

The Integrative Neuropsychological Theory of Executive-Related Abilities and
Component Transactions (INTERACT): A Novel Validation Study

by

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B.Sc., Queen's University, 2005
M.Sc., University of Victoria, 2007

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Supervisory Committee

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Abstract

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The Integrative Neuropsychological Theory of Executive-Related Abilities and Component Transactions (INTERACT; Garcia-Barrera, 2011) is a novel perspective on executive function(s), and the functional interactions among those neural systems thought to underlie them. INTERACT was examined in this validation study using structural equation modeling. A novel battery of computerized tasks was implemented in a sample of 218 healthy, adult, university students. Each of the derived indicator variables represented a specific aspect of performance, and corresponded with one of the five distinct executive components of INTERACT. After eliminating tasks that demonstrated poor psychometric properties, overall model fit was excellent, $\chi^2 = 36.38$, $df = 44$, $p = .786$; CFI = 1.00; RMSEA = .000. Further, INTERACT was superior to six alternative measurement models, which were theoretically-based. Although the structural model of INTERACT was too complex to be tested here, a novel analysis of the data was introduced to test the interactions among INTERACT's components. This analysis demonstrated the significant utility of INTERACT's fundamental theoretical predictions. Given the outcome of this initial validation study, the predictive power of INTERACT should continue to be exploited in future studies of executive function(s), and should be extended to explore executive systems in unique populations.

Table of Contents

Supervisory Committee.....	ii
Abstract	iii
Table of Contents	iv
List of Tables.....	vi
List of Figures	vii
Acknowledgements	viii
Historical Background.....	1
Executive Functions: Conceptual Difficulties.....	2
Measurement Difficulties.....	6
Relevance of the Executive Function Construct	8
New Directions.....	9
INTERACT	11
Inhibitory Control.....	12
Attentional Control.....	13
Emotional Control	16
Updating Working Memory	18
Problem Representation.....	21
Interactions	26
The Current Study.....	27
Methods.....	29
Participants	29
Procedure.....	31
Tasks.....	33
Data Analysis	54
Outliers	56
Missing Data.....	57
Normality.....	57
SEM: Testing the Measurement Model (Confirmatory Factor Analysis)	60
Structural Models	68
Hypotheses	70
Results.....	71
Missing Data.....	73
Reliability of the Indicator Variables	74

Normality.....	77
Structural Equation Modelling – Testing the Measurement Model	81
Alternative Measurement Model Comparisons.....	82
Regression Weights and Covariance Estimates.....	83
Testing the Structural Model of INTERACT, and Post-Hoc Analyses.....	86
Discussion	93
Limitations.....	105
Implications	109
References	114
Appendix A: Screener Questionnaire.....	160

List of Tables

Table 1: Descriptive Statistics for the original 15 task variables

Table 2: Correlations of All Indicator Variables, After Removing the Dual Task

Table 3: Descriptive Statistics for the Final 12 Task Variables, After Univariate Outlier
Elimination

Table 4: Alternative Model Comparisons

Table 5: Unstandardized Covariance Estimates among the Five Components

List of Figures

Figure 1. The INTERACT model (Garcia-Barrera, 2011). Double-headed arrows represent interactions among executive ‘components’.

Figure 2. Example ‘Navon figures’ (Navon, 1977), used in the Local-Global task.

Figure 3. Sample display screen for the computerized Iowa Gambling Task.

Figure 4. Sample displays from the modified Sternberg task: a) the learning display b) the cue display c) the probe display.

Figure 5. Screenshot of the Emotional Face *N*-Back task, displaying the letter stimulus (‘M’), and the two identical flanker (‘neutral’) faces.

Figure 6. Example screenshots from the Keep Track Task: a) the initial ‘category screen’, b) a sample presentation screen.

Figure 7. A sample trial from the modified Memory Updating task (Ecker, et al., 2010).

Figure 8. A hypothetical, example trial for the Matrices task.

Figure 9. Example mazes a) for trial block two; including ‘pseudo-mazes’, derived by closing all bifurcations from the original mazes b) for trial block one; original mazes. The two possible end points are denoted by small, coloured squares on either side of the maze.

Figure 10. The Tower of Hanoi task: a) example ‘start’ configuration, b) example ‘goal’ configuration.

Figure 11. The initial Measurement Model depicting the five components of INTERACT, including the original 15 task variables proposed to indicate each latent component.

Figure 12. Alternative Measurement Models depicting a) a 1-factor solution, b) a 2-factor solution, c) & d) 3-factor solutions, and e) & f) 4-factor solutions.

Figure 13. Structural (Path) Models that will be examined to test the relationships between each of the five EF components a) assuming no hierarchical relationships, b) assuming that Problem Representation ‘biases’ other control networks in a top-down fashion.

Figure 14. Confirmatory Factor Analysis results testing the latent measurement model of INTERACT; depicting its five components and the 12 specific executive task variables used as indicators for each component.

Figure 15. Path analysis model explaining performance on the ‘no help’ task block of the Matrices task, via main effects and interaction effects of the factor scores derived from the measurement model of INTERACT.

Figure 16. Path analysis model explaining performance on the second task block of the Tower task, via main effects and interaction effects of the factor scores derived from the measurement model of INTERACT.

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Historical Background

Since the time of iron tamping rods and the famous case of Phineas Gage (see Harlow, 1848), the human frontal lobes have been a popular yet mysterious topic for scientific inquiry. Even a century after Gage, the function of the frontal lobes was described as a “riddle” (Teuber, 1964). For the past 5 decades or so, innumerable researchers have examined this region of the brain, and countless theories about its role in complex human behaviour have been proposed as a result. Initially, research in this area was focused on patients with brain damage, and the resulting cognitive and behavioural sequelae that followed. For example, many authors have confirmed that several neuropsychological tests are sensitive to the effects of frontal lobe damage (e.g., the Wisconsin Card Sorting Task) (see Miyake, et al., 2000). Importantly, the commonality among these ‘frontal tasks’ appears to be the requirement for ‘high-level cognitive functions’ (Stuss et al., 2002). As a result, many psychological constructs have been proposed to explain these functions, and collectively, the term ‘executive function’ has been put forth and used as a synonym for frontal lobe function overall. At first, ‘executive functions’ were presumably carried out by the “central executive” component of Baddeley and Hitch’s (1974) model of working memory. However, despite recognizing the obvious difficulty in defining this obscure construct, critics have suggested that it is nonetheless important to avoid “recourse to a homunculus or central controller” (Garavan, 2002; p. 1820). That is, proposing that *something* performs a function does not adequately define the function itself. Later, executive functions were defined by Lezak (1983) as the ‘how’ of human behaviors. Again, however, this definition was vague in terms of its specificity and practical utility. Nevertheless, this

ambiguity has been paralleled repeatedly by other equally underspecified descriptions of executive function in the literature. In fact, several authors have suggested that “despite the frequency with which it is mentioned in the neuropsychological literature, the concept of executive function is one that still awaits a formal definition” (Jurado & Roselli, 2007; p. 213), and “efforts to explain behavior via executive function have been hampered by an inadequate characterization of executive function itself” (Zelazo, 1997; p. 198). Therefore, perhaps the most urgent issue to resolve is conceptual in nature; that is, how do we precisely operationalize the construct (see Stuss and Alexander 2000)?

Executive Functions: Conceptual Difficulties

The term ‘executive function’ remains a vague and broad construct in the literature (e.g., Pennington & Ozonoff 1996; Sergeant, et al., 2003), and theorists have yet to agree upon an integrated, consensus definition (see Castellanos, Sonuga-Barke, Milham, & Tannock, 2006). Some authors have argued that the study of executive function differs from most other areas of cognitive neuroscience because of its heavy reliance on unobservable *constructs*, due to a lack of ‘process-behaviour correspondence’ (Burgess, 1997). Namely, no specific behaviour necessarily reflects executive function. This contributes to the variability associated with executive function definitions, given that these definitions must therefore rely on a particular level of analysis. For example, definitions have been based on the context(s) within which executive functions are required, the processes explicitly attributed to executive function, as well as the theoretical outcomes of such processes (aside from specific behaviours). For instance, executive function has been described as: occurring *when* “a subject spontaneously changes a control process” (Butterfield and Belmont, 1977); *necessary for* “formulating

goals, planning how to achieve them, and carrying out the plans effectively” (Lezak, 1982; p. 281); ‘control *processes*’ or ‘regulatory *mechanisms* of the mind’ (e.g., Miyake, et al., 2000; Friedman & Miyake, 2006); and are particularly important in “nonroutine *situations*” (Banich et al., 2009; p. 3). On the other hand, the *absence* of adequate executive function has been suggested to result in a loss of behavioural and cognitive flexibility, due to information processing that is more ‘automatic’ in nature (e.g., Fernandez-Duque, 2000). More detailed definitions have also been provided, especially those focusing on the specific processes that may be attributed to executive function. For example, Crawford (1998) proposed that executive function is a “convenient shorthand for a set of behavioural competencies which include planning, sequencing, the ability to sustain attention, resistance to interference, utilization of feedback, the ability to coordinate simultaneous activity, cognitive flexibility (i.e. the ability to change set), and, more generally, the ability to deal with novelty” (p. 209). Likewise, executive function has been described as an ‘umbrella term’ used to refer to “a wide range of cognitive processes and behavioral competencies” (Chan et al., 2003; p. 201), which are “not domain-specific” (Denckla, 1996; p. 263). However, many authors have suggested that there are several problems associated with simply listing a number of functions or processes (e.g., Miyake, et al., 2000). For example, Miyake and colleagues suggest that many ‘executive functions’ share considerable overlap (e.g., ‘planning’ and ‘sequencing’) and may thus be redundant. On the other hand, some executive function labels (e.g., ‘inhibition’) are associated with multiple definitions in the literature. Therefore, the labeling of multiple ‘subprocesses’ does not necessarily imply that multiple processes are distinguishable, or that individual subprocesses are specific.

Nevertheless, many authors emphasize the notion that multiple, dissociable executive functions exist (e.g., Stuss & Alexander, 2000; Garcia-Barrera, Kamphaus, & Bandalos, 2011). For example, executive function(s) are often thought to include an assortment of abilities, such as planning, strategizing, initiation of behaviour, inhibition of behaviour and irrelevant information, performance monitoring, attention, and set switching (Castellanos, et al., 2006). In support of this argument, statistical methods rarely reveal the emergence of a single ‘executive’ factor when examining performance on different measures of executive function (see Royall, 2002). In fact, correlations among different executive tasks are often low or insignificant, and as a result factor analytic studies typically yield multiple factors for a given battery of executive function tasks (Miyake, et al., 2000), or for a given set of items measuring executive behaviours (Garcia-Barrera, Kamphaus, & Bandalos, 2011). In particular, many authors have suggested, differentiated between, or argued in favor of several independent executive functions, such as ‘inhibition’ and ‘working memory’ (e.g., Burgess, et al., 1998; Miyake, et al., 2000; Sergeant et al., 2002; Nigg, 2000; Aron, et al., 2004; Diamond, 2002; and see for review Alvarez & Emory, 2006; Chan, et al., 2008; Royall, et al., 2002; Miller & Wallis, 2009). However, there has been no consensus in the literature regarding how many dissociable executive functions truly exist, or their precise nature (Heyder et al., 2004).

Conversely, other authors suggest that subprocesses - i.e. a diversity of executive functions - should not be specified at all (e.g., Duncan, Emslie, Williams, Johnson, & Freer, 1996; Duncan et al., 1997); in other words, that executive function is best conceptualized as a unitary construct that is not comprised of ‘subprocesses’. The most

obvious examples of this argument in the literature are Baddeley's original conception of the 'central executive' (Baddeley & Hitch, 1974), and Norman and Shallice's (1982) Supervisory Attentional System. Notably, neither of these theories delegates the process of 'executive control' to subprocesses; by some unspecified means, these 'central controllers' exert control. Alternatively, other theories avert this dilemma by simply emphasizing the centrality of a *particular* process. For example, Goldman-Rakic (1996) suggests that *working memory* is central to executive control; Barkley's 'Hybrid Model of Executive Functioning' suggests that *inhibition* "permits them [executive functions], supports their occurrence, and protects them from interference..." (Barkley, 1997a; pp. 154); while Damasio's 'Somatic Marker Hypothesis' (1994; 1995) emphasizes the importance of *emotion* and social context in controlling behaviours in an executive fashion. However, it is unclear whether a unified description can explain executive *impairment* exhaustively (Stuss et al., 1994). In addition, some authors are skeptical that basic processes (e.g., inhibition) can sufficiently explain complicated, executive-like behaviours in their entirety (e.g., Stuss & Benson, 1986).

Recently, Miyake and colleagues (2000) examined this debate using confirmatory factor analyses and structural equation modeling techniques, and concluded that it is important to recognize that executive functions show both unity *and* diversity. Likewise, Stuss and Alexander (2000) have argued that although there is no unitary executive function, distinct processes do converge on a common goal of *executive control*. For example, even Barkley's theory (see Barkley, 1997a) suggests that "despite having distinct labels, (the 4 executive functions he defines) are believed to share a common purpose – to permit self-control so as to anticipate change and the future, thereby

maximizing the long-term outcomes or benefits for the individual” (p. 154). They also share a common characteristic: they represent “private, covert forms of behaviour that at one time in development were entirely public and outer- or other-directed in form” (p. 155). Thus, it appears that although a consensus definition for executive function is currently lacking, it is apparent that such a definition must account for its unitary nature, as well as its diversity of functions.

Measurement Difficulties

In addition to obvious conceptual difficulties related to defining executive function (and perhaps as a repercussion), there is also “no clear consensus among researchers on how best to measure executive functions...” (Miyake, et al., 2000; p.172). In fact, several notable difficulties related to the measurement of executive function have been suggested in the literature. First, EF tasks are typically multifactorial (Stuss & Alexander 2000), and involve nonexecutive cognitive processes as well as executive processes. This is due to the fact that executive functions, according to many definitions of the construct, “operate on other cognitive processes” (Miyake, et al., 2000; p. 174). However, executive function tasks rarely account for confounds related to these ‘other’ basic cognitive processes (see Castellanos et al., 2005; Castellanos, Sonuga-Barke, Milham, & Tannock, 2006). As a result, it is difficult to ascertain whether a low score on a particular executive function task is primarily due to executive requirements, or more basic processes. This is referred to as the ‘task impurity’ problem.

