has been reported in children with autism spectrum disorder. Children with autism spectrum disorder were found to have impaired interference suppression, but intact response inhibition (Christ, Holt, White, & Green, 2007). In light of the current electrophysiological results and prior fMRI research indicating distinct anatomical substrates for these two processes, future research using these techniques could contribute to our understanding of the underlying neural abnormalities in these clinical conditions.

The present study examined the dissociability of two domains identified within the taxonomy of inhibitory processes proposed by Nigg (2000) using ERP techniques which have high temporal resolution, but with lower spatial resolution than other cognitive neuroscience techniques such as fMRI. Future research would be needed to tease apart the differences between Nigg’s taxonomy and van Boxtel et al. ’s theory of selective and nonselective inhibition (van Boxtel et al., 2001).

In conclusion, research integrating modern cognitive neuroscience techniques in addition to behavioural measures has highlighted the ways in which two aspects of inhibitory processes previously regarded as representing a unitary construct (Friedman & Miyake, 2004) can be dissociated. Further development of taxonomy of inhibition
(Dempster, 1993; Harnishfeger, 1995; Nigg, 2000) would benefit from the continued integration of research evidence derived from these neuroscientific methods.
References


Chapter 4 – Maturation of Cognitive Control: Delineating Response Inhibition and Interference Suppression

This research was presented in an earlier form at the forty-first annual meeting of the International Neuropsychological Society, and a version of this chapter has been published in *PLoS ONE*:


Cognitive control refers to the group of processes required to resist interference from distracting stimuli or prepotent automatic responses, whilst attending to task-relevant information (Michel & Anderson, 2009; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). These inhibitory processes are often considered to be important components of intelligence (Dempster, 1991; Duan, Wei, Wang, & Shi, 2010; Obonsawin et al., 2002), as well as affecting an individual’s ability to function in everyday life (Garavan, Ross, & Stein, 1999). In the past 10-15 years, interest in how inhibition is associated with other EFs (especially shifting and updating of working memory) has been a particular area of focus (Brydges, Reid, Fox, & Anderson, 2012; Friedman et al., 2006; Miyake et al., 2000). However, although several theorists have proposed that subprocesses of inhibition should be considered as related yet separable, only a minimal amount of research has examined the validity of these claims (but see Brydges, Clunies-Ross et al., 2012; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Friedman & Miyake, 2004).

The present study focuses on response inhibition (the suppression of a prepotent or automatic behavioural response) and interference suppression (the ability to control
for distracting stimuli or information due to stimulus competition; Nigg, 2000). Nigg proposed a taxonomy of inhibition, of which response inhibition and interference suppression are two distinct yet related processes. Other prominent theories of inhibition (Dempster, 1993; Harnishfeger, 1995; van Boxtel, van der Molen, Jennings, & Brunia, 2001) may use different terminology for these constructs; however, each of these theories converges upon the notion that inhibition refers to several separate but interrelated processes, rather than a singular construct.

A recent study by Brydges, Clunies-Ross et al. (2012) reported electrophysiological evidence in support of the separability of response inhibition and interference suppression in young adults. Participants completed a hybrid Go/Nogo flanker task whilst having an electroencephalogram (EEG) recorded. The N2 event-related potential (ERP), which is commonly associated with inhibition on both Go/Nogo and flanker tasks (Carter & van Veen, 2007; Cragg, Fox, Nation, Reid, & Anderson, 2009; Falkenstein, Hoormann, & Hohnsbein, 1999; Jodo & Kayama, 1992; Tillman & Wiens, 2011), was analysed between the incongruous condition (measuring interference suppression) and the Nogo condition (measuring response inhibition). Two major findings were reported: first, the N2 peak associated with each process was maximal at different scalp sites, and the peak latency differed significantly between conditions. Specifically, the N2 elicited in the incongruous condition was maximal at the central midline site, and had a significantly longer latency than the N2 elicited in the Nogo condition, which was maximal at the frontal midline site. From this, it was suggested that these topographical differences were due to these two processes originating from different neural regions or that a common set of generators differentially contribute to each process. Additionally, the latency difference suggests that interference suppression may require additional cognitive processing over and above that required for successful
response inhibition (Logan & Buckrell, 1986; van Boxtel et al., 2001), providing further evidence for the separability of the proposed subprocesses of inhibition.

The maturation of inhibitory processes and other EFs is of critical importance in children, particularly in educational settings (St Clair-Thompson & Gathercole, 2006). Previous research has found marked improvements on behavioural measures of inhibition throughout childhood and, in some cases, into mid-adolescence (Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Leon-Carrion, Garcia-Orza, & Perez-Santamaria, 2004). Huizinga et al. reported improved performance on both a stop-signal task and a flanker task between groups of children aged 7, 11, and 15 years respectively, suggesting that there may be some common developmental process that leads to the improvement of both response inhibition and interference suppression.

From a neuroimaging perspective, Bunge et al. (2002) examined the maturation of these two processes by using functional magnetic resonance imaging (fMRI) to record neural activity whilst adults and children aged 8-12 years completed a hybrid Go/Nogo flanker task. It was reported that children displayed activation of posterior regions of the brain during successful response inhibition, whereas prefrontal regions were activated in adults. During successful interference suppression, prefrontal regions were activated for both groups; however, only the left hemisphere was activated in children, whilst only the right hemisphere was activated in adults. Hence, it is apparent that neural development of cognitive control occurs at a significant rate through late childhood and adolescence (Diamond, 1988; Fuster, 2002). One possible drawback of the task used by Bunge et al., however, is that the flanker stimuli acted as cues to inhibit responses in the Nogo condition of their task. That is, in the conditions that required a response, the flanker stimuli were meant to be ignored, but participants were required to
actively attend to them in the Nogo condition. This could have changed the manner in which participants processed the incongruous stimuli, supported by the low error rates in this condition.

No previous research has used ERPs to simultaneously examine the maturation of response inhibition and interference suppression. When examining response inhibition, Johnstone, Pleffer, Barry, Clarke, and Smith (2005) recorded EEG data whilst groups of children, and young and older adults completed a Go/Nogo task, and found that N2 peak latency significantly decreased from childhood to adulthood, perhaps due to myelinisation occurring during this period of childhood, hence increasing neural speed (Brouwer et al., 2012). N2 peak amplitude also significantly decreased with age, due to greater activation of regions of the prefrontal cortex in children than in adults (Tamm, Menon, & Reiss, 2002). Additionally, Jonkman, Sniedt, and Kemner (2007) reported that the medial frontal cortex (near the anterior cingulate cortex) is activated during response inhibition and associated with the N2 in both children and adults. There is a scarcity of literature examining the electrophysiological development of interference suppression through childhood; however, Rueda, Posner, Rothbart, and Davis-Stober (2004) found a significant decrease of N2 peak latency between four year-old children and adults during completion of a child-friendly flanker task. However, the amplitude of the N2 was very small in the group of children, and became larger in the adult group. It was claimed that these differences are neural evidence of the incomplete development of interference suppression processes in children.

The aim of this study was to examine the maturation of response inhibition and interference suppression simultaneously from an electrophysiological perspective. It was hypothesised that the results observed by Brydges, Clunies-Ross, et al. (2012)
would be replicated in the adult sample. Specifically, the N2 associated with response inhibition have a shorter latency and be more frontally distributed than that of the N2 associated with interference suppression. Additionally, it was hypothesised that the site of maximal amplitude of the N2 ERP associated with response inhibition would become increasingly frontal between childhood and adulthood (Bunge et al., 2002; Fuster, 2002), and that the N2 amplitude and peak latency would both significantly decrease with age (Johnstone et al., 2005). Furthermore, it was hypothesised that there would be no change in the site of maximal amplitude of the N2 ERP associated with interference suppression between children and adults. However, based on the results of Rueda et al. (2004) there would be a significant increase in the amplitude of the N2, and a significant decrease of peak latency, with age. In addition to ERP analyses, source localisation was conducted on each group and condition, and was expected to display further evidence of different neural generators between conditions.

Method

Participants

Twenty six participants were recruited and split into two groups of 13. The group of typically developing children were aged 8-11 years (M = 9.77 years; 9 females and 4 males), and the adults (8 females and 5 males) were all aged 18 years. Children were recruited through Project K.I.D.S. (Kids’ Intellectual Development Study), a research program examining the cognitive, social, and emotional development of children run by the Neurocognitive Development Unit of the School of Psychology of the University of Western Australia. The young adults were first-year undergraduate psychology students who participated in order to partially fulfil course requirements. Both groups completed the task as part of a larger test battery.
Materials

The same hybrid Go/Nogo flanker task used by Brydges, Clunies-Ross, et al. (2012) was used in this study. Each stimulus consisted of five fish presented on a blue background. An arrow on the body of the fish specified direction and the target was the central fish. Participants were instructed to press a response button on a keyboard (red felt patches on the ‘Z’ and ‘/’ keys) analogous to the direction of the central fish. The task had three conditions: in the congruent condition (.5 probability), the fish were green and all facing the same direction. In the incongruent condition (.25 probability), the fish were also green, however the flankers faced the opposite direction to the central target. In the Nogo condition (.25 probability), the fish were congruent but were all red, the participant was required to not respond. Each fish subtended .9° horizontally and .6° vertically, with .2° separating each fish (see Figure 10). Stimuli were presented in random order for 300 ms with a 2,000 ms inter-stimulus interval. The task was presented to the children as a game in which the participants had to feed the hungry central fish. Speed and accuracy were equally emphasized. Eight practice trials were administered to ensure the participants understood the task requirements. A total of 176 trials were subsequently presented in one block.