Perhaps given the pervasiveness of the task impurity problem, the specific executive function(s) captured by a particular task are often unclear (see Friedman & Miyake, 2006), and no obvious ‘gold standard’ measure of executive function has

emerged, against which other measures can be compared (see Royall, 2002). As a result, the construct validity of executive function tasks has rarely been established (e.g., Barcelo, 2001; Reitan and Wolfson, 1994).

Furthermore, if a given executive function task is actually measuring a number of cognitive processes, and importantly if these *other* processes significantly contribute to variance in the outcome measure(s) (but are not accounted for), measurement error should not be unexpected. Consistent measurement error can certainly contribute to the unreliability of an outcome measure. Thus, the task impurity problem may also contribute to the general finding that the reliability of EF measures is only modest at best (see Willcutt, et al., 2005), and is even lower for more complex executive tasks (e.g., Denckla, 1996). For example, the reliability of alternate forms of the Wisconsin Card Sorting Test has been found to be quite poor, ranging from .25 to .63 (Bowden et al., 1998). Consistent with previously noted definitions of the construct, several authors have suggested that low reliabilities may also be due (in part) to the fact that executive function requirements depend on the novelty of the task (Phillips, 1997).

In brief, the current state of the literature on ‘executive functions’ is fraught with obstacles. Notwithstanding a long history of debate and difficulty associated with simply defining the construct conceptually, attempting to measure such an elusive construct, though hampered by these conceptual ambiguities, poses independent challenges to researchers. Up to now, one of the greatest impediments to research in this area has been the fact that many executive functions have been defined by the tasks used to measure them (see Mahurin, 1999). As stated by Lezak (1982), “lacking a formalized scheme for

classifying the executive functions, our observations tend to be haphazard and our thinking about them tends to be unsystematic” (p. 283).

Relevance of the Executive Function Construct

Conversely, gaining a more systematic understanding of executive function(s) is important for many reasons. First, it is apparent given our previous review of the literature that little consensus exists as to the exact nature of executive functions, which presumably allow for the most uniquely-human, higher-order abilities known to man. Therefore, advancing a better grasp on this enigma is first and foremost of intellectual and basic scientific value. Second, many researchers have stressed the importance of executive function for adaptive, self-directed behaviours (see Jurado & Roselli, 2007). For example, it has been linked with medication compliance, daily living skills, and employment (e.g., Fogel, Brock, Goldscheider, et al., 1994).

Furthermore, many authors have also shown executive (dys)function is highly associated with a wide variety of known medical and mental conditions. For example, the degree to which patients with brain damage are capable of living independently and thus evincing a positive functional outcome following their injury, is significantly and directly related to the degree of impairments in executive function (Hanks, Rapport, Millis, & Deshpande, 1999). It has also been shown that executive function is the most commonly impacted cognitive ability associated with aging (e.g., Treitz, Heyder, & Daum, 2007). In addition, numerous investigators have provided evidence that executive function impairments are commonly comorbid with several mental illnesses, such as ADHD (e.g., Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), Substance and Alcohol Abuse (e.g., Cottencin, Nandrino, Karila, Mezerette, & Danel, 2009; Verdejo-Garcia, Lopez-

Torrecillas, Aguilar de Arcos, & Perez-Garcia, 2005; Fernández-Serrano, Pérez-García, & Verdejo-García, 2011), Schizophrenia (e.g., Evans et al., 1997; Morice & Delahunty, 1996; Bowie & Harvey, 2005; Heinrichs, 2005), Bipolar disorder (e.g., Bearden, Hoffman, & Cannon, 2001; Maalouf, Klein, Clark, Sahakian, LaBarbara, Versace, Hassel, Almeida, & Phillips, 2010), Depression (e.g., Harvey, Le Bastard, Pochona, Levy, Allilaire, Dubois, & Fossati, 2004), Parkinson's Disease (e.g., Zamarian, Visani, Delazer, Seppi, Mair, Diem, Poewe, & Benke, 2006), and Obsessive Compulsive Disorder (e.g., Alarcon, et al., 1994; Greisberg & McKay, 2003), among others. Therefore, executive (dys)function may provide a common thread among a vast array of disorders and conditions, which could potentially lead to unified assessment and treatment strategies across these conditions (e.g., Fogel, 1994) - if a unified account of executive function could first be established. As a result, it is not surprising that some authors have suggested that some of the most significant scientific advancements in the past decade have been attempts to identify the specific cognitive processes carried out by the frontal lobes (i.e. executive functions; see Chan, et al., 2008).

New Directions

Previously, examinations have studied executive function(s) by creating comprehensive neuropsychological batteries thought to capture an array of executive-related abilities, and subsequently used factor analysis to reveal how many separable 'executive functions' best captured performance (see Zelazo & Muller, 2002b). However, as Zelazo aptly points out (2003), the results of these types of exploratory studies are limited, in that the labels that authors attach to the factors derived "may lead to the impression that researchers actually understand the cognitive processes underlying

performance on various tasks, but this is rarely the case” (p. 1). Therefore, it is difficult to support the validity of a theory of executive function on this basis. On the other hand, recent studies such as that conducted by Miyake and colleagues (2000), have utilized a slightly different approach. Specifically, Miyake and colleagues implemented a latent variable approach (aka ‘*confirmatory* factor analysis’), in which factors are not derived blindly by the data, but rather, this technique evaluates the degree to which pre-specified factors (defined by a particular theory *a priori*) fit the observed data. The primary advantage of this methodology is that measurement error, commonly associated with tests of executive function, is minimized; each ‘latent factor’ (in this case, a specific executive function) is a product of only that variance which is *shared* between those tasks presumed to measure it. Thus, the influence of idiosyncratic requirements of a given task is significantly reduced (Miyake, et al., 2000).

Notably, the study by Miyake et al (2000) did not put forth a new *theory* or *model* of executive functions, but rather intended to “specify how separable these [three] functions are and how they contribute to so-called frontal lobe or executive tasks” (p. 50). As a result, the latent variable approach implemented by these authors provided a much needed, novel direction for the study of executive functions, and made a significant contribution to the literature by revealing critical insights about the unity and diversity of such a mysterious construct. That said, an integrated and comprehensive *model* of executive function(s) is still lacking, which accurately and succinctly delineates separable components of an executive system (see Chan, et al., 2008), that each contribute toward a unitary goal (e.g., control). Within such a framework, “what is needed is a characterization of the complex processes attributed to executive function that captures

their diversity without simply listing them (Zelazo, 1997; p. 199). The current study investigates one such model.

INTERACT

Recently, Garcia-Barrera (2012), proposed an Integrative Neuropsychological Theory of Executive-Related Abilities and Component Transactions (INTERACT), which addresses the conceptual issues associated with executive function by integrating much of the extant literature. Specifically, INTERACT proposes that the *interactions between five specific executive systems* permit the emergence of executive-like control of behaviours. Therefore, executive functions are defined theoretically as the unitary byproduct of these interactions, but also in terms of a diversity of distinguishable functional systems. The five distinct executive function ‘components’ (see Figure 1 below) are directly associated with known neural networks of the brain. According to the model, each of these five components is necessary, and together the five components interactions should be sufficient to explain a significant proportion of the behavioral outcomes that we currently theorize to be related to executive control functions.

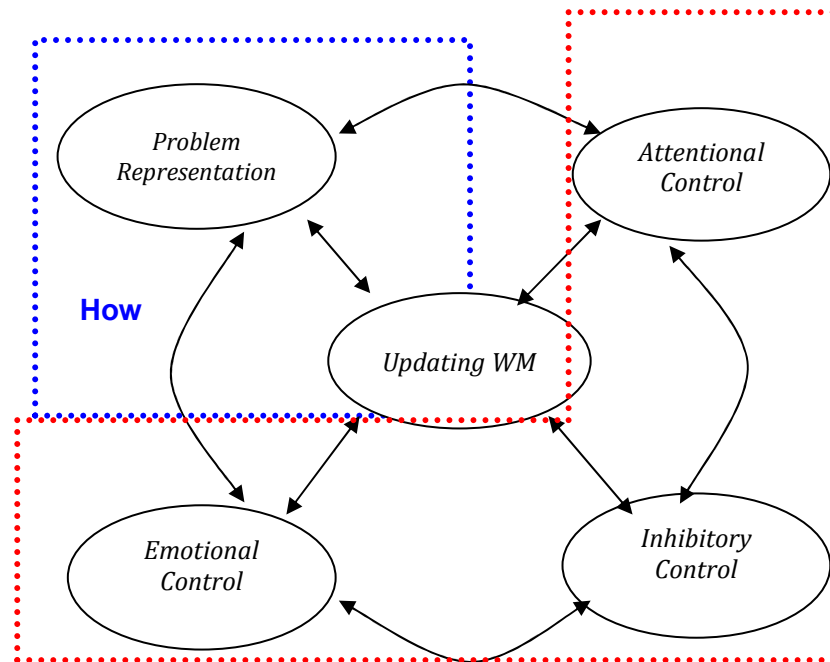


Figure 1. The INTERACT model (Garcia-Barrera, 2012). Double-headed arrows represent interactions among executive ‘components’.

Inhibitory Control

The first three of these components comprise a “cybernetic” dimension (Royall, et al., 2002) or “When” (Denckla, 2007) of executive functions, *which control other non-executive systems in a top-down fashion*. These components include systems that regulate behaviour (Inhibitory Control), attention (Attentional Control), and emotions (Emotional Control). The first of these control components is referred to as Inhibitory Control (IC), also referred to more generally in the literature as simply ‘inhibition’. IC has been operationalized in several ways in the literature, but a few authors have unified these definitions by creating taxonomies of IC. For example, Casey and colleagues (1997) based their taxonomy on stages of processing (i.e., sensory selection, response selection, and response execution); while Nigg (2000) provided a taxonomy of IC based on a comprehensive set of features, such as effortful versus automatic processes, as well as

executive versus motivational processes. Although terminology has varied across these theories, several consistencies are apparent. For example, many authors distinguish between suppression of a practiced, automatic, or ‘prepotent’ behavioural response, and the ability to suppress or ignore information that is irrelevant but is currently interfering with or eliciting a conflicting response on the immediate task. The first of these two processes has generally been named response inhibition (e.g., Barkley, 1997) or behavioural inhibition (Nigg, 2000); while the second process is typically referred to as interference control (Nigg, 2000), conflict resolution (Posner & DiGirolamo, 1998), or even executive attention (Posner & Rothbart, 2007). In general, INTERACT views Inhibitory Control as the collection of these control functions (i.e. control over motor responses as well as cognitive processes). Consistent with the literature, this component of INTERACT is associated with a network of brain regions, including dorsal and lateral regions of the prefrontal cortex (PFC), as well as their interconnections with the basal ganglia and the cerebellum (Middleton & Strick, 2000; Robbins, 2007). The cingulate cortex has also been identified as an important area associated with inhibitory control in the literature (Gothelf, et al., 2007; Nosarti, et al., 2006); however, the right inferior PFC has most frequently been associated with IC, and has been shown to be an important region involved in the regulation of behaviour in general (Rubia, Smith, Brammer, & Taylor, 2003).

Attentional Control

The second control component, named Attentional Control in INTERACT, also exemplifies a ‘cybernetic’ quality. Although the construct of *attention* is conceptualized as involving multiple component functions and processes, and cannot be described in

terms of a single system (Parasuraman, 1998), Attention Control as per INTERACT only concerns those processes and functions related to *executive control over attention* (Garcia-Barrera, 2012). For example, the Attention Network Theory (Posner & Petersen, 1990) details three distinct, yet related neural networks of attention, including a network responsible for orienting attention, one for maintaining a state of attentional alertness, and finally a system of attention under the influence of executive control. This third attentional system, the ‘anterior attentional system’, is involved with shifting attention, disengaging attention (highly related to IC), as well as conflict and error monitoring (see Posner & Rothbart, 2007). Importantly, this system is thought to be regulated by dopamine, and mainly involves networks in the PFC, especially including the ACC and DLPFC (Kaufmann, Koppelstaetter, Delazer, Siedentopf, Rhomberg, Golaszewski, et al., 2005; Kaufmann, Koppelstaetter, Siedentopf, Haala, Haberlandt, Zimmerhackl, et al., 2006; MacDonald, Cohen, Stenger, & Carter, 2000). Attentional Control, as per INTERACT, is closely aligned with this executive attentional network, and is responsible for exerting ‘top-down’ control over attention. Specifically, this system is engaged whenever attention to external stimuli must be redirected or enhanced *according to goals*. As a result, normal attention processes may be overridden, and may not necessarily be dictated by the saliency of external stimuli. For example, attentional control was defined by LeDoux (1994) as being important for the selection of relevant information for action, by attending only to information that is pertinent to strategic voluntary control (i.e. a goal). As a consequence, one specific function of this control system is to monitor the effectiveness of cognitive control operations during the execution of goal-directed tasks (i.e. direct attention toward cues that provide feedback about performance). Thus, this

system is continually active during goal-directed activities. For example, van Meel, Heslenfeld, Oosterlaan, and Sergeant (2007) suggest that adaptive goal-directed behaviors require a consistent comparison of current behaviours with internal goals, and if discrepancies are detected adaptive control processes are engaged to correct behaviours. Therefore, Attentional Control likely encapsulates several abilities, currently operationalized as ‘attentional switching’, ‘set-shifting’, ‘divided attention’, ‘mental flexibility’, and ‘conflict monitoring’, for example.

Attentional Control most likely reflects a distributed network of brain regions, including the PFC, the ACC, and perhaps more posterior regions as well. For example, several authors have suggested that the PFC is important for regulating attention based on relevance (meaning), and also for ignoring distractions, sustaining attention, and shifting/dividing attention according to goals (e.g., Arnsten, 2009). In addition to the DLPFC (BAs 8, 9 and 46), which is believed to be important for implementing a top-down attentional bias or *goal state* (Banich, et al., 2000a; Milham, Banich, & Barad, 2003; Milham, Banich, Claus, et al., 2003), and the dACC (BA 24) (see Makris, et al., 2007), other regions such as the posterior parietal cortex, as well as the angular gyrus (BA 39) and supramarginal gyrus (BA 40) at the temporo-occipito-parietal junction, may also be involved in networks supporting attentional functions (e.g., Posner & Petersen 1990; Cabeza & Nyberg 2000; Duncan & Owen 2000; Corbetta & Shulman 2002). For example, some authors have suggested that the posterior parietal cortex may be involved with disengaging attention from a particular target (Rafal & Robertson, 1995) and the superior parietal lobe may aid in the process of volitional shifting of attention (Devinsky & D’Esposito 2004).

Emotional Control

The final cybernetic or control component is Emotional Control, which has rarely been articulated as a distinct functional system *in the EF literature*. Emotional Control refers to the *regulation* of the impact of emotion on behaviours, rather than the elicitation of specific emotional *states* (Garcia-Barrera, 2012). Although seemingly unified on a behavioural level, these two processes appear to be distinct on a neural level (Goldsmith & Davidson, 2004), despite what appears to be a bi-directional relationship in terms of their temporal occurrence (Bridges, Denham, & Ganiban, 2004; Cole, et al., 2004). In general, ‘emotion regulation’ has been defined as an ongoing process of responding to the environment with emotions, in a way that is socially acceptable and context-appropriate (Cole, Michel, & Teti, 1994). Therefore, dysregulated emotions may result from a lack of knowledge about social norms regarding emotional displays, or may rather reflect an intrinsic deficit with respect to the ability to modulate emotional reactions in response to the environment (e.g., Saarni, 1999). Emotional Control, as per INTERACT, concerns this latter possibility (i.e. that dysregulation results from a deficit in ability rather than knowledge). Recently, ‘emotion-related self-regulation’ was coined as a construct in the literature, to underscore the importance of emotion in executive regulation processes. Eisenberg and Spinrad (2004) define this concept as “the process of *initiating, avoiding, inhibiting, maintaining, or modulating* the occurrence, form, intensity, or duration of *internal feeling states, emotion-related physiological, attentional processes, motivational states, and/or the behavioral concomitants of emotion* in the service of accomplishing affect-related biological or social adaptation or achieving individual goals” (p. 338). This definition, although complex, coincides with Emotional Control defined by INTERACT;

by stressing the role of an executive system in purposely affecting change (i.e. initiating, avoiding, inhibiting, maintaining, or modulating), and also by suggesting that emotion may impact numerous auxiliary processes (e.g. attention, motivation, and behaviour). In general, the literature has referred to Emotional Control as a ‘hot’ executive function, involved in the regulation of behaviour within several contexts, notably including reward and punishment, social behaviors, and emotional decision-making (Bechara, Damasio, Damasio, & Lee, 1999; Bechara, Tranel, Damasio, & Damasio, 1996; Damasio, 1995; Grafman & Litvan, 1999; Rolls, 1995). In this respect, Emotional Control is closely associated with Damasio’s notion of ‘somatic markers’ (e.g., Damasio, 1996) – i.e. that cues in the environment can elicit emotional states based on previous experience with similar situations, and subsequently influence one’s responses to stimuli. Somatic markers are thus important cues in the environment, which help to automatically guide our responses in an appropriate fashion. However, the responses that have previously been associated with these markers can sometimes be at odds with higher-order (executive) goals. Therefore, situations involving particularly salient somatic markers might require heightened executive control, if it is necessary to overcome the response that has been linked with the emotional valence of the situation and produce an alternative response that is consistent with a new goal. For example, displaying a sad face during a continuous performance task can cause examinees to slow their responses, even if they are aware that these faces are irrelevant (see Fernandez-Duque, 1999). In this case, being told to respond as quickly as possible (i.e. the executive goal) is at odds with responding slower and perhaps more cautiously in the face of negative emotional valence. It would therefore require greater Emotional Control to respond quickly, despite

the sad face. More broadly, Emotional Control is the ability to respond to a stimulus in a way that is consistent with an executive goal, regardless of the emotional valence of the given situation, which naturally elicits specific behavioural tendencies.

Several authors have proposed that ventral and medial regions of the PFC are especially involved in emotion regulation because of their connections with the amygdala, hypothalamus, nucleus accumbens, and brainstem nuclei responsible for modulating arousal (Price, Carmichael, & Drevets, 1996). For example the hippocampus, normally associated with learning and memory (e.g., Jarrard, 1995) has also been associated with emotional control. Specifically, it has been posited that the hippocampus might be involved in emotional decision-making (Wall & Messier, 2001), by activating emotional representations of prior experience to inform current behaviours (Groenewegen & Uylings, 2000).

Updating Working Memory

The fourth executive component proposed by INTERACT is responsible for storing and processing information that is continuously updated on the basis of current task goals (Garcia-Barrera, 2012). It has often been labeled “Updating Working Memory” (e.g., Miyake et al., 2000). Generally, Working Memory (WM) is thought to reflect the ability to “hold an item of information ‘in mind’ for a short period of time and to update information from moment to moment,” (Goldman-Rakic, 1998, p. 90), as well as the ability to manipulate information in mind (e.g., Karatekin, 2004). This conceptualization of WM, emphasizing both storage *and process* elements of a short term memory system, has largely stemmed from the work of Alan Baddeley and colleagues (see Baddeley & Hitch, 1974). Their model of WM consisted of a ‘central executive’

component, as well as two slave systems responsible for temporarily storing and rehearsing modality-specific information, namely the phonological loop and visuospatial sketchpad. The ‘central executive’ component coordinates and controls the two subsystems, alters WM functioning as a result of changing task demands (i.e. it controls attention; see Baddeley, 1993), and provides a bridge between WM and long-term memory (see Baddeley, 2003). WM is thought to play a critical role in guiding everyday behaviours, and is vital to performance on complex tasks like learning, reasoning, and planning, by providing “an interface between perception, attention, memory, and action” (Baddeley, 1996b, p. 13472). Irrespective of its definition, WM is critical because it allows individuals to retain information received from the environment or retrieve information from longer-term storage, and subsequently maintain it if it is relevant to a current task (Kane & Engle, 2002; Unsworth & Engle, 2007). On the other hand, if information becomes irrelevant, it is deleted and replaced with new, relevant information (e.g., Engle, et al., 1999). As a consequence, an individual can organize and utilize this updated information to execute goal-directed behaviours. However, unlike the ‘central executive’ of Baddeley’s WM, Updating of WM (as per INTERACT) does not maintain any ‘homunculus-like’ properties, i.e. the ability to *control* and *direct* cognition and attention without any explanation of a mechanism by which this may be possible. However, it is absolutely necessary for any system concerned with executive function(s) to include a short-term storage component that maintains current (updated), task-relevant information until it is no longer needed, according to the goals of a given task at a given time. This is consistent with Fuster’s proposal that the PFC functions to maintain

stimulus representations across time; i.e. ‘the temporal organization of behaviour’ (see Fuster, 1995).

Recently, Baddeley (2000) introduced a fourth component to his model – the ‘episodic buffer’, which serves a function that also closely parallels that of Updating Working Memory (according to INTERACT). Specifically, the episodic buffer is a limited-capacity temporary storage system, which integrates information from a variety of sources, and may be controlled by the central executive (Baddeley, 2000). Moreover, “it holds episodes whereby information is integrated across space and potentially extended across time” (Baddeley, 2000; p. 421). Similarly, INTERACT suggests that WM is continuously updated based on an interaction between goal representations (e.g., rules) and incoming information. In support of this description, several recent authors have found that the construct of ‘updating working memory’ appears to be a unique executive ability (e.g., Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000).

Several neural correlates have been associated with working memory in the literature. In general, it appears that WM processes involve a few cortical regions, especially including the PFC, but also parietal regions and the cerebellum (Owen, McMillan, Laird, & Bullmore, 2005; Vance, Silk, Casey, Rinehart, Bradshaw, Bellgrove, et al., 2007). More specifically, previous authors have suggested that WM tasks recruit the right PFC (BA 9), medial parietal cortex (BA 7 & 40), and the left occipital lobe (BA 18 & 19; Cohen, Perlstein, Braver, Nystrom, Noll, Jonides, et al., 1997). Most commonly, however, the DLPFC has been implicated in WM processes (D'Esposito & Postle, 1999; Levy & Goldman-Rakic, 1999). For example, neuroimaging studies have implicated the DLPFC in the ‘manipulation’ of information during WM tasks (e.g.

D'Esposito, Detre, Alsop, Shin, Atlas, & Grossman, 1995; D'Esposito & Postle, 1999; Postle, Berger, & D'Esposito, 1999). In addition, several investigations have demonstrated activation of the VLPFC when subjects are required to simply maintain information using rehearsal strategies (usually subvocal); whereas more posterior regions such as the parietal and temporal lobes are generally associated with the storage of stimulus information during these WM tasks (Paulesu et al., 1993; Awh et al., 1996; Fletcher & Henson, 2001). Interestingly, some studies have suggested that the relative role of these different regions also depends on the delay period during WM tasks. For example, Karatekin (2004) proposed that longer delays (generally greater than 10-20 seconds) recruit more frontal regions, because of the requirement for more complex mnemonic strategies in order to hold information 'on line'; while shorter delays recruit more posterior regions because stimulus representations need only be maintained in their basic form.

Problem Representation

Finally, INTERACT includes a component involved in the identification of goals and the subsequent initiation of behavior, via the creation of a plan (Garcia-Barrera, 2012). INTERACT refers to this last component as Problem Representation, which reflects the "How" of executive functions (Denckla, 2007), and is most important in those situations involving novelty. The function(s) of this component is implicit in almost any task of EF, but again, defining this component more explicitly is quite novel in the EF literature. The first three control components of INTERACT are defined by their ability to regulate responses to external and internal stimuli; that is, these components allow individuals to carry out intentional plans of action, despite external contingencies. For

example, these systems allow individuals to either inhibit a response or to respond in novel ways to familiar stimuli; shift attention away from salient stimuli and onto relatively less salient stimuli; and reduce the impact of emotionality on behaviour - *when they wish to do so*. It has also been established that it is necessary to maintain and process updated information about the environment in a brief storage system, in order to use this information to guide responses. However, it has been assumed that an overarching goal and plan for *how to act* have already been established. Problem Representation is responsible for this task by determining *how* individuals are to respond to novel circumstances, based on a formulation of the current situation and a given set of goals.

For example, some authors suggest that executive function(s) allow individuals to formulate goals and plans, and execute them efficiently (see Makris, 2009). That is, rather than acting on impulses (i.e. automatically) and in a predictable manner in response to specific stimuli, executive function(s) allow for volitional, organized, and planned behaviours based on internally represented goals. For example, Fuster (1995) suggests that the inability to plan is one of the most characteristic features of prefrontal dysfunction. It is logical that only once a specific goal is established and a given plan of action is selected, is it possible to regulate (control) behaviours, attention, and emotions in a manner consistent with such a goal/plan. This is especially true when situations are novel, and an individual cannot solely rely on previously established patterns of behaviour. Zelazo (1997) identifies ‘problem representation’ and ‘planning’ as discrete stages within a larger context of *problem solving*, which is suggested to be the primary function of executive function(s). This theory suggests that executive function(s) are necessary whenever a *problem* exists that requires a novel or less-than-habitual response.

These authors suggest that in order to solve a problem (i.e. to know how to act), one must construct a problem representation (i.e. identify a goal, and all possible solutions), and then create a plan for action selected on the basis of a particular goal (or goals). The plan can then be put into action, and subsequently monitored in terms of effectiveness.

Executive components necessary for these latter stages (executing the response and monitoring the outcome) have already been discussed in terms of Inhibitory Control, Attentional Control, and Emotional Control. In addition, Updating of WM is necessary in order to maintain in mind the goal(s) and plan for action, while continually updating information about the situation during the course of responding. On the other hand, the first few stages of this problem solving process are precisely what constitute the final component of INTERACT– Problem Representation – which determines the *how* of executive control.

However, Problem Representation does not simply represent an alternative description for a ‘central executive’ or ‘supervisory attentional system’, by proposing another homunculus-like function of the frontal lobes. INTERACT simply proposes that a component must exist, which functions to create an active, neural representation of a problem, in which a new solution must be found. In order to formulate a plan (arrive at decisions), incoming sensory information from the environment is likely integrated with internal representations of previous stimulus-response contingencies. For example, Fuster (1997) suggested that the process of decision making might be resolved as a result of competition between a diversity of available sources of information (e.g., memorial, experiential, affective, and motivational inputs). In any case, this plan must subsequently be relayed to other systems that are responsible for carrying out the desired response.

Although a lack of consensus still exists as to a clearly identified and empirically supported *mechanism* by which decisions are made and control is exerted, such a component is nonetheless necessary. Therefore, the Problem Representation component is essential to a model of executive function(s), and must be discussed despite the difficulty in elucidating exactly how it works. What is important is that problems must be identified, goals must be established, and a plan must be created in order to provide a blueprint that dictates how other executive function components are to be enacted. Therefore, this component can be conceptualized as being a core element underlying performance on cognitive tasks involving problem-solving, planning, organizing, sequencing, and decision making, especially when these tasks are still novel.

Due to the significant relationship between this component and that of Updating WM, it is difficult to decipher the specific neural substrate of the Problem Representation component. For example, it is conceptually likely that the mental representation of a problem is held within WM, and also processed within this storage component. Not surprisingly then, many authors have also situated the ‘coordinator’ of executive control in the DLPFC (Faw, 2003). Similarly, other authors have argued that the DLPFC is responsible for implementing a top-down bias or ‘goal state’ that is maintained over time (see Banich, et al., 2000a). This hypothesis reiterates the close interaction between the Problem Representation component and WM, such that goals and plans must also be represented and maintained across time, in addition to other information about the environment. For example, Nigg and Casey (2005) suggested that once information about the structure of the environment is learned via frontocerebellar and frontostriatal

networks, this information is integrated with goals that are represented within WM, and this allows for subsequent top-down control of behaviour.