Figure 5. The six stimuli used in the present experiment (taken from Brydges, Clunies-Ross, et al., 2012).
**Electrophysiological Acquisition**

The EEG was continuously recorded using an Easy-Cap™. Electrodes were placed at 33 sites based on Easy-Cap montage 24 (see [http://www.easycap.de/easycap/e/products/products.htm](http://www.easycap.de/easycap/e/products/products.htm) for more details). Eye movements were measured with bipolar leads placed above and below the left eye. The EEG was amplified with a NuAmps 40-channel amplifier, and digitized at a sampling rate of 250 Hz. Impedances were below 5 kΩ prior to recording. During recording, the ground lead was located at AFz and the right mastoid was set as reference, and a common averaged reference was calculated offline. Scan 4.3 was used to conduct the ERP processing. Offline, the EEG recording was digitally filtered with a 1-30 Hz zero phase shift band-pass filter (12 dB down). The vertical ocular electrodes enabled offline blink reduction according to the standard algorithm proposed by Semlitsch, Anderer, Schuster, and Presslich (1986).

**Data Analysis**

Epochs encompassing an interval from 100 ms prior to the onset of the stimulus and extending to 1000 ms post-stimulus were extracted and baseline corrected around the pre-stimulus interval. Epochs containing artifacts larger than 150 μV or where an incorrect behavioural response was committed were excluded from the ERP average. Difference waveforms were then calculated by subtracting the individual ERP average elicited following presentation of the congruent stimuli from the ERP average elicited following presentation of the incongruent stimuli and the Nogo stimuli. We calculated the interval over which the N2 inhibition effect was significant by comparing the amplitude of the difference waveforms at each time point from 100 - 550 ms against a mean value of zero. To control for the number of comparisons conducted, we required a successive sequence of 11 statistically significant values based on an autocorrelation of
0.9 and graphical threshold of 0.05, as detailed by Guthrie and Buchwald (1991). In the group of children, the incongruous N2 effect was not significant at Fz, FCz, or Cz. In the Nogo condition, the N2 effect was significant at Cz between 388-464 ms only. In the adult group, the incongruous waveform was significant at Fz, FCz, and Cz, during respective latencies of 312-360, 304-380, and 296-388 ms. These latency windows were averaged to 304-376 ms for analyses. In the Nogo condition, the N2 waveform was significant at Fz (128-180 ms and 224-264 ms) and FCz (136-180 ms). However, upon examination of the difference waveforms, it was apparent that the two early waveforms at these sites were N1 peaks, and were excluded from analyses.

Source localisation analyses were conducted on each condition in the adult group using BESA 5.1. The same analyses were attempted on the group of children; however, the observed results were inadmissible. Instantaneous dipole models were computed on grand average ERP difference waveforms of each condition within the latency windows mentioned previously. A four-shell ellipsoidal head model with default values of bone thickness (7.0 mm) and conductivity (0.0042) was used for analyses. Dipole pairs were fitted with locations and orientations constrained to be mirror-symmetrical. Source models were computed in a 12 ms window around the N2 difference peak latency at the site of maximal amplitude for each of the conditions (276 ms at Fz for the Nogo – congruous difference waveform, and 352 ms at FCz for the incongruous – congruous difference waveform). Source models were considered acceptable if they explained at least 95% of the variance, and were stable across different starting points. The reported solutions were stable across different starting positions.

A mixed design ANOVA with scalp site (Fz, FCz, Cz) as a repeated measures factor was conducted on the mean amplitudes extracted. Latency and amplitude of the
N2 effect were quantified for peaks within a 212-464 ms latency interval at the site of
maximal amplitude only. This window was chosen to capture the intervals identified in
difference waveform analyses for both conditions in each age group, and to ensure the
maximum point was identified in each participant's waveform.

Results

Behavioural Results

Descriptive statistics of behavioural results are presented in Table 13. A 2 x 2 mixed design ANOVA with reaction time (congruous and incongruous) as a repeated measures factor found that performance was impaired in the incongruous condition in comparison to the congruous condition ($F(1, 24) = 57.22, p < .001, \eta_p^2 = .70$).

Additionally, performance significantly improved with age ($F(1, 24) = 28.23, p < .001, \eta_p^2 = .54$). However, the interaction between age group and condition was not significant ($F(1, 24) = 0.38, p = .54, \eta_p^2 = .02$).

Table 9

Descriptive statistics of behavioural measures between groups (means, with standard deviations in parentheses).

<table>
<thead>
<tr>
<th>Age group</th>
<th>Congruous</th>
<th>Incongruous</th>
<th>Nogo</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reaction Time</td>
<td>% correct</td>
<td>Reaction Time</td>
</tr>
<tr>
<td>Children</td>
<td>637 (184)</td>
<td>.91 (.06)</td>
<td>705 (167)</td>
</tr>
<tr>
<td>Adults</td>
<td>379 (35)</td>
<td>.97 (.04)</td>
<td>437 (51)</td>
</tr>
</tbody>
</table>

ERP Results

The mean N2 amplitude of the incongruous – congruous difference waveform of one adult participant was considered an extreme value (greater than 3 SDs from the
mean), and was replaced with a value 3 SDs from the mean for statistical analyses.

Figure 11 shows the stimulus-locked grand averaged waveforms for each condition
between age groups, and Figure 12 shows the difference waveforms computed by
subtracting the ERPs elicited to the congruous stimuli from each of the other two
waveforms. The amplitudes and latencies of the N2 peak identified in the difference
waveforms are summarised in Table 14.

The results of Brydges, Clunies-Ross, et al. (2012) were generally replicated: the
negativity observed in the Nogo – congruous difference waveform was more frontally
distributed (Fz>FCz>Cz) than that observed in the incongruous – congruous difference
waveform (FCz>Cz>Fz), as evidenced by a significant interaction between scalp site
and condition \((F(2, 24) = 3.96, p = .033, \eta^2_p = .25)\). Additionally, the peak latency of the
incongruous – congruous difference waveform was significantly longer than that of the
Nogo – congruous difference waveform \((F(1, 12) = 8.24, p = .014, \eta^2_p = .41)\).

The negativity observed in the Nogo – congruous difference waveform did not
produce a significant main effect of electrode site \((F(2, 48) = 0.47, p = .63, \eta^2_p = .02)\) or
of age group \((F(1, 24) = 0.18, p = .90)\). However, a significant interaction between site
and age group was observed (quadratic trend; \(F(1, 24) = 19.30, p < .001, \eta^2_p = .45)\).
Specifically, the N2 peak was centrally distributed in children (Cz>FCz>Fz), but was
frontally distributed in adults (Fz>FCz>Cz). The peak latency of the negativity
observed in the Nogo – congruous difference waveform significantly decreased with
age \((F(1, 24) = 7.18, p = .013, \eta^2_p = .23)\). Additionally, peak amplitude also decreased
with age, although this effect was marginally significant \((F(1, 24) = 3.93, p = .059, \eta^2_p
= .14)\). As no significant N2 effect was observed for the incongruous – congruous
difference ERP in the group of children, no analyses were conducted.
Figure 6. Stimulus-locked grand average ERP waveforms in response to congruous (blue), incongruous (green), and Nogo (red) stimuli with the amplitude (μV) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset.
**Figure 7.** Grand-averaged difference waveforms computed as the incongruous – congruous waveform (green) and Nogo – congruous (green) with the amplitude (μV) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset.
Table 10

*N2 amplitude and latency summary statistics between groups (means, with standard deviations in parentheses).*

<table>
<thead>
<tr>
<th>Group</th>
<th>Condition</th>
<th>Site</th>
<th>N2 MA</th>
<th>N2 PkA</th>
<th>N2 PkL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children</td>
<td>IS – CS</td>
<td>Fz</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FCz</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cz</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NG – CS</td>
<td>Fz</td>
<td>0.00 (1.16)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FCz</td>
<td>-0.93 (1.78)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cz</td>
<td>-1.86 (1.93)</td>
<td>-4.08 (1.79)</td>
<td>352.00 (64.06)</td>
<td></td>
</tr>
<tr>
<td>Adults</td>
<td>IS – CS</td>
<td>Fz</td>
<td>-1.04 (1.19)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FCz</td>
<td>-2.37 (2.11)</td>
<td>-3.35 (2.00)</td>
<td>350.46 (36.90)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cz</td>
<td>-1.80 (0.94)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG – CS</td>
<td>Fz</td>
<td>-1.70 (1.80)</td>
<td>-2.66 (1.86)</td>
<td>275.69 (80.22)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FCz</td>
<td>-0.90 (2.07)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Cz</td>
<td>-0.41 (1.43)</td>
<td></td>
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</tbody>
</table>

**Source Localization Results**

Source localization analyses were conducted on grand average ERP difference waveforms of each condition in the adult group (see Figure 13). In the Nogo condition, two symmetrical dipoles at Talairach coordinates (11.7, 27.1, 26.8) and (-11.7, 27.1, 26.8) accounted for 95.47% of the variance, mapping onto a more anterior region of the cingulate gyrus in each hemisphere (Lancaster et al., 1997, 2000). In the incongruous condition, two symmetrical dipoles at (8.1, -10.5, 28.8) and (-8.1, -10.5, 28.8) accounted for 95.17% of the variance in the ERP, mapping onto the cingulate gyrus in each hemisphere.
Figure 8. Source localisation analyses for (a) Nogo – congruous and (b) incongruous – congruous N2 effects in the adult group.