Indeed, several studies have provided support for the notion that the DLPFC is necessary for performance on a variety of tasks involving problem solving, planning, strategizing, organizing, among others. For instance, Newman, Carpenter, Varma, and Just (2003) found that both the left and right DLPFC were significantly activated during the Tower of London task, and this activation increased as the task became more difficult. In addition, these authors argued that the right DLPFC was more involved in planning, whereas the left DLPFC was more involved with control processes (i.e. goal execution). Other studies have found that tasks requiring goal management in general activate the right PFC more so than the left PFC (Braver & Bongiolatti, 2002). Similarly, studies examining patients with frontal lobe lesions have found impaired performance on these ‘tower tasks’, specifically when lesions occur in the right hemisphere (e.g. Morris et al., 1997). On a multitasking paradigm, patients with lesions to the right DLPFC (i.e. BAs 8, 9, & 46) demonstrated poor planning (Burgess, et al., 2000). On the other hand, cortical regions other than the DLPFC have also been shown to be involved in tasks of strategic planning (e.g., the Tower of London task), including the lateral premotor cortex, the ACC, the caudate nucleus, as well as the parietal cortex and cerebellum (e.g., Dagher et al., 1999; Rowe et al., 2001). In brief, it appears clear that the DLPFC is not only associated with Updating WM, but is also involved in tasks of goal management, planning, and strategy execution; all of which are abilities supported by the underlying Problem Representation component.

Interactions

INTERACT proposes specifically that the *interactions* between each of these five systems discussed, rather than the activation of a specific system in isolation, are precisely what permit the emergence of executive-like control of behaviours. This is certainly the most novel aspect of INTERACT, in comparison to the existing EF literature. According to INTERACT, executive function(s) are theoretically defined not only as the *unitary* byproduct of these interactions, but also in terms of a *diversity* of distinguishable functional systems. For example, without the ability to hold in mind representations for goals and plans (i.e. in WM), the Problem Representation component responsible for devising the ‘how’ of executive control could not execute its specific role in the process. In turn, if the Problem Representation component deemed it necessary to withhold a certain response (IC), and attend to a previously irrelevant stimulus dimension (AC), all the while preventing oneself from acting impulsively to procure an immediate reward (EC); each of these control systems would need to be engaged in order to achieve the overarching goal of the task or situation. Importantly, these examples illustrate how intricately intertwined each of these processes are in reality. As a result, it is necessary to exert simultaneous control over each of these basic processes in order to regulate behaviour in an executive fashion. This idea is consistent with previous conceptualizations. For example, Barkley (1997) suggests that the four executive functions of his model are both “interactive and interreliant” and that it is “the action of these functions in concert that permits and produces normal human self-regulation” (Barkley, 1997a; pp. 156). Interestingly, recent imaging studies have shown that a large proportion of PFC neurons are activated across a variety of tasks and stimulus domains

(see Grafman, 2006), and this has led some authors to suggest that there is little functional specialization between PFC regions (see Duncan, 2001). However, this widespread activation may rather be indicative of simultaneous engagement of separable processes - and thus according to INTERACT - the importance of the interactions between component executive 'processes' (and their respective systems). In this sense, the neural networks associated with each of the different components of INTERACT can be regarded as being "...hierarchically organised modules with specific contributions of each component to processing and output organization..." (Heyder, et al., 2004; p. 273).

In summary, INTERACT proffers a new solution to an old problem; that the engagement of five distinguishable neuroanatomical systems (networks), each regulating a unique aspect of cognition or behaviour, can together account for executive control *as a whole* via their interactions. Therefore, although a measurement problem persists, INTERACT proposes to make a meaningful contribution to the current *conceptual* debate regarding the nature of executive function(s).

The Current Study

Given the state of the literature, and subsequently the impetus for this study, it would be premature to refer to INTERACT as a comprehensive model. However, most existing models of EF, already discussed, have thus far described only a particular aspect of EF (e.g., working memory), from a particular level of analysis (e.g., behavioural), or within a specific context (e.g., clinical). Consequently, these models have failed to explain EF-related phenomena comprehensively. Therefore, INTERACT represents a *relatively* more comprehensive model, by virtue of being an amalgamation of many of the most influential models of EF previously proposed, in addition to new components. As

such, akin to its central premise, INTERACT's relative comprehensiveness as a unitary model relies on the interactions among those diverse models that were its predecessors, but nonetheless comprise it. The aim of this study was therefore to examine the validity of INTERACT as an *integrative* model of executive function. To this end, a latent variable approach was utilized, similar to the seminal study by Miyake and colleagues (2000) previously discussed. Numerous tasks were chosen or designed with the aim of capturing the unique engagement of each component of INTERACT in the pursuit of executive control. Of note, it was not assumed that the components of INTERACT were unitary in their own right. Each component represented a latent construct, which was intended to embody a particular functional system, potentially comprised of a diversity of processes (e.g., divided attention and attentional switching) that together converge on a relative, common goal (attentional control). As such, variables derived from diverse tasks served as indicator variables for each of the latent components of INTERACT.

Confirmatory factor analysis techniques (within a structural equation modeling or 'SEM' framework) were implemented to explore the extent to which the components of INTERACT fit the observed data, and thus contribute support for INTERACT as a valuable model of EF overall. In addition, the 'interactions' between components were examined; given that these interactions are a fundamental assumption of INTERACT. As such, this study extended the work of Miyake and colleagues by testing a complete *model* of executive function, rather than merely evaluating "three of the most frequently postulated executive functions in the literature" (Miyake et al., 2000; p. 50).

Methods

Participants

At present, INTERACT reflects the structure of a *mature* executive function system. However, Garcia-Barrera (2012) suggests that developmental factors must be considered for any comprehensive, working model of executive function. For example, the five components of INTERACT may only be fully differentiated or ‘fractionated’ later in development, in parallel with the maturation of the prefrontal cortex and related neural circuits. Thus, at different stages of development, perhaps only some of the five INTERACT components emerge as independent, dissociable functions. These plausible hypotheses should be addressed in future studies. However, the current study focused on mature executive systems to examine the fundamental assumptions of INTERACT, from which these future developmental studies may build upon. Given this criteria, 218 students were recruited from the University of Victoria (UVic). Participants were enrolled in first-year psychology (PSYC 100) and were required to be at least 18 years of age. This population served as a sample of convenience, and therefore was presumed to be an adequate representation of healthy (adult) university students, but not adults from the general population *per se*.

It was postulated *a priori* that a sample size of 218 was sufficient. Although there is significant variability in the SEM literature with respect to ‘adequate’ or ‘minimal’ sample sizes (see MacCallum, Widaman, Zhang, & Hong, 1999), a minimum sample of 200 was selected for several reasons. First, it coincides with those recommendations put forth by several authors, in order to achieve reliable results (Guilford, 1954; Kline, 1979; Gorsuch, 1983). According to Comrey and Lee (1992), a sample size of 200 corresponds

with a “fair” sample size. On the other hand, some authors have emphasized that sample size should be considered *relative to the number of variables analyzed* (the $N:p$ ratio; see MacCallum, Widaman, Zhang, & Hong, 1999). Given that 15 indicator variables were initially proposed (see Figure 11 in *Data Analysis*), a sample size of 200 would be adequate, according to those $N:p$ ratios previously recommended (e.g., Everitt, 1975; Cattell, 1978; Gorsuch, 1983). Finally, other authors recommend that 5-10 cases are necessary *per parameter estimated* (see Bentler & Chou, 1987). Given that the original INTERACT model required 40 parameters to be estimated using an SEM analysis (Figure 11 in *Data Analysis*), 200-400 participants would be necessary to fulfill this requirement. However, despite these historical ‘rules of thumb’, it is important to note that several factors inherent in SEM analyses can have a significant impact on the importance of sample size. For example, some authors have suggested that the influence of sample size on SEM results is greatly reduced when factor loadings and communalities are high (e.g., Velicer and Fava, 1998). Thus, if clear, strong factors exist, a larger sample size is not necessarily required (Barrett & Kline, 1981). In addition, the degree of ‘overdetermination’ for each factor is relevant for choosing a sample size for the purpose of an SEM analysis. Essentially, overdetermination refers to the extent to which a factor is represented by a sufficient number of indicator variables (MacCallum, et al., 1999). Thus, with a sufficient number of indicators, it is more likely that latent factors will emerge reliably; reducing the need for a larger sample size. In light of the task impurity problem previously alluded to, it was therefore be important to ensure that multiple, ‘clean’ indicators were chosen to reflect each component of INTERACT.

Participants did not receive monetary compensation for their participation, but rather received ‘credit’ toward their final grade in PSYC 100. Given that a typical psychology class at UVic consists of an approximate 3:1 ratio of females to males, it was impractical to aim for a balanced number of males and females recruited. The original sample included 163 females and 55 males, aged 18 to 47 years (mean age = 21.04 ± 3.92), who were predominantly right-handed (90.4%). According to the results of the initial screening questionnaire, previous diagnoses included: depression or anxiety (8.3%), Attention-Deficit/Hyperactivity Disorder (2.3%), and learning disorders (1.4%). These screener results also indicated that 5.5% of the participants had previously received learning assistance at school, 2 participants had a history of speech/language difficulties, and 25.8% reported having suffered at least one concussion in their lifetime. In addition, 20.3% of participants reported having consumed alcohol and 2.3% reported using marijuana within 48 hours prior to the study. One-third of the sample (33.2%) reported being bilingual.

To ensure adequate comprehension of a diverse set of task instructions, English language proficiency was also a requirement. Normal or corrected vision, as well as normal hearing were important as well, and were established via a screener questionnaire (detailed below in *Procedure*). Each participant was examined on every task, within a single testing session.

Procedure

Initially, pilot testing was conducted with a small sample of adults ($n = 10$) to a) ensure that the computerized tasks were functioning properly and the procedure was without flaws, b) estimate the time allotted for completion of all 15 tasks, c) and c)

examine the utility of the chosen tasks for each component (the indicators); by examining the correlations between similar tasks. Once this pilot stage of testing was completed and preliminary data suggested that the chosen indicators were appropriate, data collection commenced.

Testing took place in a small group setting of up to 10 participants per session. Upon arrival, participants were collectively apprised of the nature of the study, its inherent risks and benefits, and its voluntary nature. Participants were asked to provide written, informed consent, and to complete a brief screener questionnaire (see Appendix A). The questionnaire consisted of basic demographic information (e.g., age, gender), but also asked participants to report any previous diagnoses for learning disorders, developmental disorders (e.g., ADHD), neurological conditions (including impaired hearing or vision), or any history of significant head injuries. The purpose of this screening questionnaire was to ensure that the sample of participants collected were generally representative of the normal population.

All 15 tasks were administered on a computer. Similar to Miyake and colleagues (2000), the order of task administration was the same for all participants, and tasks indicating the same latent component were never administered consecutively. Participants were seated in front of a computer screen situated at eye height and approximately 16” from the participant. Responses were executed a number of different ways, depending on the particular task (see *Tasks*, below). Participants were provided with verbal as well as on-screen instructions for the tasks, and were given the opportunity to ask questions throughout testing if they wished to clarify the rules of a particular task. Participants

proceeded with the computerized tasks at their own pace, and average time to complete all 15 tasks was approximately 1.5 hours.

Of note, testing always took place in the same computer lab. The lab was a spacious, windowless room that allowed ample space and separation between participants, to minimize distractions. To this end, pilot testing using this setup confirmed that no participant was able to see another participant's computer screen.

Tasks

Indicator variables for each of the latent components of INTERACT were derived from a range of computerized cognitive tasks. Although task selection was partially guided by previous proposals in the literature regarding the specific cognitive abilities tapped by existing measures, more important for the current study was the selection of tasks that were believed to capture the precise nature of each of the theoretical components of INTERACT. Task selection was also based on relative ease of administration, minimal time requirements, and a non-invasive nature. In addition, because many authors have suggested that executive function tests traditionally do not account for all of the cognitive processes that they engage (i.e. due to the task impurity problem) (Burgess, 1997), it was critical to devise measures that were as 'pure' as possible, reflecting the essence of only one particular component of INTERACT. For similar reasons, it has been suggested that "it may be useful to choose simpler 'executive' tasks that have fewer idiosyncratic requirements..." (Miyake, et al., 2000; p. 181). With these criteria in mind, each of the tasks used in this study were created using E-Prime 2 software (Schneider, Eschman & Zuccolotto, 2002).

The following tasks were used to indicate **Inhibitory Control**:

According to Barkley (1997), inhibition can be divided into three separate processes: inhibition of a prepotent response, inhibition of an ongoing response, and interference control. These three processes are captured by two of Nigg's (2000) taxonomic divisions between 'executive motor inhibition' and 'executive interference control', and thus represent the Inhibitory Control component of INTERACT quite well. As such, each of the three IC tasks chosen for the current study represented one of the three inhibitory processes specified by Barkley.

First, a **Go/No-Go** paradigm (Donders, 1868/1969) was used to measure inhibition of a prepotent response. This task required participants to respond to visual stimuli (i.e. a single letter appearing in the middle of the computer screen, presented at a rate of approximately 1 word every 1,400 msec) by pressing the spacebar as quickly as possible. The first task block only consisted of these 'go' trials, to allow participants to develop a prepotent response tendency to press the spacebar. In a second trial block, participants were again instructed to press the spacebar as quickly as possible whenever a letter appeared; however, there were to withhold their response if the letter 'J' appeared (the 'no-go' stimulus). Of note, these no-go stimuli were randomly presented among go stimuli, although much less frequently. As a result, inhibitory control was required to *not respond* according to the prepotent tendency (i.e. to press the spacebar for letters). Due to the additional inhibitory control requirements recruited on no-go trials, it was expected that participants would make more errors in response to the rarer no-go stimuli - indicating inhibitory control failures. Thus, total number of errors on no-go trials was evaluated as an indication of Inhibitory Control.

Second, a **Stop Signal** paradigm (Logan, 1994) was implemented to measure inhibition of an ongoing response. On this task, participants were asked to respond to a word presented in the middle of the computer screen by pressing one of two response keys as quickly as possible. Similar to the Stop paradigm utilized by Miyake and colleagues (2000), stimuli consisted of words belonging to one of two categories (animals or non-animals). Participants were told to respond by pressing one key for animals, and another key for non-animals; building up a prepotent response to categorize words via key presses. However, during a second trial block, participants were instructed to withhold this response on trials when a visual ‘stop signal’ appeared on top of the word, shortly after the presentation of the word. These ‘stop signal’ trials occurred at random, but participants were monitored throughout the second trial block to ensure that they did not slow their responses in general to anticipate the stop signal. Stop signals were presented at five different delays (occurring equally often): 50 ms, 100 ms, 150 ms, 200 ms, and 250 ms after the onset of the word. The average of participants’ estimated Stop Signal Reaction Times (see Logan, 1994) was used as the second indicator of Inhibitory Control.