Discussion

The results of this study showed that the N2 ERP changed in latency and topography between childhood and adulthood, and that the N2 effect was different following presentation of incongruous and Nogo stimuli in the two groups. The differences of amplitude, latency, and topography between conditions during development (as evidenced by the significant main effects and interactions of ANOVAs), as well as differences observed in the source localisation analyses conducted on the adult group, provide evidence of the separability of response inhibition and interference suppression (Brydges, Clunies-Ross, et al., 2012; Nigg, 2000).

In the Nogo condition, the N2 effect was maximal at central scalp sites in children, but was maximal at frontal sites in adults. Additionally, source localisation found that the dipoles observed in adults are in frontal regions (see Figure 4). Previous research has found that neural activation associated with response inhibition becomes increasingly frontal with age through childhood development (Bunge et al., 2002). Frontal regions, including the anterior cingulate cortex, are commonly associated with behavioural performance on Go/Nogo tasks in adults (Braver, Barch, Gray, Molfese, &
Snyder, 2001; Devinsky, Morrell, & Vogt, 1995), and are one of the last regions of the brain to complete development (Fuster, 2002; Reiss, Abrams, Singer, Ross, & Denckla, 1996). It appears that in the early stages of development of this region, children are more reliant upon more posterior regions of the brain in order to successfully inhibit responses (Bunge et al., 2002; Hershey et al., 2010). Additionally, a significant main effect of latency was observed. This may be explained by the large-scale myelination occurring throughout childhood and adolescence (Brouwer et al., 2012; Tamnes et al., 2010), which is commonly thought to decrease ERP latency (Cardenas et al., 2005; Picton & Taylor, 2007). A marginally significant decrease in amplitude was also observed between the two age groups, providing some support for previous research by Johnstone et al. (2005), who found that N2 amplitude decreased with age, thought to be caused by fewer cognitive demands and increasingly efficient recruitment of relevant brain regions as individuals develop through childhood (Tamm et al., 2002).

In the incongruous condition, there was no significant N2 effect in the group of children, whereas the effect was maximal at fronto-central sites in adults. Although an increase in the size of the effect from childhood to adulthood was hypothesised, it is somewhat surprising that no N2 effect at all was observed in children. It is possible that this lack of significant neural activation in children is caused by differences in the propagation of neural activation between childhood and adulthood. Previous neuroimaging research has reported that children display more diffuse activation of frontal regions, whereas the neural activation observed in adults is more focalised due to a gradual decrease in the number of synapses through childhood and adolescence, and an increase in the strength of connections between the remaining synapses during this time (Casey, Giedd, & Thomas, 2000; Kelly et al., 2009). Due to these weaker, more inefficient connections between synapses in children, it may be plausible that children
‘spread the load’ across a larger region of the brain, which results in less dense neural activation.

The results of this study could contribute to several avenues of future research, particularly in clinical settings. For example, examining the effects of traumatic brain injury (TBI) on response inhibition and interference suppression would provide further insight into the underlying neural generators of the two processes. Whilst some previous research (Caeyenberghs et al., 2012; Kinnunen et al., 2011) has examined the effects of TBI on various cognitive tasks, no study has attempted to determine whether a differential deficit exists between these inhibitory subprocesses. Considering that previous research has highlighted clear differences in white matter integrity between TBI patients and control groups (Kinnunen et al., 2011), it would be of particular interest to examine the latency of the N2 ERP, as an increased latency in TBI patients would provide a new perspective on the link between brain and behaviour in atypical groups.

Alternatively, examining differences between typically and atypically developing groups of children may be of benefit. Children born preterm, for instance, have been shown to be at increased risk of various cognitive deficits, including executive dysfunction (Bayless & Stevenson, 2007), in addition to neurophysiological differences such as decreased brain volume (Cooke & Abernethy, 1999; Nosarti et al., 2002). Research into differences between typically and atypically developing children can potentially provide further evidence of the separability of inhibitory subprocesses from a new perspective, strengthening theories of inhibition and its development (Nigg, 2000).

In conclusion, the present study has added evidence from an electrophysiological perspective to the predominantly behavioural-based knowledge of
the development of inhibitory processes (Friedman & Miyake, 2004; Huizinga et al., 2006; Nigg, 2000). Results from ERP analyses have reported topographical changes in both response inhibition and interference suppression, and latency and amplitude reductions in response inhibition. Additionally, source localisation analysis has provided evidence that the neural generators of response inhibition and interference suppression are distinct. Consistent with previous research, the current study suggests that the cingulate cortex is involved in, and highly important to, response inhibition and interference suppression respectively (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999; Fassbender et al., 2004; Konishi et al., 1999; Swick & Jovanovic, 2002; Tanji & Hoshi, 2008). Furthermore, there are marked differences between age groups within each condition, providing neurophysiological evidence of different developmental trajectories of the two constructs. Theories of the development of inhibition and other higher-order cognitive functions (such as working memory) would greatly benefit from the integration of neuroscience with behavioural evidence.
References


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Chapter 5 - Predictive validity of the N2 and P3 ERP components to executive functioning in children: A latent-variable analysis

This research was presented in an earlier form at the fourth annual meeting of the Australasian Cognitive Neuroscience Society, and a version of this chapter has been submitted for publication in *Frontiers in Human Neuroscience*:


Executive functions are higher-order cognitive functions that are associated with goal directed behaviour (Miller & Cohen, 2001). The development of executive functions throughout childhood is of critical importance, as these functions are associated with academic achievement in children (St Clair-Thompson & Gathercole, 2006) and successful living (Garavan, Ross, & Stein, 1999). Previous research has found electrophysiological correlates of specific executive functions in both adults and children (Cragg, Fox, Nation, Reid, & Anderson, 2009; Krug & Carter, 2012; Polich, Ladish, & Burns, 1990; van Veen & Carter, 2002; Walhovd & Fjell, 2002), providing evidence of distinct neural substrates of these processes. However, these studies have not taken differences in the structure of executive functions between adults and children into account (Brydges, Reid, Fox, & Anderson, 2012; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Miyake et al., 2000). Executive functions in adults are generally considered to be related yet separable constructs (Miyake et al., 2000); however, recent psychometric evidence suggests that the latent traits of inhibition, working memory, and
shifting are indistinguishable from each other in typically developing children up to at least the age of 9 years (Brydges, Reid, et al., 2012). Given this, the current study aims to determine how these distinct components in the event-related potential (ERP) are related to aspects of executive functioning when incompletely developed in children.

One widely accepted model of executive functions was initially proposed by Miyake et al. (2000), who used confirmatory factor analysis (CFA) on multiple measures of three commonly postulated executive functions (prepotent response inhibition, updating of working memory, and task switching). The use of CFA in this context is advantageous because measures of executive functions all have some degree of task impurity (Rabbitt, 1997). Non-executive processes (such as motor control) are a necessary part of any task that is designed to measure executive functioning. CFA alleviates this problem by using several measures of each executive function and extracting the common variance between these measures, to create a ‘pure’ latent variable, or factor, which can then be correlated with other factors. The resultant model reported by Miyake et al. provided evidence these three constructs were found to be related yet are distinct from one another, as evidenced by moderately strong correlations between each factor, ranging from $r = .42$ to $r = .63$.

Several studies have attempted to replicate the Miyake et al. (2000) model of executive functions in children. In young children, these executive functions are indistinguishable, resulting in a unitary model of executive functioning in children at least up to the age of 9 years (Brydges, Reid, et al., 2012; Hughes, Ensor, Wilson, & Graham, 2009; Wiebe, Espy, & Charak, 2008; Willoughby, Wirth, Blair, & Greenberg, 2012). Hughes et al. conducted a longitudinal study to examine the development of executive functions in young children, and reported a single factor was the best fit for the data at both 4 and 6 years of age. Additionally, Brydges, Reid et al. tested a group of
7-year-old and a group of 9-year-old children, and found that the structure of executive functions was invariant between groups, despite improved performance with age. However, as children develop past the age of 9 years, these executive functions are thought to become increasingly separable. Lehto et al. (2003) reported three related yet separable executive functions in children aged 8-13 years (mean age of 10.5 years). Furthermore, Wu et al. (2011) and Duan, Wei, Wang, and Shi (2010) also both reported unity and diversity of executive functions in older children (mean ages of 10.9 years and 11.8 years respectively). Hence, it is possible that executive functions develop globally until about 9 years of age, before differentiation occurs in mid to late childhood. It should be noted, however, that the age at which executive functions are distinguishable is subject to some variation, possibly due to the nature of the tasks used in each study (van der Sluis, de Jong, & van der Leij, 2007).

To further knowledge regarding the links between brain and behaviour, previous research in both adults and children has attempted to examine the relationship between specific neural processes associated with executive functions and behavioural performance on psychometric measures of these functions (Krug & Carter, 2012; Polich, 2007; Rushworth, Passingham, & Nobre, 2002; van Veen & Carter, 2002). Two components of direct relevance to the model of executive functions described above are the N2 and P3b peaks of the ERP.

The N2 peak is a fronto-central maximal negativity observed approximately 150-400 ms after stimulus onset (although often later in children), and has been repeatedly associated with the detection of response conflict in both children and adults (Cragg et al., 2009; Jodo & Kayama, 1992; van Veen & Carter, 2002). Jodo and Kayama used an electroencephalogram to record electrophysiological activity in young adults during a Go/Nogo task, and reported larger N2 amplitudes were associated with
fewer errors on Nogo trials. Cragg et al. reported a significantly larger N2 amplitude on Nogo trials than on go trials in typically developing children aged 7-9 years, providing further evidence of the N2 being an electrophysiological correlate of response conflict and inhibition.

The P3b peak is a positivity seen at central and parietal scalp sites approximately 300-500 ms after stimulus onset (again, often observed later in children), and has been associated with updating of working memory (Donchin & Coles, 1988; Polich, 2007). Walhovd and Fjell (2002) found positive associations between P3b amplitude, latency (both obtained during an auditory oddball task at central midline scalp sites) and performance on a digit span task in a sample of adults aged 21-94 years. These relationships were also observed in a sample of children and young adults aged 4-20 years (Polich et al., 1990), further highlighting a link between the P3b and working memory.

The central issue of the current study is that the ERP correlates of executive functions are observable in mid- to late-childhood (Cragg et al., 2009; Polich et al., 1990); however, psychometric research suggests that the latent traits of these functions are not distinguishable from each other during this developmental period (Brydges, Reid et al., 2012; Hughes et al., 2009). From this, it is possible that ERP components develop before specific executive abilities. If associations between ERP components and executive functioning exist, ERPs could potentially be used as a more sensitive measure of neuropsychological development than traditional psychometric measures.

To the authors’ knowledge, no previous study has attempted to examine associations between ERPs and executive functions using structural equation modelling (SEM). The current study aimed to determine (a) if there is a correlational association between brain and behavioural measures of executive functions; and (b) if the
electrophysiological activity predicts behavioural performance. Hence, it was predicted that both ERP latent variables would significantly correlate with an executive function latent variable in a CFA, and both be significant predictors of the executive function latent variable in a structural equation model.

**Method**

The data used in the current study has been taken from the merging of two previously published datasets: The behavioural data has previously been reported in Brydges, Reid, et al. (2012), where full descriptions of the participants, procedures, and eight executive functioning measures are provided. ERP data from the Flanker task (described below) of a subset of approximately 120 of these children have also been previously reported by Richardson, Anderson, Reid, and Fox (2014). Approval for the study was provided by the Human Research Ethics Office of The University of Western Australia. Parents/guardians of the child participants provided written informed consent.

**Participants**

Participants were 215 typically developing children aged 7 years 1 month to 9 years 11 months (110 male and 105 female, $M = 8$ years 4 months, $SD = 1$ year 1 month). 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. Advertisements were placed in newsletters of local schools, and interested parents/guardians were sent screening questionnaires to ensure the eligibility of their child. 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 the time 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 \((M = 107.05, SD = 12.63)\).

**Materials**

The executive function latent variable was created using performance on the Stroop task (Stroop, 1935), Compatibility Reaction Time, WISC-IV Letter-Number Sequencing (Wechsler, 2003), WISC-IV Backwards Digit Span (Wechsler, 2003), NEPSY Sentence Repetition (Korkman, Kirk, & Kemp, 1997), Wisconsin Card Sorting Test (WCST; Heaton, Chelune, Talley, Kay, & Curtiss, 1993), BAS-II Verbal Fluency (Elliott, Smith, & McCullouch, 1997), and a Letter Monitoring task (Duncan, Emstlie, Williams, Johnson, & Freer, 1996). These tasks were selected as they are commonly regarded as indicators of one of the three executive functions tested in the original Miyake et al. (2000) model. A Go/Nogo task (Cragg et al., 2009) was also administered, but was found to not significantly load onto the executive function factor. Removing the task did not have any effect, so it was excluded from all analyses (descriptive statistics and correlations for this task have been provided for reference in Tables 11 and 12, respectively).

In addition, participants also completed a modified visual flanker task (Richardson, Anderson, Reid, & Fox, 2011; Rueda, Posner, Rothbart, & Davis-Stober, 2004) whilst EEG data were recorded. Each stimulus consisted of five fish presented on a blue background (see Figure 3). An arrow on the body of each fish indicated direction and the target was the central fish. Participants were instructed to press a response button situated on a keyboard (red felt patches on the ‘Z’ and ‘/’ keys) corresponding to the direction of the central fish. There were three conditions: in the congruent condition (.5 probability), the five fish were green and all pointing in the same direction; an incongruent condition (.25 probability), where all the fish were also green, however, the
flankers pointed in the opposite direction to the central target; and a reversed condition (.25 probability), in which the flanker fish were congruent, but all five fish were red, and required a response in the opposite direction to the central fish. The reversed condition in this study replaced the Nogo condition used in chapters 3 and 4 to minimize any pop-out effects, as a correct response on these trials is still reliant upon the participant having to perceive the form of the stimuli, rather than just the colour. Each fish subtended .9° horizontally and .6° vertically with .2° separating each fish and were randomly presented for 300 ms. A keyboard response was required before the next trial began. The task was presented as a game in which the participants had to feed the hungry central fish. Speed and accuracy were equally emphasized. A practice block of 8 trials was administered to ensure the participants understood the task requirements. A total of 352 trials were presented in two blocks.

![Figure 9. The six flanker task stimuli used in the current experiment.](image)

**Electrophysiological Acquisition**

The EEG was continuously recorded using an Easy-Cap™. Electrodes were placed at 33 sites based on Easy-Cap montage 24 (excluding TP9 and TP10; see http://www.easycap.de/easycap/e/products/products.htm for more details). Eye movements were measured with bipolar leads placed above and below the left eye. The EEG was amplified with a NuAmps 40-channel amplifier, and digitized at a sampling rate of 250 Hz. Impedances were below 5 kΩ prior to recording. During recording, the ground lead was located at AFz and the right mastoid was set as reference. After
recording, a linked mastoid reference was calculated offline, and Scan 4.3 was used to conduct the ERP processing. Offline, the EEG recording was digitally filtered with a 1-30 Hz zero phase shift band-pass filter (12 dB down). The vertical ocular electrodes enabled offline blink reduction according to the standard algorithm proposed by Semlitsch, Anderer, Schuster, and Presslich (1986).

**ERP Data Analysis**

Epochs encompassing an interval from 100 ms prior to the onset of the stimulus and extending to 1000 ms post-stimulus were extracted and baseline corrected around the pre-stimulus interval. Epochs containing artefacts larger than 150 μV or where an incorrect behavioural response was made were excluded from the ERP average. Additionally, the ERP data of participants who did not score significantly higher than chance on the congruous condition of the flanker task (\( n = 2 \)) or had fewer than 25 acceptable epochs in any condition (\( n = 4 \)) were excluded and treated as missing data. The average number of trials included in each grand-averaged waveform was 151 trials for the congruous condition, 71 for the incongruous condition, and 70 for the reversed condition.

PCA with varimax rotation was used to determine the time windows of the P3b peaks. An epoch of 0 – 700 ms was used, with individual average waveforms from all three conditions at sites Fz, FCz, Cz, and Pz. The first extracted component was 584 – 648 ms (explaining 29.48% of the variance), matching a visual inspection of the P3b peaks (see Figure 10). Visual inspection of the individual participants’ ERPs also revealed that not all of the participants displayed identifiable P3b peaks, so mean amplitudes were calculated across this interval. The N2 was calculated by extracting difference waveforms; that is, the individual ERP average from the congruous condition was subtracted from the individual ERP averages of the incongruous and reversed
conditions. We calculated the interval over which the N2 inhibition effect was significant by comparing the amplitude of the difference waveforms at each time point from 0 - 600 ms against a mean value of zero. To control for the number of comparisons conducted, we required a successive sequence of 12 statistically significant values based on an autocorrelation of 0.9 and graphical threshold of 0.05, as detailed by Guthrie and Buchwald (1991). In the incongruous difference waveform, the N2 effect was significant over the interval 360 – 424, 348 – 468, and 348 – 472 ms at Fz, FCz, and Cz respectively. In the reversed difference waveform, the N2 effect occurred over the latency 316 – 496, 308 – 484, and 304 – 476 ms, at Fz, FCz, and Cz respectively. Visual inspection of the individual participants’ ERPs also revealed that not all of the participants displayed identifiable N2 peaks in the difference waveforms, meaning that analyses on peak amplitude values were not possible. As a result, mean amplitudes were calculated across the interval 352 – 456 ms for the incongruous condition and 308 – 484 ms for the reversed condition, as these are the average latency windows for the two difference waveforms. Fractional area latencies for the P3b ERP components were measured by calculating the total positive area in the 584 – 648 ms measurement window (extracted by the PCA), and then determining the earliest latency at which the summed positive area exceeded 25% of the total (Hansen & Hillyard, 1984). The same process was used for the N2 difference waveforms, except examining the negative area in the two intervals mentioned above. Difference waveforms were calculated for the N2 components, but not for the P3b, because it is argued that the N2 is an index of response conflict. As there is no conflict in congruous condition of the flanker task, then it follows that any ‘extra’ N2 amplitude is indicative of the response conflict presented within a trial (Lucci, Berchicci, Spinelli, Taddei, & di Russo, 2013; Nieuwenhuis, Yeung, & Cohen, 2004; Nieuwenhuis, Yeung, Wildenberg, & Ridderinkhof, 2003; van Veen & Carter, 2002). Conversely, every trial of the flanker task requires the context to
be updated, as new information is entering working memory (Polich, 2007). Hence, difference waveforms were not necessary.