Third, an **Eriksen Flanker** task was used to measure interference control. The Flanker task measures the extent to which irrelevant information interferes with a participant’s ability to execute a motor response (Eriksen & Eriksen, 1974). First, a central fixation cross (“+”) was presented in the middle of the screen. Next, an array of five arrows were presented in a horizontal line; the middle arrow was located where the fixation cross was previously presented. Participants were required to press a key on the left side of the keyboard (“A”) if the middle arrow pointed to the left; and a key on the

right side of the keyboard (“L”) if they arrow pointed right. Importantly, on some trials the ‘flanker arrows’ (i.e. the four arrows presented on either sides of the middle arrow) were pointed in the same direction as the middle arrow (congruent trials; e.g., →→→→→); versus other trials in which the flanker arrows pointed in the opposite direction as the middle arrow (incongruent trials; e.g., →→←→→). The arrows were displayed until a response was made, and there were an equal number of congruent and incongruent trials. Notably, incongruent trials required participants to inhibit pressing the response key that was associated with the direction of the flanker arrows, in order to press the response key associated with the direction of the middle arrow. Therefore, it was expected that participants would demonstrate more errors on incongruent trials versus congruent trials. As a result, accuracy (i.e. number of errors) on incongruent trials was used to indicate Inhibitory Control.

The following tasks were used to indicate **Attentional Control**:

It has previously been noted that Attentional Control represents several theoretical abilities. First, it accounts for instances where normal attention processes must be overridden, in accordance with a specific goal. Processes such as attentional switching and divided attention are exemplary of this notion.

To examine attentional switching ability, two tasks were utilized. First, the **Number-Letter** task (Rogers & Monsell, 1995) was used to indicate Attentional Control, which was also implemented by Miyake and colleagues (2000) to indicate ‘Switching’. On this task, participants were shown a number-letter pairing (e.g., 4A), which appeared in one of four quadrants on the computer screen. When the stimulus appeared in either of the bottom two quadrants, participants were instructed to respond by indicating whether

the number was even or odd; when the stimulus appeared in either of the top two quadrants, participants were instructed to respond by indicating whether the letter was a vowel or consonant. Thus, participants were required to switch their attention back and forth between the number and letter components of the stimuli, and respond accordingly. Responses were made according to key presses on the keyboard (i.e. press the letter ‘A’ to indicate even numbers or vowels; press the letter ‘L’ to indicate odd numbers or consonants). This task consisted of three trial blocks. In the first trial block, all stimuli were presented in the bottom two quadrants. Similarly, in the second trial block, all stimuli were presented in the top two quadrants. In the third block, stimuli were presented in all four quadrants; rotating in a clockwise direction to ensure that an equal number of ‘switch’ and ‘non-switch’ trials occurred. ‘Switch costs’ were derived by a) subtracting average reaction time to numbers (in trial block 1) from average reaction time to numbers *after previously responding to letters* (in trial block 3; requiring a ‘shift’ of attention) and b) subtracting average reaction time to letters (in trial block 2) from average reaction time to letters *after previously responding to numbers* (in trial block 3; also requiring a ‘shift’ of attention). An average of these switch costs was used as an indicator of Attentional Control.

Second, the **Local-Global** ‘switching’ task (also employed by Miyake et al., 2000) was used as a measure of Attentional Control. On this task, participants were shown ‘Navon figures’ (Navon, 1977). Globally, these figures represent geometric shapes (e.g., a square); however, the lines comprising this overall shape are different ‘local’ geometric shapes (e.g., triangles) – see Figure 2 below. Participants were instructed to respond by pressing a number key on the keyboard, according to the number of lines

contained in either the global or local geometric figure (circle = 1, triangle = 3, square = 4). Participants were instructed to attend to the global figure if the stimulus was blue, but attend to the local figures if the stimulus was red. Therefore, participants had to ‘switch’ between attending to the global features of the figure, versus the local features. Similar to the Number- Letter task, the first two trial blocks consisted of only blue stimuli (global cue) and only red stimuli (local cue), respectively. The third block consisted of both blue and red stimuli, presented at random. Switch costs were calculated in the same manner as that described for the Number-Letter task, and average switch cost was again used to indicate Attentional Control.

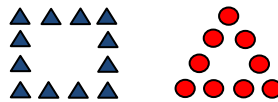


Figure 2. Example ‘Navon figures’ (Navon, 1977), used in the Local-Global task.

To examine divided attention, a ‘dual’ task was used, which was similar to the **Telephone Search** subtests from the Tests of Everyday Attention (TEA; Robertson et al., 1994). On this task, participants were required to search serially through a visual array for a pair of identical symbols (16 out of 96 symbol sets). A time-per-target score was calculated from this first task block. Likewise, participants completed this same visual search task for the second task block; but they were required to simultaneously count the number of times that the background screen changed colour. Given that the second task block was identical to the first task block, other than the addition of a ‘divided attention’ requirement; subtracting the time-per-target score for the first block from that of the second (divided attention) block resulted in a “dual-task decrement” score, which was used as the third indicator variable for Attentional Control.

The following tasks were used to indicate **Emotional Control**:

The quantification of emotional regulation has been almost as difficult as defining the construct itself. Unlike behaviours, it is difficult to observe internal emotional states, or further observe the process of altering such states. For example, one can measure how quickly or accurately an individual responds to a stimulus requiring Inhibitory Control (e.g., to an incongruent Flanker stimulus), but an analogous scenario is much more difficult if the aim is to somehow capture an individual ‘*not* letting emotional reactions interfere with task performance’. It is worth recalling that INTERACT views Emotional Control as the ability to respond to stimuli according to a goal, irrespective of the behaviour that is naturally elicited by the emotional valence of the situation. Nonetheless, experimenters have found ways to indirectly measure and make inferences regarding this construct. For example, it is often possible to infer emotion regulation based on its impact on other processes, such as behaviour (e.g., Yamasaki et al., 2002). Emotion regulation is commonly examined using paradigms that intentionally elicit frustration from participants, and is typically quantified via affective and behavior coding (Martel, 2009). These tasks might involve giving participants an undesirable reward (Cole, 1986; Saarni, 1984), or asking participants to complete an impossible puzzle (e.g., Melnick & Hinshaw, 2000). Measurement of emotion during such tasks has involved coding of participants’ facial expressions, as well as problem-solving strategies, help-seeking, overt expression of emotion, and disruptive behaviours (see Melnick & Hinshaw, 2000). However, the impact of emotional control on *cognitive* processes has also been studied (see Vasey & MacLeod, 2001). Emotionality has been successfully elicited by showing participants emotional facial stimuli (e.g., Hare, Tottenham, Davidson, et al., 2005), and by simply

asking participants to read words with emotional valences (e.g., Elliott, Rubinsztein, Sahakian, & Dolan, 2000a), and on a more basic level, by tasks that involve explicit reward and punishment. Importantly, the elicitation of emotion has been shown to have a detrimental effect on participants' attentional capacity (e.g., Derryberry, et al., 2002), inhibitory control ability (e.g., Elliott, et al., 2000a), decision making (e.g., Drechsler, Rizzo, & Steinhausen, 2009), and the ability to update the contents of WM (e.g., Joormann & Gotlib, 2008). Emotional Control would be indicated by the ability to overcome the detrimental impact of emotional valence.

The first task that was used to indicate Emotional Control is referred to commonly as the **Iowa Gambling Task** (Bechara, et al., 1994). A computerized version was used, similar to that implemented by Garon and Moore (2007). This task required participants to select cards from four decks, one card at a time by pressing the number keys 1-4 (corresponding with the 4 numbered decks). Participants made 100 such selections. All cards were associated with either a reward or punishment (i.e. an arbitrary 'gain' or 'loss' value). The explicit goal of this task was to procure maximal gains, and avoid losses. Importantly, two of the decks were considered 'advantageous'; they yielded small gains (e.g., \$2) and also small losses (e.g., \$2), but resulted in a net profit across trials. On the other hand, the other two decks were considered 'disadvantageous'; they frequently yielded larger immediate gains (e.g., \$4), but infrequently yielded much greater losses (e.g., \$10), and therefore led to a long-term, net loss. Thus, card selection was expected to be random at first, but research has shown that normal participants learn across trials that it is more beneficial to choose from the advantageous decks in order to maximize their gains in the long-run (e.g., Bechara, et al., 2000; Dunn, Dalgleish, & Lawrence, 2006).

Therefore, Emotional Control should be indicated by the ability to overcome the tendency to respond to immediate rewards (associated with reinforcing emotional valence), in favor of procuring long-term gains (i.e. according to the executive goal of the task). An example of the display screen is illustrated in Figure 3 below. Upon each card selection a message was displayed indicating the gain or less value of the card, along with a happy emoticon face for gains and a sad emoticon face for losses. In addition, a horizontal bar was displayed beneath the cards at all times, and indicated the current net total of all gains and losses by increasing or decreasing in size along a scale. This bar was green when the net value was positive, but turned red if the net total fell below zero. Similar to the study by Roca, Parr, Thompson, Woolgar, Torralva, Antoun, and colleagues (2010), the variable derived from this task that was used to indicate Emotional Control was the total number of advantageous deck selections, minus the number of disadvantageous deck selections.

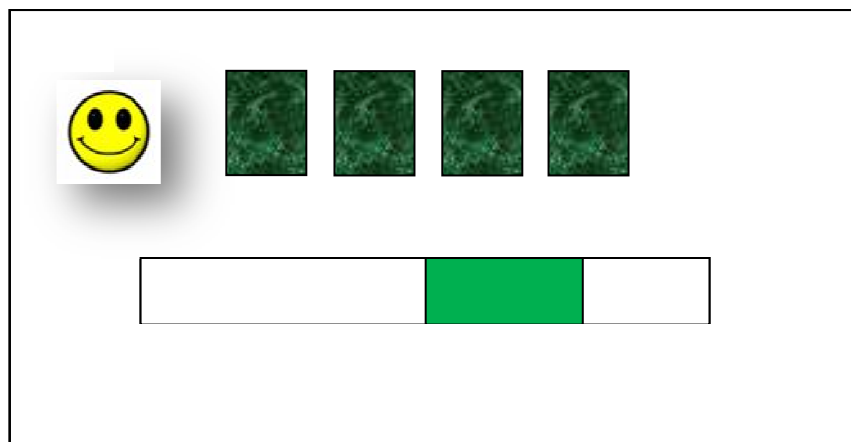


Figure 3. Sample display screen for the computerized Iowa Gambling Task.

A **Modified Sternberg** task (see Oberauer, 2001, 2005a, 2005b) was also used to indicate Emotional Control. This task was designed to assess the effects of irrelevant emotional information on the ability to update working memory. Each trial consisted of

three separate display screens. The first screen was the learning display, on which participants were presented with two lists of three words displayed side-by-side (see Figure 4a below). All of the words in one list were coloured blue; the words in the other list were coloured red. The next screen displayed the cue - a coloured frame (either blue or red) - indicating which of the two lists from the learning display would be relevant for the upcoming recognition task (see Figure 4b). The third screen displayed the recognition task; a single word presented in black ink situated within the coloured frame (Figure 4c). This 'probe' word was either from the relevant list (i.e. correct), from the irrelevant list (i.e. an intrusion), or a new word from neither list. Participants were asked to press one of two response keys as quickly and accurately as possible; the 'Y' key for 'yes' if the probe word was on the cued list (i.e. if it is correct), and the 'N' key for 'no' if the word was not. Importantly, the words used in this task differed in terms of emotional valence; by using a set of positive and negative words chosen from the Affective Norms of English Words (Bradley & Lang, 1999). Using this task previously, Joormann and Gotlib (2008) found that depressed patients demonstrated several 'intrusion effects' for words with a negative valence. More specifically, depressed patients took longer to respond to negative intrusion probes (a negative word from the *irrelevant* list) than did controls. This was not the case for positive intrusion probes. In addition, depressed patients showed a greater 'intrusion effect' (i.e. average reaction time to intrusion probes minus average reaction time to new probes of the same valence) versus controls, and for negative words only. Given that individuals with depression were presumed to exemplify poor Emotional Control, albeit at the extreme end of a normal distribution, it was expected that relatively 'poorer' Emotional Control would be indicated by a similar pattern of intrusion effects. In

contrast, it was expected that individuals with enhanced Emotional Control would overcome the impact of negative word valence, and respond as quickly as they would to neutral words. As such, for the current study, intrusion effects were calculated separately for positive and negative words, by the same methods as those implemented by Joormann and Gotlib. The difference between participants' positive intrusion effect score and their negative intrusion effect score served as an indicator of Emotional Control for the current study. The formula for this indicator is depicted below:

$$(RT\text{-NegIP} - RT\text{-NegNew}) - (RT\text{-PosIP} - RT\text{-PosNew})$$

Note. RT-NegIP = mean reaction time to negative intrusion probes; RT-NegNew = mean reaction time to new negative probes; RT-PosIP = mean reaction time to positive intrusion probes; RT-PosNew = mean reaction time to new positive probes.

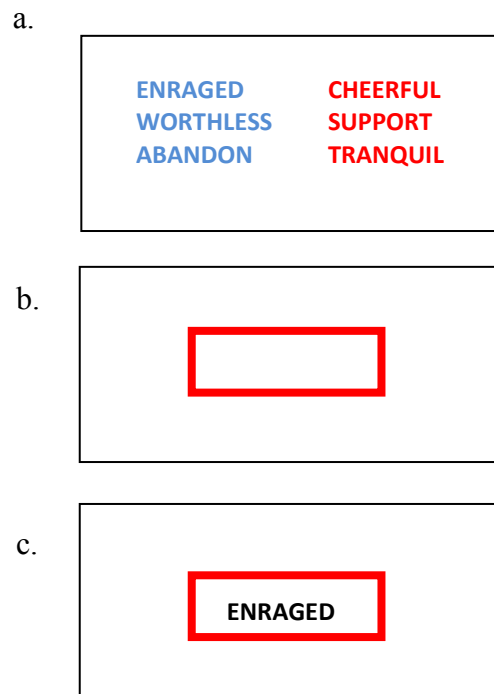


Figure 4. Sample displays from the modified Sternberg task: a) the learning display b) the cue display c) the probe display.