**Transformation and Outlier Analysis**

The transformation procedures for the eight executive function measures followed those conducted by Miyake et al. (2000), and are described in detail by Brydges, Reid et al. (2012). Briefly, these were the use of arcsin transformations on proportion variables (Judd and McClelland, 1989), and a two-stage trimming procedure of scores that were more than 3 SDs from the mean in the compatibility reaction time task. Also, scores on all reaction time tasks, the Stroop task, and WCST were multiplied by -1 so that a higher score indicated better performance. When analyses were initially conducted, Heywood cases (i.e. models with standardised regression weights > 1) occurred on each of the ERP latent variables (most likely due to multicollinearity, as correlations between indicators were generally very high). As a result of this, single indicator latent variables were created for each of the ERP factors, by adding the two related indicators together to form a composite variable (Landis, Beal, & Tesluk, 2000) for each ERP index (i.e. the incongruous – congruous and reversed – congruous N2 amplitudes were added to make an N2 amplitude composite, the incongruous and reversed P3b amplitudes were added to make a P3b amplitude composite, and the incongruous and reversed P3b latencies were added to make a P3b latency composite). The N2 latencies were not included in the final analyses as every model with them included reported an inadmissible solution. Additionally, a single indicator latent variable could not be created with the two latencies as the correlation between them was very low (see Table 12). The other three composite variables all achieved a satisfactory level of normality without any transformations.
As CFA and structural equation modelling (SEM) are very sensitive to outliers, univariate and multivariate outlier analyses were conducted on the 11 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 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). Forty-eight participants had missing data for one or more tasks; however, Little’s (1988) MCAR test was non-significant \(\chi^2(125) = 141.86; p = .14\), indicating that the data were missing completely at random. These scores were estimated using the expectation maximisation method.

**Statistical Analysis**

Amos 19 (Arbuckle, 2010) was used to estimate the latent variable models. In both CFA and SEM, several fit indices were used to evaluate the fit of each model to the data. The \(\chi^2\) statistic is commonly used in latent variable analysis to measure goodness of fit; a non-significant \(\chi^2\) indicates that data entered into a theorised model does not significantly deviate from the model, inferring good model fit (Blunch, 2008). Bentler’s comparative fit index (CFI), the root-mean-square error of approximation (RMSEA), and the standardised root mean residual (SRMR) were also used to measure model fit. The criteria for excellent model fit based on these indices is greater than .95, less than .05, and less than .05 respectively (Blunch, 2008). Significance of correlation and path coefficients was determined using the same technique as Friedman et al. (2006). Specifically, \(\chi^2\) difference tests were conducted when removing an individual parameter. If the difference was significant, it indicated that the removed coefficient was statistically significant, and should be kept in the model. This technique is more
reliable than using test statistics that are based upon standard errors (Gonzalez & Griffin, 2001).

**Procedure**

A maximum of 24 children at a time attended Project K.I.D.S. for two consecutive days over a two week period during the school holidays. All testing was presented in a child friendly manner, and each testing session lasted no longer than 25 minutes. Meals and activities (such as games and art) were scheduled between sessions to ensure the participants enjoyed themselves and did not become fatigued. All participants were given a Project K.I.D.S. t-shirt as a memento of their participation at the end of the second day.

**Results**

**Descriptive Statistics**

Descriptive statistics of raw scores of the 11 measures (as well as Go/Nogo and flanker behavioural performance and N2 latencies) before any transformation procedures were conducted are presented in Table 11, and the correlations between the measures (after transformation, outlier analysis, and missing data estimation) are presented in Table 12. Additionally, the N2 amplitude variables were both found to be maximal at Cz, and the P3b component amplitudes were all maximal at Pz (see Figure 10).

**Latent Variable Analysis**

To test that the P3b and N2 amplitudes and P3b latency are associated with a unitary executive function, a four-factor CFA was conducted with correlations between the P3b amplitude, N2 amplitude, P3b latency, and executive function factors allowed to vary freely and alternative nested models tested afterwards. The full four-factor
model had very good model fit statistics ($\chi^2 = 58.75$, df = 44, $p = .07$, CFI = .94, RMSEA = .040, SRMR = .049). However, after testing the significance of parameter estimates, the best model only included correlations between P3b amplitude and executive functioning ($p = .025$), and N2 amplitude and executive functioning ($p = .012$). This final model had very good model fit statistics ($\chi^2 = 61.94$, df = 48, $p = .09$, CFI = .95, RMSEA = .036, SRMR = .051), and was not a significantly worse fit for the data than the full three-factor model ($\Delta\chi^2 = 3.19$, $\Delta$df = 4, $p = .53$). All other correlations were nonsignificant (see Table 13).

From this, an SEM was conducted, as this allows us to calculate the unique predictive contribution of each ERP factor on the executive function factor. The distinction between this analysis and the CFA is that SEM allows us to determine the unique contribution of each predicting factor after common variance has been accounted for. Figure 3 shows that, consistent with the findings of the CFA, both the P3b amplitude and N2 amplitude factors were significant predictors of the executive function factor, but the P3b latency factor was not ($p = .049$, $p = .026$, and $p = .77$, respectively).
Table 11

*Descriptive statistics of executive functions and ERP measures before transformation (N=215)*

<table>
<thead>
<tr>
<th>Task</th>
<th>M</th>
<th>SD</th>
<th>Range</th>
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</thead>
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<td><strong>Executive Functioning</strong></td>
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</tr>
<tr>
<td>Stroop*</td>
<td>25.72</td>
<td>14.55</td>
<td>0.00 – 97.89</td>
</tr>
<tr>
<td>Go/no-go*</td>
<td>.45</td>
<td>.22</td>
<td>.00 – 1.00</td>
</tr>
<tr>
<td>Comp. Reaction Time c</td>
<td>155.99</td>
<td>249.37</td>
<td>-811.97 – 1426.94</td>
</tr>
<tr>
<td>Letter-Number Sequencing</td>
<td>15.18</td>
<td>4.29</td>
<td>4 – 22</td>
</tr>
<tr>
<td>Backward Digit Span</td>
<td>6.21</td>
<td>1.54</td>
<td>2 – 11</td>
</tr>
<tr>
<td>Sentence Repetition</td>
<td>21.67</td>
<td>4.03</td>
<td>2 – 32</td>
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<td>19.14</td>
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<td>3.34</td>
<td>1.98</td>
<td>0 – 6</td>
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<td><strong>ERPs</strong></td>
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<td></td>
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<tr>
<td>P3b ERP mean amplitude composite</td>
<td>12.86</td>
<td>7.64</td>
<td>-4.53 – 35.72</td>
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<td>at site Pz</td>
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<tr>
<td>P3b ERP latency composite</td>
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<td>1168 – 1272</td>
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<td>N2 difference waveform mean amplitude composite at site Cz</td>
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<td>-14.39 – 4.76</td>
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<td>N2 difference waveform latency</td>
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<td>(reversed – congruous)</td>
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<td><strong>Flanker task</strong></td>
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<td>Congruous condition reaction time</td>
<td>869.05</td>
<td>233.08</td>
<td>450.30 – 2062.30</td>
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<td>Congruous condition accuracy</td>
<td>.89</td>
<td>.08</td>
<td>.59 – 1.00</td>
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<td>Incongruous condition reaction time</td>
<td>1011.40</td>
<td>330.70</td>
<td>481.60 – 3133.60</td>
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<td>Incongruous condition accuracy</td>
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<td>.13</td>
<td>.33 – 1.00</td>
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<tr>
<td>Reversed condition reaction time</td>
<td>1020.07</td>
<td>285.18</td>
<td>569.80 – 2487.45</td>
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<tr>
<td>Reversed condition accuracy</td>
<td>.81</td>
<td>.12</td>
<td>.26 – 1.00</td>
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*Note.* aDifference between incongruous and neutral conditions (s). bProportion correct. cDifference between block 5 and blocks 1-4 (ms). dTotal points scored. ePerseverative errors. fNumber of words. gTotal items correct. hμV. i ms. *Note that the SD for Compatibility Reaction Time are quite high, but decreased after trimming and transformation to -154.79 ms (SD = 208.46).*
Table 12

Correlations between measures of executive functioning and ERPs (N=215)

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Note. *p < .05; **p < .01.
**Figure 10.** Stimulus-locked ERP waveforms and difference waveforms. Panel (A): Grand-averaged ERP in response to congruous (blue), incongruous (green), and reversed (red) stimuli with the amplitude (μV) as the y-axis and time (ms) as the x-axis. Time 0 represents stimulus onset. Panel (B): Grand-averaged difference waveforms computed as the incongruous – congruous waveform (green) and reversed – congruous (red).

**Table 13.**

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<tr>
<td>1. Executive Function</td>
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<tr>
<td>2. N2 Amplitude</td>
<td>-.29*</td>
<td>-</td>
<td></td>
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<tr>
<td>3. P3b Amplitude</td>
<td>.19*</td>
<td>-.19</td>
<td>-</td>
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<td>4. P3b Latency</td>
<td>.00</td>
<td>-.12</td>
<td>.04</td>
<td>-</td>
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**Note:** *p < .05.
Figure 11. Structural equation model predicting executive functioning with the N2 difference waveform amplitude, P3b ERP amplitude, and P3b latency. Single-headed arrows have standardized factor loadings next to them. The numbers on the right are the squared multiple correlations for each variable. The dotted regression weight between the P3b latency and Executive Function factors is nonsignificant. All other coefficients are significant to $p < .05$.

**Discussion**

The current study aimed to examine associations between components of the ERP and executive functioning. Previous research has reported associations between the P3b peak and working memory in both adults and children (Polich et al., 1990; Walhovd & Fjell, 2002), and between the amplitude of the N2 and response
conflict/inhibition in adults and children (Cragg et al., 2009; Jodo & Kayama, 1992; van Veen & Carter, 2002). The latent variable analyses used in the current study revealed that the N2 difference waveform and the P3b mean amplitudes are associated with executive functioning, but not the latency of the P3b component.

Previous research has found associations between behavioural performance on working memory tasks and P3b amplitude (Polich et al., 1990; Walhovd & Fjell, 2002), and between behavioural performance on response inhibition tasks and N2 amplitude (Cragg et al., 2009; Jodo & Kayama, 1992). The current study brings together this research with studies examining the structure of executive functions in children (Brydges, Reid, et al., 2012; Lehto et al., 2003). As individual executive functions (such as response inhibition and updating of working memory) are psychometrically indistinguishable in typically developing children in this age range (Brydges, Reid, et al., 2012; Hughes et al., 2009; Willoughby et al., 2012), it may follow that the ERPs associated with these specific executive functions are associated with a general executive function (the opposing view being that the respective ERPs will not be observable as the specific executive abilities are not sufficiently developed in this age group). The current study found that both the N2 difference waveform and the P3b amplitudes correlated with, and were predictive of, a unitary executive function in children. However, whilst the N2 amplitude associated with performance on Nogo tasks in adults is typically maximal at frontal scalp sites (Folstein & Van Petten, 2008), our results support the notion that the N2 amplitude is maximal at more central scalp sites in children (Jonkman, 2006).

It is also worth noting that the current analysis only used mean amplitude values of the two electrophysiological variables, as no clear peaks were identifiable. As a result of this, peak latency could not be included as a predictor of executive functioning, and it
usually accounts for a significant proportion of variance in executive functioning (Walhovd & Fjell, 2002). However, when fractional areas latencies were calculated, no associations between latency and executive functioning were observed. This leads to the speculation that these ERPs begin to develop clear peaks around the same time as specific executive abilities develop, although, having said this, the deflections in the ERP were observable (even without any clear peak), yet the behavioural constructs were indistinguishable from each other. That is, whilst executive functioning is unitary in younger children, the N2 difference waveform and P3b component of the ERP are apparent. However, the change in the structure of executive functions, from unitary in children up to 9 years (Brydges, Reid, et al., 2012; Wiebe et al., 2008), to related yet separable functions in children aged around 11 years (Duan et al., 2010; Lehto et al., 2003) may be due to changes in the propagation of neural impulses – the peaks in the ERP become apparent before the specific behavioural abilities emerge. This could have important implications for the diagnosis of dysexecutive syndromes in samples where executive functions are psychometrically indistinguishable, as the ERP components may be a more sensitive measure of cognitive development. A longitudinal study would be required to test this conclusively.

Alternatively, using latent variables to test for associations between ERP components and executive functions in adults may be an informative area of future research. If the development of clear ERP peaks is associated with the development of abilities specific to single executive functions, then correlations between ERP and executive functioning factors should increase from the relatively low (but still significant; \( r = -.29 \) and \( r = .19 \)) values reported in this sample of children.

Additionally, the predictive power of other ERP peaks may have been missed in this study. For instance, Fjell, Walhovd, Fischl, and Reinvang (2007) found associations
between both P3a amplitude and latency (commonly associated with novelty detection, although generally not associated with any specific executive function) were both associated with higher-order cognitive functions in a sample of adults. Considering that the N2 difference waveform and P3b factors only accounted for 10% of the variance in the executive function factor (although both factors predicted a significant proportion of variance), it may be fruitful to also consider other predictor ERP peaks.

Another possible avenue of research involves examining differences between behavioural and electrophysiological development of individual executive functions. For instance, researchers have proposed taxonomies of both inhibition and working memory (Nigg, 2000; Oberauer, Süß, Wilhelm, & Wittman, 2003). Specifically, Nigg proposed four subtypes of inhibition, which are all separate yet related constructs. From an electrophysiological perspective, previous research has suggested some common neural regions of activation, including the dorsolateral prefrontal cortex and the anterior cingulate cortex (Carter & van Veen, 2007; Chambers et al., 2006; Chambers, Garavan, & Bellgrove, 2009; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). A few studies have examined two of these subprocesses (response inhibition and interference suppression), and have also found differential patterns of activation (Brydges, Anderson, Reid, & Fox, 2013; Brydges, Clunies-Ross, et al., 2012; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Bunge et al. (2002) reported multiple differences in regions of neural activation between task conditions requiring response inhibition and interference suppression. From a behavioural perspective, however, previous research has suggested that two of these subprocesses are actually indistinguishable (Friedman & Miyake, 2004). It may fruitful to further examine any potential differences (from both behavioural and neural perspectives) between subtypes of EFs such as inhibition to further our understanding of the architecture of EFs, and how these subtypes contribute to behaviours on complex tasks.
In conclusion, the present study has added evidence of the development of ERP correlates of executive functioning being observable before the specific executive functions themselves are psychometrically distinguishable. Additionally, evidence of the predictive qualities of ERPs on executive functioning from a latent variable perspective adds to the predominantly correlational-based knowledge of associations between brain and behaviour (Cragg et al., 2009; Polich et al., 1990; Walhovd & Fjell, 2002). SEM analyses found that both the N2 difference waveform and P3b (thought to be electrophysiological correlates of response conflict/inhibition and updating of working memory, respectively) were significant predictors of executive functioning. Theories of developmental cognition would greatly benefit from the integration of neuroscientific techniques with behavioural evidence.
References


Chapter 6 – General Discussion

Chapter Summary

The previous chapters outline a series of studies examining the development of EFs in childhood from a behavioural perspective, and developmental changes of one of these EFs (inhibition) from childhood to adulthood, from an electrophysiological perspective. This chapter presents a synopsis of the preceding four chapters, summarising the main findings, and offers new research directions and a new hypothesis as to the development of EFs through childhood.

As outlined in chapter 1, EFs are commonly thought to display ‘unity and diversity’. That is, specific EFs (such as inhibition, updating of working memory, and shifting) are separate entities and are distinguishable from one another, yet are related (Miyake et al., 2000). It is well known that EFs develop until late childhood or early adolescence (Huizinga & van der Molen, 2007; Luciana, Conklin, Hooper, & Yarger, 2005; Romine & Reynolds, 2005), however, the structure of EFs also changes during this period. Specifically, a unitary structure (i.e. where individual EFs are indistinguishable from each other) is apparent in children up to at least the age of 7 years (Shing, Lindenberger, Diamond, Li, & Davidson, 2010; Wiebe et al., 2008; Wiebe, Espy, & Charak, 2008; Willoughby, Wirth, Blair, Greenberg, & The Family Life Project Investigators, 2012). By the age of 10-11 years, however, children display unity and diversity of EFs – each individual function is separable, yet related to other EFs (Duan, Wei, Wang, & Shi, 2010; Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003; Wu et al., 2011) as in studies of adults. This trajectory towards increasingly specialised functions is also reflected in the neural development of the brain. That is, the brain grows rapidly in terms of weight and volume until about the age of 6 years (Geidd et al., 2009; Krestchmann, Kammradt, Krauthausen, Sauer, & Wingert, 1986; Reiss, Abrams,
Singer, Ross, & Denckla, 1996). After this point, the volume of white matter, which is associated with the development of cognitive functions during this period (Nagy, Westerberg, & Klingberg, 2004), continues to increase (Barnea-Goraly et al., 2005; Schmithorst, Wilke, Dardzinski, & Holland, 2005). Additionally, neural activation becomes less diffuse and more focalised through late childhood and adolescence (Dosenbach et al., 2010; Durston et al., 2006; Fair et al., 2009; Khundrakpam et al., 2013), possibly due to synaptic pruning (Casey, Geidd, & Thomas, 2000). Therefore, it is possible that these developmental changes in the brain lead to the development of and changes in the structure of EFs.