Finally, an **Emotional Face N-Back** task, similar to that used by Ladouceur, Silk, Dahl, Ostapenko, Kronhaus, and Phillips (2009), was implemented to indicate Emotional Control. This task was designed specifically to assess the impact of positive or negative valence on working memory ability. It is a modified version of a typical visual *n*-back task, in which participants are asked to attend to letters appearing in the middle of a screen one at a time, and press a response button whenever the current letter matches the letter that appeared *n* screens previously. For the current study, both a 3-back and a 2-back design were implemented. As such, participants were required to press the spacebar if the current letter matched the letter that was presented 3 (or 2) screens previously; but make no response if it did not. Targets (matches) occurred on approximately 30% of all trials. The *Emotional Face version* of this task involves flanking the letter stimuli on either side with two identical faces (see Figure 5 below). There were two distractor conditions; a neutral face condition (positive valence) and a fearful face condition (negative valence). The faces were identical to those implemented by Ladouceur and colleagues (2009); taken from the NimStim set (Tottenham, 2009). Although the face stimuli are irrelevant to the goal of the task, negative emotional valence has been shown to impact cognitive processing during this task (Ladouceur, et al., 2009). Thus, Emotional Control would again be indicated by overcoming this impact. For the current examination, an index score was derived for both the 2- and 3-back conditions, to reflect the varying impact of emotional valence on working memory performance. Specifically, mean reaction time in the neutral face condition was subtracted from mean reaction time in the fearful face condition. The average of this difference for the 2- and 3-back conditions served as the third indicator of Emotional Control.



Figure 5. Screenshot of the Emotional Face *N*-Back task, displaying the letter stimulus ('M'), and the two identical flanker ('neutral') faces.

The following tasks were used to indicate **Updating Working Memory**:

Recently, Ecker, Lewandowsky, Oberauer, and Chee (2010) found via task analysis that 3 subprocesses appear to be relevant to most Updating Working Memory paradigms: retrieval of information from short-term storage, transformation of such information, and substitution (eliminating old information and replacing it with newly relevant information). Therefore, the current study aimed to use indicators that reflected a variety of these subprocesses.

The **Keep Track** task was the first task used to measure updating WM. This task was also implemented by Miyake and colleagues (2000), adopted from Yntema (1963). On this task, participants were initially presented with the names of either 3 or 4 stimulus categories (e.g., animals, etc.) at the bottom of the display (see Figure 6a). Next, 15 words were presented one at a time, in random order, while the names of the stimulus categories remained visible at the bottom of the screen (see Figure 6b). The 15 words consisted of 3-5 exemplars from each of the target categories listed. Participants were asked to recall only the last word presented from each of the categories (3 or 4 words in total), by typing these words when prompted at the end of each trial block. Participants completed three trial blocks of 15 words (1 block with 3 categories; 2 blocks with 4

categories), and the total percentage of words recalled correctly across trial blocks (out of 11) was used as the first indicator variable for Emotional Control.

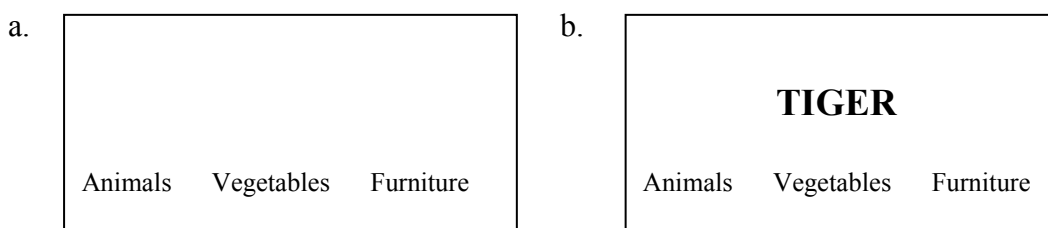


Figure 6. Example screenshots from the Keep Track Task: a) the initial ‘category screen’, b) a sample presentation screen.

A running memory task was used as the second indicator of Updating WM. In particular, the **Letter-Memory** task (see Morris & Jones, 1990) was used. On this task, participants were presented with a running sequence of letters of random length (typically between 7-12 letters). They were instructed to silently, but continuously rehearse the last four letters of the sequence as they were presented. When prompted at the end of the sequence (indicated by a display screen), participants were asked to type the final 4 letters. For example, if the series of letters included ‘B, G, H, R, M, D, C’, participants would rehearse the following as the sequence progressed: “B... BG... BGH... BGHR... GHRM... HRMD... RMDC”. They would then type the final 4-letter combination (‘RMDC’). Four trials were completed, and the total number of letters recalled correctly and in order (out of a possible 16) was used as the indicator variable.

Finally, a version of the **Memory Updating Task** was included (Salthouse, et al., 1991; Oberauer, 2000), modified by Ecker and colleagues (2010). On this task, participants were shown three boxes; each containing a letter of the alphabet, for a total of 2 s. They were asked to remember the identity and position of all three letters. As Ecker and colleagues point out, previous research (e.g., Oberauer, et al., 2000) has shown

that this set size offers an intermediate level of difficulty, and minimizes both floor and ceiling effects. Next, the letters were cleared from the boxes, and an ‘updating operation’ was displayed within one of the three empty boxes. The operation displayed was to be performed on the letter that previously appeared in that same box (see Figure 7 below).

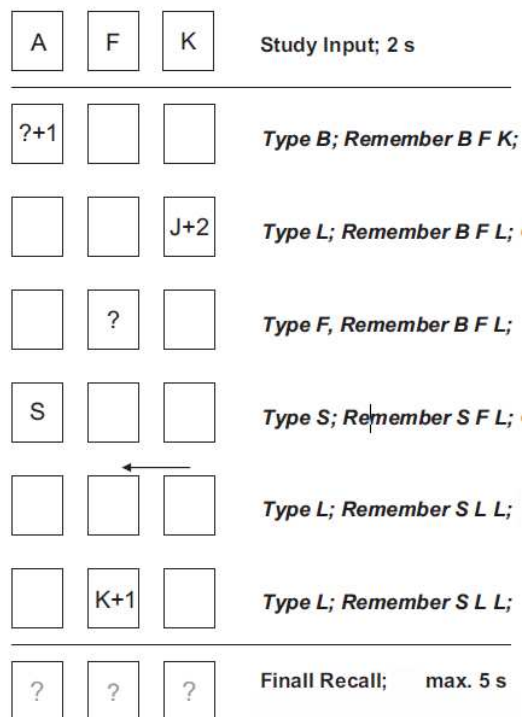


Figure 7. A sample trial from the modified Memory Updating task (Ecker, et al., 2010).

Participants were instructed to respond to each updating operation by typing the letter that resulted from the operation. Reaction time to do so was recorded by the computer. Similar to Ecker and colleagues, each trial consisted of 6 updating steps, and at the end of each trial participants were asked to type the final set of 3 letters. Five trials were completed in total. Of note, no feedback was given at any point in time during this task. In order to capture the time required to update and the correctness of updating, an index score was derived as follows:

$$\text{Memory Updating Score} = \frac{\text{Total number of correct final responses}}{\text{Mean updating time for each step}}$$

The following tasks were used to indicate **Problem Representation**:

The difficulties associated with defining the mechanism by which Problem Representation functions have previously been discussed. However, INTERACT suggests that this component is necessary when the executive system is faced with any novel problem, which requires a novel solution. Thus, this component is involved in identifying a goal for the novel task, and planning a course of action; which might consist of organizing or sequencing information in new ways and decision-making. As such, tasks that present participants with novel problems, and require them to derive novel solutions as efficiently as possible best represent the Problem Representation component of INTERACT. However, these types of tasks are rare in the literature, due to the difficulty in operationalizing the processes involved in such unstructured tasks. Nonetheless, three tasks fit these criteria, and were used to indicate this component.

The first task that was implemented was a modified, computerized version of **Raven's Advanced Progressive Matrices** (Raven, Raven, & Court, 1998). Although this has historically been considered a task of 'nonverbal' or 'fluid' intelligence (e.g., Marshalek, Lohman, & Snow, 1983), both of these constructs have been associated with executive function in the literature (e.g., Duncan, et al., 1996). Essentially, this task requires participants to organize and sequence novel information, by deducing rules and applying them, in order to solve novel problems (see Carpenter, Just, & Shell, 1990). Hence, this task exemplifies many of the proposed functions of Problem Representation. More specifically, participants were presented with a series of visual puzzles; each displayed in the form of a 3x3 matrix of geometric figures and patterns (see Figure 8 below). However, one piece of the matrix was always missing. Participants were required

to deduce the pattern of the missing piece, given the properties of the available matrix, and select the piece that best completed the matrix from a set of multiple choice options. Importantly, the pattern of each matrix followed a logical sequence, and a limited number of ‘rules’ have been articulated in the literature (see Vigneau & Bors, 2008), which describe how to deduce the missing piece of the matrix by progressing across the rows or down the columns of the matrix. Four of these rules include: “quantitative pairwise progression” (i.e. a constant change occurs in the size, number, or position of a specific feature between neighbouring cells in a row), “figure addition or subtraction” (a figure from one cell is added to or subtracted from a figure in a second cell to produce a figure in the third cell), the “distribution of three values” (a different value of a categorical feature appears in each of the three cells of a row), and the “distribution of two values” (two values of a categorical feature are distributed through the row, but the value for the third cell is immaterial) (Carpenter, et al., 1990).

Given that multiple executive processes are likely engaged by this task, due to the complexity of any task that will capture the Problem Representation component, it was vital that an attempt be made to isolate the specific contribution of only this component. As such, two separate trial blocks were run. First, participants were asked to solve 8 different matrices according to standard procedures (2 matrices representing each of the 4 rules noted above). Participants were told to press the spacebar when they were ready to attempt each new matrix, and responses were made by typing the number that corresponded with one of the 8 possible answers. However, prior to commencing the second trial block, participants were ‘taught’ each of the aforementioned rules, and were told that when applied appropriately, these rules would lead to the successful completion

of any given matrix. After ensuring comprehension of these rules via practice examples, participants proceeded with 8 new trials in the second trial block (again; 2 matrices representing each of the 4 rules). In this block of trials, participants were explicitly informed, prior to each trial, which particular rule would apply to the upcoming matrix. On these trials, participants were told to press the spacebar once they had processed the upcoming rule to be applied, and were ready to attempt the matrix. For both trial blocks, the computer recorded the time that elapsed from the press of the spacebar to begin each new trial, until the selection of the response option. The average time to make correct responses in the second trial block was subtracted from the average time to make correct responses in the first trial block (which should have been more difficult, and thus take more time). It was hypothesized that this would provide an estimate of the incremental engagement of the Problem Representation component. That is, when the task of following through with a given rule (via an output component) was accounted for by subtraction, the time that remained after this subtraction should have theoretically represented the time it took to discover the novel rule.

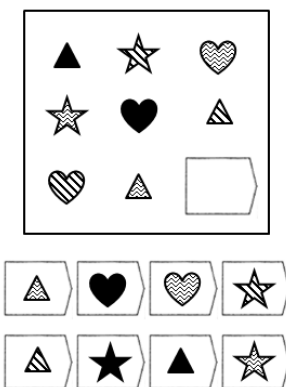


Figure 8. A hypothetical, example trial for the Matrices task.

The second task that was used to indicate Problem Representation was a maze task, previously used by Kirsch, Lis, Esslinger, Gruppe, Danos, Broll, and colleagues (2006). Maze tasks have historically been used as measures of planning ability. That is, the ability to plan out a route before ‘entering’ a visual maze minimizes errors (i.e. proceeding down blind alleys). Thus, minimizing errors was a crucial instruction for this task, and accuracy was stressed over speed. However, it was again also important to minimize the contribution of cognitive processes other than Problem Representation, which are undoubtedly engaged during this task. To this end, two separate trial blocks were once again implemented. The first block involved 10 standard, computerized mazes. These mazes were modified for computer administration as suggested by Nevo and colleagues (see Nevo, Arronson, & Israeli, 1984), such that participants were not required to draw a line through the maze from start to finish. Rather, participants always started in the middle of the maze, navigated through the maze *mentally*, and then decided which of two end positions (situated on either side of the maze) were correct (see Figure 9a below). Responses were made by pressing the ‘A’ key on the left side of the keyboard if the correct end point was on the left side of the maze; or the ‘L’ key on the right if the correct end point was on the right side. The proportion of correct ‘left’ and ‘right’ responses was balanced. However, similar to the study by Kirsch, Lis, Esslinger, Gruppe, Danos, Broll, and colleagues (2006), the second trial block consisted of 10 mazes that were fundamentally altered (‘pseudo-mazes’). Specifically, all blind alleys in the mazes presented in the second trial block were blocked off (see Figure 9b below). As such, participants’ ability to navigate through the maze, by way of visuo-spatial stimulus analysis and motor control, were tested; but not their ability to plan an appropriate route

or make decisions along the way. Responses were made in the same way as in trial block 1. As a result, the variable that was used to indicate Problem Representation was the average time to navigate through mazes in trial block 1, minus the average time to navigate through mazes in trial block 2.

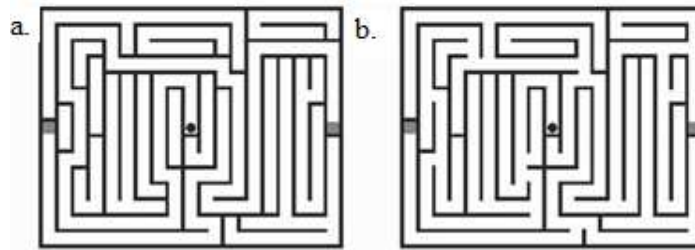


Figure 9. Example mazes a) for trial block two; including ‘pseudo-mazes’, derived by closing all bifurcations from the original mazes b) for trial block one; original mazes. The two possible end points are denoted by small, coloured squares on either side of the maze.

The third task that was used to indicate Problem Representation was a modified, computerized version of the **Tower of Hanoi task** (Piaget, 1976), similar to that used by Mataix-Cols and Bartres-Faz (2002). Initially on this task, participants were shown a display consisting of three pegs, placed side-by-side, and three circular disks of different size and colour, stacked on top of the left-most peg (see Figure 10a below). This was the ‘start’ configuration of the disks. Participants were also shown a ‘goal’ configuration (see Figure 10b). They were informed of three rules: i) only one disk could be moved at a time, ii) disks always had to remain on one of the pegs, except for the one disk that was in the process of being moved, iii) a larger disk could never be placed on top of a smaller disk. Given these rules, the start and goal configurations were manipulated to produce various difficulty levels for the task. In the original version of this task, the goal is simple – *using the fewest number of moves*, move the disks until the goal configuration is

achieved. Thus, this task has been viewed as a task of planning. For example, in the literature several indices have been used to represent ‘planning’; total number of moves taken to reach the goal configuration, total time to complete the problem, initial planning time (prior to the first ‘move’), and execution time (after the first move is made) (see Ouellet, Beauchamp, Owen, & Doyon, 2004). However, recent studies have shown that a number of different cognitive processes may contribute significantly to performance on this task (e.g., inhibition; Miyake, et al., 2000), and thus (not surprisingly), it is not a straightforward test of ‘planning ability’ per se.

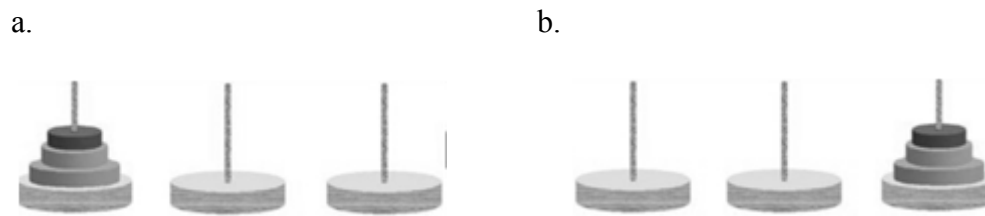


Figure 10. The Tower of Hanoi task: a) example ‘start’ configuration, b) example ‘goal’ configuration.

Therefore, for the current study this task was modified, to isolate the process of planning. First, rather than instructing participants to *move* the disks, they were told initially to “make a mental plan”; their task was merely to *discern the minimum number of moves* required in order to achieve the goal configuration. They were instructed to type this response via the keyboard. Once this portion of the task was completed for trial 1, they were then asked to carry out their plan, by moving the disks until the goal configuration was reached. This task was developed in a similar fashion to Mataix-Cols and Bartres-Faz (2002), in that participants used the mouse to ‘drag and drop’ disks from one peg to another. The computer program did not allow illegal moves to be executed. The time required to execute the movements and reach the goal was recorded.

Participants completed 5 such trials. However, trial block 2 was different. Participants were told simply to move the disks until the goal configuration was achieved; they were not asked to first think about an efficient plan. Given that trial block 1 always preceded trial block 2, it was assumed that participants were ‘primed’ to consider the benefits of planning their moves as part of the procedure in solving the problems. Again, 5 trials were completed, and total time to complete each problem was recorded. However, in trial block 2, ‘total time’ also included any time that participants required to plan or strategize; whether it was at the beginning of the trial, or throughout the trial. Therefore, by subtracting the total time for block 1 from the total time for block 2, it was hypothesized that this difference score would reflect the time specifically required to plan, or at least the incremental benefit of such planning. This subtraction method should have eliminated the contribution of any other cognitive processes (e.g., inhibition) toward the final outcome measure, as these processes were presumably engaged during the execution of the task in *both* task blocks.

Data Analysis

Structural Equation Modeling (SEM) allows one to examine data and test for the existence of underlying constructs (i.e., latent variables) that reflect hypothesized relationships between measured (indicator) variables. That is, SEM tests how well a theoretical ‘factor’ model (specified *a priori*) fits empirical data, via analysis of covariance. Importantly, an assumption of SEM is that some degree of measurement error is associated with measured variables (see Raykov, Tomer, & Nesselrode, 1991); compared to more classical statistical methods (e.g., regression analyses) that fit models to data but assume no measurement error exists. Therefore, SEM is considered an

important tool for theory development and construct validation (e.g., Anderson, 1987; Anderson & Gerbing, 1988). In addition, SEM allows one to examine if structural, directional relationships exist among latent constructs. That is, the effects of latent variables on each other are tested.

Based on this description of SEM, it is clear that this statistical technique was well-suited to the current research aims. First, SEM is clearly applicable to model testing. As a result, a specific factor structure (i.e. the 5 components of INTERACT) was imposed on the obtained test data to see how well the theory ‘fit’. In addition, SEM was advantageous for the current study because of the significant degree of variability that is normally associated with the construct of executive function, as well as its measurement. Specifically, SEM minimizes the impact of variability by accounting for unique variance (including error) associated with indicator variables. As a result of using multiple indicators per latent component, SEM extracts only the remaining *common variance* associated with a particular component. Thus, SEM disattenuates for measurement error by extracting what is reliably shared (variance) between indicator variables, thus leading to ‘purer’ measurement of executive function components. In brief, the ‘messiness’ of the construct and measurement of executive function(s) lends itself to a latent variable analysis, whereby ‘messiness’ can be accounted for.

However, SEM techniques generally require that several assumptions are met for the data being analyzed. To ensure valid conclusions from any SEM analysis, it is thus imperative to examine these assumptions during preliminary data analysis. As suggested by Schreiber, Nora, Stage, Barlow, and King (2006) in their review of reporting SEM results, the following technical issues should be reported pre-analysis: outliers, missing

data, multivariate normality, and multicollinearity. Given that several of the indicator variables were derived for the current study and were novel, an examination of the reliability of the indicators was also undertaken. Each of these issues was addressed prior to SEM analyses.

Outliers

Because SEM techniques are sensitive to outliers and missing data (see Kline, 1998); the data were first analyzed for these properties. Each task was examined for outliers according to a 2-step procedure similar to that described by Dixon, Garrett, Lentz, MacDonald, Strauss, and Hultsch (2007). First, implausible responses were discarded (e.g., a reaction time of 30 s on a task with an average reaction time of 200 ms; or 80 errors during a task block of 80 trials). Second, responses that fell outside of the range of $\pm 3SD$ from the mean for a particular task variable (i.e. across subjects) were trimmed from the analysis. These outliers were eliminated for theoretical reasons. For example, on occasion participants did not fully understand the instructions for a particular task. He or she would raise their hand and wait for one of the examiners to arrive at their computer station to clarify the task; all the while the first stimulus for the task remained on-screen awaiting a response. Thus, response times that were clearly out of the normal range were excluded from the analysis because they were not representative of participants' true responses (or the cognitive processes presumably underlying them), and would therefore skew estimated averages illegitimately.

Missing Data

It has been suggested that inappropriate strategies for dealing with missing data can bias parameter estimates (Jones, 1996), standard errors and test statistics (Glasser, 1964), and can undermine the utility of obtained data (Afifi & Elashoff, 1966). However, according to Rubin (1976) missing data can be ignored if missing completely at random (MCAR) or missing at random (MAR). Little's MCAR test can be employed using SPSS software, within the Missing Value Analysis module. However, MCAR is a strict assumption that rarely holds true in the real world (e.g., Graham, Hofer, & MacKinnon, 1996; Muthen, Kaplan, & Hollis, 1987). Nonetheless, if a high proportion of participants have missing data, regardless of the nature of missing data, pairwise- and listwise deletion methods for resolving missing data are inappropriate. Full Information Maximum Likelihood (FIML) estimation computes a case-wise likelihood function using those variables that have been observed (Wothke, 1998), which results in more stable parameter estimates, and has generally been shown to result in a high percentage of admissible solutions compared to other estimation methods (e.g., Enders & Bandalos, 2001). It is easily employed by AMOS SEM software.

Normality

The distribution of each indicator variable was examined, as SEM methods also rely on the assumption of multivariate normality. However, a few issues are noteworthy. First, it has been postulated that the assumption of multivariate normality in the normal population is often violated, but Maximum Likelihood methods are implemented anyways as a result of “software limitations, lack of simple alternatives, or the

researcher's unfamiliarity with existing non-normal methodologies" (Savalei, 2008, p. 2).

In a related fashion, estimates of multivariate normality are not calculated by popular SEM programs like AMOS when there is missing data. This poses a dilemma for researchers, since it is currently unknown whether such estimates of multivariate normality are valid with missing data (see Yuan, et al., 2004).

Second, even if the data are found to be non-normally distributed, many studies have demonstrated that ML estimation methods are still fairly robust. For example, studies have shown that χ^2 estimates for common SEM models can remain robust to violations of normality under several different conditions (e.g., Amemiya & Anderson, 1990; Browne, 1987; Browne & Shapiro, 1988; Mooijart & Bentler, 1991; Satorra & Bentler, 1990). Simulation studies have shown that even in cases of severe non-normality, many SEM parameter estimates are still accurate, although χ^2 estimates can be inflated (Curran, et al., 1996; Hu, et al., 1992). However, because this inflation increases the chances of Type I errors as a result, it is *more difficult* to find *good* model fit. This finding has led some authors to suggest that non-normality is actually a blessing in disguise; that is, it allows for a stronger test of a model (Savalei, 2008). Although the issue of incomplete data must be addressed in conjunction with non-normality, there is also an array of literature supporting similar conclusions (Gold & Bentler, 2000; Graham et al., 1996). For example, Gold, Bentler, and Kim (2003) examined Maximum Likelihood estimation with non-normal data under both MCAR and MAR conditions. They compared data sets with 15% and 30% missing data, and found that although standard errors were biased in the range of 14% to 35% for both MCAR and MAR data, rejection rates for χ^2 were always reasonable. Likewise, Savalei and Bentler (2005)

examined data sets with missing data but more severely non-normal data, and also found relative biases for standard errors but acceptable rejection rates for χ^2 for MCAR and MAR data.

Finally, some authors have argued that there are potential pitfalls associated with ‘treating’ data for non-normality too strictly. For example, as a result of a paper published by Gao, Makhtarian, and Johnston (2008), these same authors presented an argument at the Transportation Research Board’s 87th Annual Meeting. Essentially, they suggested that despite the obvious advantage of eliminating multivariate outliers, a major disadvantage is that this process entails the loss of observations, and subsequently variance and model power. This suggestion was put forth after observing with their own data that using the typically recommended cut-off ratio of 1.96 for Mardia’s Coefficient ($p < .05$; see Mardia, 1970) led to improved multivariate normality, but no significant difference in model fit was found. These authors cite previous studies that found similarly negligible results when comparing various levels of multivariate kurtosis (e.g., Muthen & Kaplan, 1985; Hallow, 1985). Gao and colleagues suggest that perhaps the reason for using such a strict cut-off for Mardia’s Coefficient is only because simulation and empirical studies focusing on non-normality have not typically provided any recommendations for different cut-offs for multivariate normality. In summary, Bagley and Mokhtarian (2000) have discussed a trade-off between sample size and desire for multivariate normality; i.e., “the need to take full advantage of what the original data can tell us and the need for statistical confidence in what the data do tell us” (Gao, et al., 2008, p. 347). Therefore, for the present study the intent will be to eliminate multivariate

outliers to an extent; i.e. according to a conservative p value ($< .001$) (e.g., Schreiber, et al., 2006).

In this way, non-normality will be reduced, but important information contained in the outcome variables (variance) should be preserved. That said, if the results of the SEM analysis reveal a significantly inflated χ^2 value (corresponding with a significant critical ratio), or unusually small standard errors, the impact of multivariate normality might be revisited at that time. With these caveats in mind, an analysis of the normality of the data was undertaken.

SEM: Testing the Measurement Model (Confirmatory Factor Analysis)

The measurement model of INTERACT is displayed below (see Figure 11): the five (latent) components of INTERACT are depicted as ellipses; indicators for each component are represented by rectangular boxes; small circles on the right represent error variance contributing to each indicator item; and the curved, double-headed arrows represent covariances between the components. Of note, AMOS uses Maximum Likelihood (ML) to estimate latent variable loadings (represented by straight, single-headed arrows in Figure 11), based on the covariance matrix.

Model fit was examined using several methods. First, the χ^2 goodness of fit index (Loehlin, 1998) indicates the degree to which a proposed model ‘fits’ the data, relative to a saturated (full) model that fits the data perfectly. Thus, larger χ^2 estimates represent greater divergence between these two models, and the worse the ‘fit’ of the proposed model. However, χ^2 should not be used as the only indicator of model fit. Additional ‘ad hoc’ indices of fit are considered useful as adjuncts to χ^2 (Byrne, 1998), and were selected to represent different types of fit (e.g., absolute and incremental fit). Together

these indices are considered sensitive to model misspecification while also being relatively insensitive to small samples (e.g., Hu & Bentler, 1995, 1998). For example, given the χ^2 statistic, it is possible to calculate a relative χ^2 ratio (Bollen, 1989), reflecting the ‘parsimony’ of a given model relative to degrees of freedom (χ^2 /df). Conservative approaches generally reject models with such a ratio greater than a value of 3. In addition, a Comparative Fit Index (CFI; Bentler, 1990) can be computed in AMOS (ranging from 0 to 1), which reflects the relative fit of a given model (compared to the independence model) by essentially computing a χ^2 difference value. In general, CFI values of .95 and greater are considered indicative of excellent model fit (Hu & Bentler, 1995). Finally, the Root Mean Square Error of Approximation index (RMSEA; Steiger, 1990) is a relatively newer statistic used to determine model fit in SEM. It estimates a *lack* of fit per estimated parameter (therefore accounting for model complexity), relative to a saturated model, and is regarded as a reliable indicator by modern standards. Typically, RMSEA values closer to zero are regarded as reflecting good model fit; Hu and Bentler (1999) recommend using a cutoff score of .06.