Chapter 2 (Brydges, Reid, Fox, & Anderson, 2012) examined the structure of EFs, as well as fluid and crystallised intelligence, in a sample of typically developing children aged either 7 or 9 years. It was hypothesised that development of EFs occurs with age (V. Anderson, 1998; Huizinga, Dolan, & van der Molen, 2006). Additionally, it was hypothesised that both groups of children would display increased unity of EFs when compared to the original Miyake et al. (2000) model of EFs (tested on a sample of young adults), and that the 9 year old group would show increased differentiation of EFs in comparison to the 7 year old group. Multiple measures of inhibition, working memory, shifting, and intelligence (fluid and crystallised) were administered in order for latent variable analyses to be conducted. The results from the study showed that performance on all executive functioning and intelligence measures improved between 7 and 9 years of age. However, measurement invariance testing found that associations between these measures did not significantly differ between age groups, implying that the structure of EFs and intelligence does not change between the two age groups. A CFA of the EF measures consistently reported a one-factor model as the best model for the data (i.e. when the two groups were analysed separately, and when the groups were combined into one). When a CFA was conducted on the measures of intelligence, two
distinct (yet related) factors emerged. A structural equation model showed that the unitary executive functioning factor strongly predicted both fluid and crystallised intelligence, but the correlation between the residuals of fluid and crystallised intelligence became nonsignificant (in comparison to the correlation between fluid and crystallised intelligence in a CFA).

The findings are indicative of global development or improvement in level of performance with no observable changes in the structure of executive functions between the ages of 7 and 9 years. These findings are consistent with previous research, demonstrating the unity of EFs in children aged 7 years (Shing et al., 2010; Wiebe et al., 2008, 2011; Willoughby et al., 2012). Additionally, a gap in the literature has been covered by testing this model on a sample of 9 year old children. It has been shown that the reported global development of EFs continues until at least the age of 9 years, and that the differential development of specific EFs has not occurred to an observable degree at this age.

By contrast, fluid and crystallised intelligence were clearly distinguishable from each other in these age groups and are highly (and equally) related to EFs as in adults. Hence, it is apparent that gF and gC become distinguishable from each other earlier in development than EFs. This indicates, at least, that the distinction between the constructs of EF and intelligence is valid. This could be due to gF being associated with activation of the prefrontal cortex (Duncan & Owen, 2000) and gC being associated with the activation of the parietal lobes (Geary, 2005), which mature at different rates (Fuster, 2002). Additionally, it is clear that EFs are also highly related to gF and gC, as can be seen in the very high correlations between the constructs (EF-gF $r = .89$ and EF-gC $r = .83$) and the nonsignificant correlation between the residuals of gF and gC once EF is accounted for. This nonsignificant residual correlation implies that the process of
converting gF into gC is entirely mediated by EFs. Specifically, the engagement of EFs is of crucial importance during learning in children, as the engagement of these functions appears to be critical to the process of creating knowledge (i.e. gC) from fluid abilities (gF).

Chapter 3 (Brydges, Clunies-Ross et al., 2012) investigated differences between two subprocesses of cognitive control (response inhibition and interference suppression) from an electrophysiological perspective. Specifically, N2 difference waveform peaks were extracted from a hybrid flanker/Nogo task, and compared in terms of amplitude, latency, and topography. Although previous research has examined this area using fMRI (see Niendam et al., 2012, for a detailed meta-analysis), the use of ERPs can be advantageous due to the high temporal resolution of the technique, allowing for any differences in the timing of neural activity to be observed. It was hypothesised that, based on previous fMRI research (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Blasi et al., 2006), there would be differences in the topography of maximal N2 amplitude. Additionally, it was hypothesised that the latency of the N2 elicited as a result of interference suppression would be significantly longer than the latency elicited as a result of response inhibition.

The findings of this study show that response inhibition and interference suppression should be considered as two distinct entities, despite previous behavioural research suggesting they are indistinguishable (Friedman & Miyake, 2004). The N2 difference waveforms displayed topographical and significant peak latency differences between conditions. Specifically, the N2 difference waveform associated with response inhibition was maximal at frontal midline scalp sites, whereas the N2 difference waveform associated with interference suppression was maximal at central midline
scalp sites. Additionally, the peak latency of the response inhibition N2 was significantly shorter than the interference suppression N2.

These results complement and extend those reported by Niendam et al. (2012), in that the regions of activation associated with response inhibition and interference suppression were replicated in this study. Other studies have also found that EFs, including inhibition, are commonly implicated in the prefrontal cortex (Chambers, Garavan, & Bellgrove, 2009; Duncan & Owen, 2000), but other key areas, such as the anterior cingulate cortex, also play prominent roles in the behavioural manifestations of EFs (Chambers et al., 2007; MacDonald, Cohen, Stenger, & Carter, 2000; Posner & Raichle, 1994). Indeed, Nigg (2000) lists the prefrontal cortex as being implicated in response inhibition, and the prefrontal and anterior cingulate cortices as regions that are key to interference suppression, this overlap perhaps explaining the strong relationship between behavioural measures of these two inhibitory subprocesses. Furthermore, the latency differences observed in this study provide an insight into the timing of the underlying neural activation of these two processes.

Chapter 4 (Brydges, Anderson, Reid, & Fox, 2013) examined the development of the N2 peaks associated with response inhibition and interference suppression, as well as the behavioural development of these two constructs. The same hybrid flanker/Nogo task from chapter 3 was administered whilst EEG data were continuously recorded from a group of 13 children aged 8-11 years and a group of adults. It was hypothesised that the N2 associated with response inhibition would show smaller amplitude and peak latency, and be more frontally distributed in the adult group than in the child group (Bunge et al., 2002; Fuster, 2002; Johnstone, Pleffer, Barry, Clarke, & Smith, 2005). Additionally, it was hypothesised that the N2 associated with interference suppression would increase in amplitude, but decrease in latency between children and
adults (Rueda, Posner, Rothbart, & Davis-Stober, 2004). It was also hypothesised that adults would display better performance (shorter reaction times and increased accuracy) than children on all conditions. Source localisation analyses were also conducted on the data, and were expected to display differences of neural activation between groups and conditions.

The results of this study showed that behavioural performance on the incongruous task improved with age (analyses were not conducted on the behavioural performance of the Nogo condition as the adult group displayed a ceiling effect and the data were highly skewed). The ERP results showed significant N2 waveform differences between the adult and children groups for both conditions. For the Nogo condition (measuring response inhibition), the N2 difference waveform elicited in the adult group was frontally maximal, and had a significantly shorter peak latency than that of the child group, which was centrally maximal. Additionally, amplitude decreased with age, although this was only marginally significant. For the incongruous condition (measuring interference suppression), however, no significant N2 effect was elicited in the child group. The ERP source localisation showed that the neural generators for the response inhibition N2 were more frontal than those generating the interference suppression N2 in adults, and that no admissible solution was observed for the response inhibition N2 in the child group (source localisation for interference suppression N2 could not be conducted in the child group, as no significant waveform was observed).

These findings clearly indicate that the N2 waveform is not fully developed in children, as demonstrated by the topographical and latency differences (as well as marginal amplitude differences) between groups for the response inhibition N2, and that no interference suppression N2 was observed in the child group. This adds to the evidence that the frontal lobes are relatively late to mature (Fuster, 2002), and that
children rely more heavily on posterior regions of the brain to successfully inhibit responses (Bunge et al., 2002). Additionally, latency decreases are thought to be caused by myelination, which occurs on a large scale between childhood and adulthood (Brouwer et al., 2012; Tamnes et al., 2010). Amplitude decreases are also commonly reported between childhood and adulthood, often thought to be due to increased neural efficiency (Tamm, Menon, & Reiss, 2002).

Chapter 5 (Brydges, Fox, Reid, & Anderson, 2013) tested associations between brain and behaviour from an electrophysiological perspective. Specifically, latent variables of the P3b ERP peak and N2 difference waveform peak were entered into structural equation models with the unitary executive functioning factor reported in chapter 2. Although much previous research has found associations between these peaks in the ERP and the associated EF in both adults and children (e.g., Cragg, Fox, Nation, Reid, & Anderson, 2009; Jodo & Kayama, 1992; Lucci, Berchicci, Spinelli, Taddei, & Di Russo, 2013; Polich, 2007; Polich, Ladish, & Burns, 1990), each of these studies only used single tasks. Considering that there is clear evidence of the incomplete development of EFs, and EFs being indistinguishable from each other in children (Brydges, Reid et al., 2012; Shing et al., 2010; Weibe et al., 2008, 2011; Willoughby et al., 2012), this study aimed to fill the gap in the literature by examining whether the ERP correlates of response inhibition and updating are associated with EFs in children, when the specific EFs are indistinguishable from each other. It was hypothesised that the ERP correlates of EFs would be associated with a general EF, as previous research has shown these ERP peaks to be observable in children aged 7-9 years (Cragg et al., Polich et al., 1990). The same sample and measures from chapter 2 were used, with the addition of EEG data recorded during a modified flanker task (Richardson, Anderson, Reid, & Fox, 2011), from which ERPs were extracted. The results from the study
showed that both ERP peaks (N2 difference waveform and P3b) were observed, and were both correlated with and predictive of executive functioning.

The P3b ERP and N2 difference waveform peaks demonstrated the predictive validity of ERPs for psychometric measures of executive functioning. Despite individual EFs being indistinguishable from each other at the level of psychometric or behavioural performance, the ERP correlates of inhibition and updating of working memory are observable and distinctive in children aged 7-9 years, and these electrophysiological components are associated with executive functioning. The results of the study also showed that although the ERP variables were observable, there were no clearly identifiable peaks for any of them, an extension of this being that peak latency could not be added to the structural equation models as a predictor of executive functioning. However, the implication of this is that the development of specific EF behavioural abilities may occur as a consequence of the maturation of the electrophysiological correlates of EFs. That is, for example, the P3b is observable before updating/working memory is distinguishable from a general EF factor, and as the peak becomes increasingly clear, the specific updating abilities develop, which cause the differentiation of EFs to occur.

Conclusions

This thesis presents significant results concerning the psychometric and electrophysiological development of EFs in children. Psychometrically, 1) behavioural performance on measures of executive functioning improves rapidly throughout childhood; and 2) the overall structure of EFs is unitary until at least the age of 9 years. That is, specific EFs cannot be distinguished from one another until at least mid to late childhood. Electrophysiologically, 3) distinct EFs can be identified before they can be discriminated behaviourally, however, these ERP correlates appear to be relatively
weak. Specifically, the N2 difference waveform and P3b ERP (commonly associated with response inhibition and updating of working memory, respectively) can be observed in large samples, but the N2 difference waveform elicited during interference suppression may not be observable in small samples, and 4) the N2 (associated with response inhibition) is not fully developed in children.

Based on these results, it is possible that these are two sequential developmental processes of executive functions: first, a global executive ability begins to develop relatively early in childhood, explaining the continued improvement on behavioural measures of EFs, and the stability of the structure of EFs in this age group. However, at some point in mid to late childhood, abilities specific to individual EFs begin to develop, which could explain individual EFs becoming increasingly distinguishable from each other, and the continued improvement on measures of EFs.

In the same age range, the N2 difference waveform and P3b ERP (electrophysiological correlates of inhibition and updating or working memory, respectively) are observable, with two caveats: first, the N2 difference waveform was apparent when elicited during both response inhibition and interference suppression in a large sample \((N = 215)\), but was not observed during interference suppression in a small sample \((N = 13)\), despite appearing in an adult sample of the same size. From this, it can be inferred the N2 difference waveform is relatively weak in children. Second, it is clear that there are significant differences between the N2 observed in children and that seen in adults, primarily in topography and latency. It could be argued that neither of these points are surprising, as large scale neural changes occur through childhood and adolescence (e.g., Casey et al., 2000; Dosenbach et al., 2010; Reiss et al., 1996). However, whilst it is clear that the N2 is under developed in children, it can be observed.
This key difference between the development of ERPs and behavioural manifestations of EFs (i.e. ERP components can be observed, whereas individual EFs are not) suggests that the emergence of ERP components may be a precursor to the behavioural development of EFs. Specifically, as the N2 difference waveform becomes increasingly clear with development, only then will behavioural abilities specific to inhibition be seen, leading to increased diversity between EFs. Extending upon this, the results of this thesis could begin to provide evidence for a cascade effect in the development of EFs. Myelination occurs at a rapid rate from the age of about 6 years (Geidd et al., 2009; Krestchmann et al., 1986; Reiss et al., 1996; Spencer-Smith & Anderson, 2009), which causes changes in the profile of the ERP correlates of EFs. That is, ERP amplitude and latency decrease through childhood (Cragg et al., 2009; Jonkman, Sneidt, & Kemner, 2007). Two points should be noted here: first, the frontal lobes are thought to be one of the last regions of the brain to mature (Fuster, 2002), possibly explaining topographical differences of ERPs between children and adults. Second, although the absolute amplitude of ERP components decrease through childhood, research presented in this thesis has demonstrated that the difference in amplitude between executive and non-executive processes (such as the N2 difference waveform) is predictive of executive functioning (Brydges, Fox et al., 2013). The maturation of these ERP components then leads to the development of behavioural abilities specific to each EF, causing the increased differentiation between EFs.

Limitations

It should be noted that this thesis had four limitations that are pertinent for future research. First, it should be acknowledged that Chapters 2-5 employ cross-sectional study designs. Hence, the interpretation of the results from these studies assumes that between-individual differences in cross-sectional data are similar to within-individual
patterns of development (McCall, 1977; Shing et al., 2010), when it is known that cross-
sectional analysis techniques can be insensitive to between-individual variation,
particularly in developmental psychology (Molenar, 2008). Longitudinal studies to
determine whether executive functions and intelligence continuously differentiate
(Garrett, 1946), of it the developmental process consists of several stages (e.g.
Demetriou et al., 2014) would be worthwhile. A related limitation is the use of
chronological age as an indicator of cognitive development. Specifically, chronological
age is not a perfect measure of cognitive development (Barak & Schiffman, 1981), and
mental/cognitive age is a more sensitive measure of within-individual development in

A further limitation is the small sample size reported in Chapters 3 and 4. The
obtained statistical power, particularly in Chapter 4 where effect sizes were also quite
low, has possibly impacted upon the ability with which differences could be identified.
Specifically, an N2 ERP component may have been identifiable with a larger sample of
children, from which more detailed analyses could have been conducted, although some
previous research has also failed to observe an N2 in children (Ladouceur, Dahl, &
Carter, 2007). It should also be noted that the statistical power obtained in Chapters 2
and 5 was acceptable (MacCallum, Browne, & Sugawara, 1996).

Lastly, there are a couple of inherent limitations in EEG/ERP techniques that
should be addressed. First, it is well-known that the technique has relatively bad spatial
resolution, especially in comparison to functional and structural MRI (Srinivasan,
1999). Second, EEG and ERP techniques cannot be used to test causal relationships
between brain and behaviour, although Chapters 3 and 4 have provided evidence of
associations between subprocesses of inhibition and activation of the anterior cingulate
cortex. In order to test a causal hypothesis based on these findings, it is possible that the
use of transcranial magnetic stimulation would be beneficial, as it provides a pulse of magnetic stimulation to the scalp in order to excite (or inhibit) neural activation in the area of interest (Kluger & Triggs, 2007), and is safe for use with children (Frye, Rotenberg, Ousley, & Pascual-Leone, 2008). In particular, this technique could be applied by administering a pulse of magnetic stimulation to frontal and central regions in adults and children during the hybrid Go/Nogo flanker task to determine if these regions are differentially responsible for response inhibition and interference suppression.

**Future Research**

The results of this thesis highlight the importance of neuronal integrity in children with regards to the typical development of EFs. Children born very preterm, for instance, are known to be at increased risk of neurological problems (Peterson et al., 2000; Woodward, Anderson, Austin, Howard, & Inder, 2006), which then can lead to developmental delays and cognitive outcomes, including executive dysfunction (Anderson & Doyle, 2003; Bayless & Stevenson, 2007). Given that preterm children display delayed development of EFs (Ritter, Nelle, Perrig, Steinlin, & Everts, 2012) and white matter abnormalities (Nagy et al., 2003; Yung et al., 2007), future research could examine the structure of EFs and the electrophysiology of age-matched samples of preterm and full-term children to provide further support for this theory of EF development.

In order to further test this theory, a potentially promising avenue of research would be to examine the development of the ERP correlates of other EFs, and how they relate to the relevant behavioural constructs in children and adults. This thesis only examined developmental differences of the N2 difference waveform, commonly associated with inhibition (Lucci et al., 2013). For instance, the P3b ERP and late
Parietal positivity components are often associated with updating of working memory and shifting respectively (Polich, 2007; Rushworth, Passingham, & Nobre, 2002), and differences in the electrophysiological profile of these components between children and adults may shed further light upon the development of EFs, and the associations between them. However, the P3b and late parietal positivity ERPs are both maximal in parietal regions of the brain (Polich, 2007; Rushworth et al., 2002), which may hinder the observation of frontal development in samples of children.

Another possible avenue for research involves testing a sample of children that are of an age where unity and diversity of EFs is apparent, such as a group of children aged 11 years (Duan et al., 2010; Lehto et al., 2003; Wu et al., 2011), in comparison to a younger group where EFs are not yet distinguishable from each other. It would be of interest to examine any electrophysiological differences between younger and older children, given that the older children would hypothetically display a fully mature structure of EFs (even if the abilities themselves continue to develop for a while longer; Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001; Huizinga et al., 2006). Specifically, smaller ERP (but larger difference waveform) amplitudes and shorter latencies would be expected with increasing age, and these ERP components would be predictive of the individual EFs in the older sample. If evidence was found in support of this, this would strengthen the cascade theory by showing the continued development of the electrophysiological correlates of EFs influencing the development of the behavioural manifestations of the same EFs.

This thesis presents new data examining the development of EFs from both behavioural and electrophysiological perspectives. Firstly, it presents original data showing that EFs are indistinguishable from each other from a behavioural perspective until at least the age of 9 years; secondly, it presents original data identifying the
electrophysiological correlates of two commonly theorised EFs (namely, inhibition and updating of working memory), which are observable, though not fully developed by any means, in children of this age group; thirdly, it presents an original hypothesis whereby the development of the structure of EFs (i.e. the process of differentiation between individual EFs) is explained in a cascade model by integrating current behavioural and electrophysiological data, and previous research from behavioural, electrophysiological, and other neuroimaging perspectives. Future research examining the development of other ERP correlates of EFs, and testing the predictive power of these ERP components onto EFs in older children is encouraged.
References


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