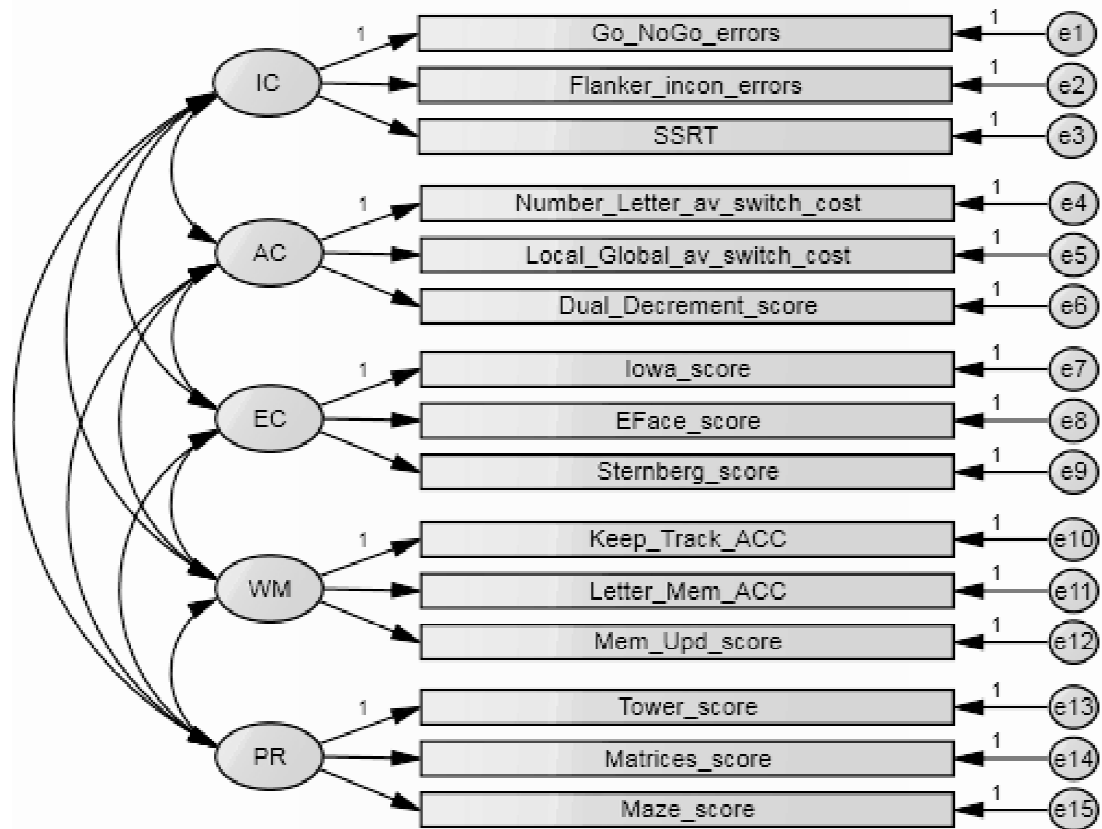


Figure 11. The initial Measurement Model of INTERACT, including the original 15 task variables proposed to indicate each latent component. Note that IC = Inhibitory Control, AC = Attentional Control, EC = Emotional Control, WM = Updating WM, and PR = Problem Representation.

In order to provide stronger support for INTERACT; its model fit was tested against several alternative measurement models (depicted in Figure 12 below). These alternative models were constructed on the basis of theoretical and empirical evidence from the literature.

First, despite overwhelming evidence in favor of distinguishing these executive systems, hence the theoretical basis for distinct components in INTERACT; an association between Inhibitory Control and Emotional Control often occurs in the literature. For example, some authors have speculated as to “whether an active inhibitory mechanism applies over and above the fairly immediate control of the motor system and

into the control of emotion, attention, and memory” (Aron, 2007, p. 227). The notion that IC perhaps accounts for cognitive control *over* emotions certainly blurs the distinction between these components. For example, some authors to suggest that these Inhibitory Control deficits may be closely associated with poor emotional self-regulation in general (Barkley, 1997; Braaten & Rosén, 2000; Friedman et al., 2003). Other authors actually combine these two aspects of executive control into one ‘hot EF’ domain (e.g., Castellanos, Sonuga-Barke, Milham, and Tannock, 2006). Some authors have suggested that depression, presumably representing deficient emotional control, might be associated with deficient *inhibitory processing* of negative information (e.g., Leyman, et al., 2011), and not simply emotional dysregulation. Perhaps this is not surprising, given the ways in which EC is commonly measured in the literature. More specifically, EC has typically been studied by examining that impact of emotional valence on IC performance. For example, EC has been studied by adding an emotional component to the Stroop task (e.g., Dai & Feng, 2011), Go/No-Go tasks (e.g., Albert, Lopez-Martin, et al., 2010), the antisaccade task (e.g., Derakshan, et al., 2009), and the Simon task (e.g. Sommer, M., G. Hajak, et al., 2008). In addition, many studies have suggested that EC and IC tasks sometimes recruit similar cortical areas, and thus might share neural substrate (e.g., Tabibnia, et al., 20011), or common neuromodulators (e.g., Cools, et al., 2008). Finally, many studies have provided evidence that clinical populations with known IC deficits also demonstrate poor performance on EC tasks compared to controls (e.g., Walcott, et al., 2004), or vice versa (e.g., Dai & Feng, 2011; Derakshan, et al., 2009; Domes, G., B. Winter, et al., 2006; Langenecker, et al., 2005; Nigg, et al., 2005).

Second, a potential bridge between Updating of WM and Problem Representation is apparent in the literature. This is similar to the original conception of WM (Baddeley & Hitch, 1974); combining a ‘central executive’ and slave ‘storage systems’, which together process and store information for the purpose of problem solving. In addition to the close *conceptual* link between updating of WM and PR outlined previously (e.g., the mental representation of a problem is likely held within WM), both updating of WM and PR likely share common underlying neural substrate (i.e. DLPFC). For example, the DLPFC has commonly been implicated in WM processes (D’Esposito & Postle, 1999; Levy & Goldman-Rakic, 1999). Likewise, task performance across several measures believed to represent components of PR has been associated with activation of the DLPFC (for a review, see *Introduction*). Thus, a DLPFC factor was created by combining these two components of INTERACT, and were implemented in several of the alternative models.

Two final combinations of INTERACT components were also introduced for the purposes of alternative model comparisons. First, a “cybernetic” factor was included (Royall, et al., 2002); referring to IC, AC, and EC from INTERACT; which theoretically share the characteristic ability to control other non-executive systems in a top-down fashion, and all constitute the “When” of executive functioning (Denckla, 2007). Finally, although evidence in favor of a *unitary* EF factor is sparse in the literature (see Royall, 2002); a 1-factor model was also included.

Model fit comparisons were made using Akaike Information Criterion (AIC) values for each model, as well as CFI difference values (Δ CFI). The AIC statistic is essentially a modified χ^2 value, which accounts for model complexity by incorporating degrees of freedom into its calculation. As a result, lower AIC values represent more

'parsimonious' models, and indicate relatively better fit (Hu & Bentler, 1995). Thus, the AIC statistic is a way of selecting a model from a set of models (see Burnham & Anderson, 2002). CFI difference (Δ CFI) scores of .01 or greater are typically considered significant (e.g., Cheung & Rensvold, 2002; French & Finch, 2006; Kim, Cramond, & Bandalos, 2006).

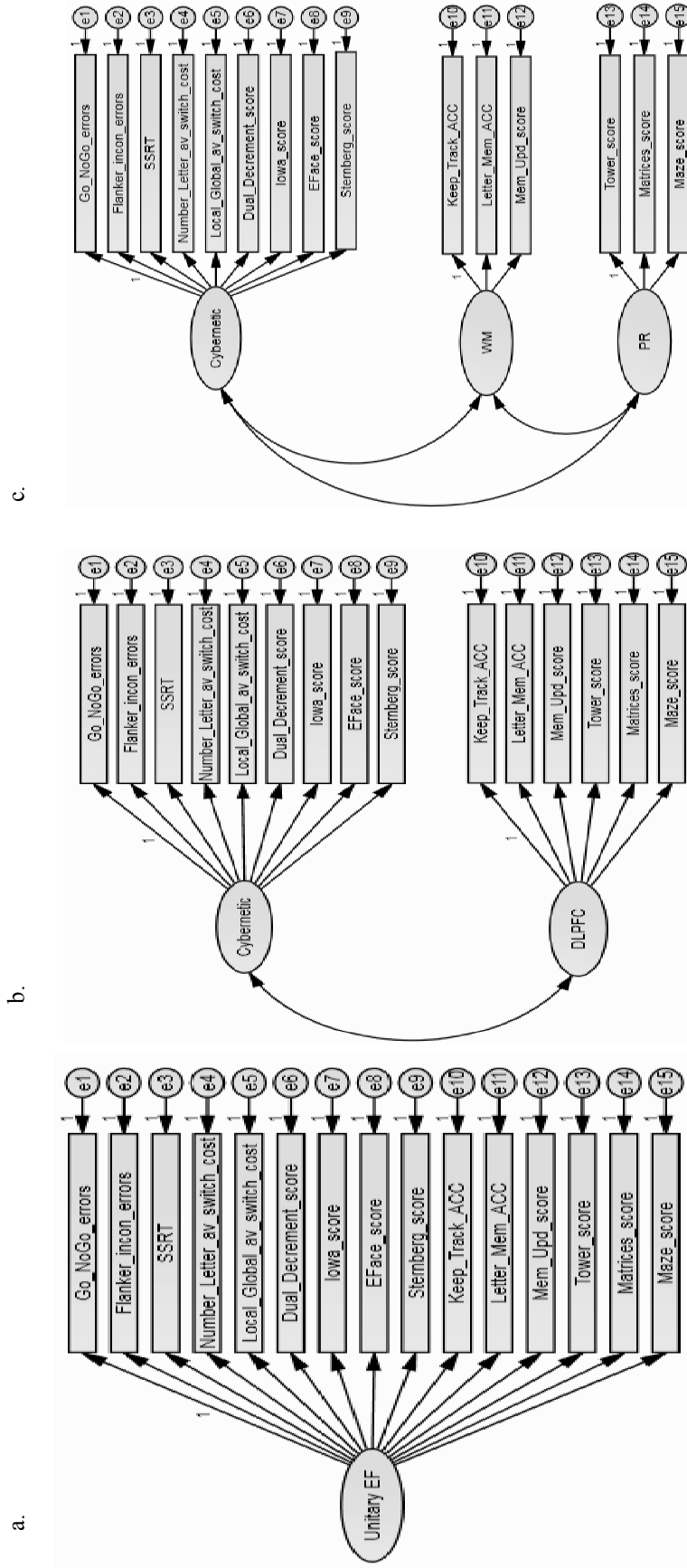


Figure 12. Alternative Measurement Models depicting a) a 1-factor solution, b) a 2-factor solution, c) & d) 3-factor solutions, and e) & f) 4-factor solutions (continued on next page). Note that IC = Inhibitory Control, AC = Attentional Control, EC = Emotional Control, WM = Updating WM, PR = Problem Representation, DLPFC = Updating WM + Problem Representation, and Cybernetic = Inhibitory Control + Attentional Control + Emotional Control.

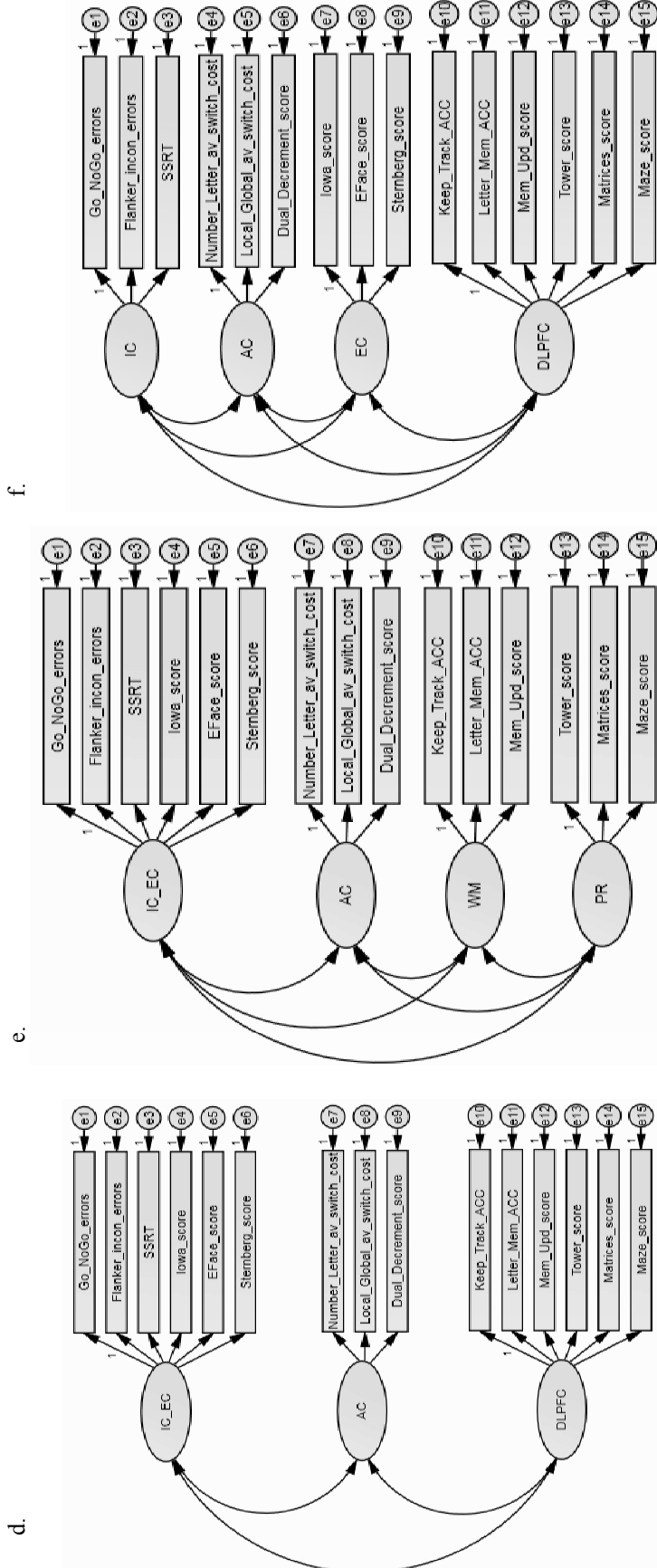


Figure 12 (continued).

Structural Models

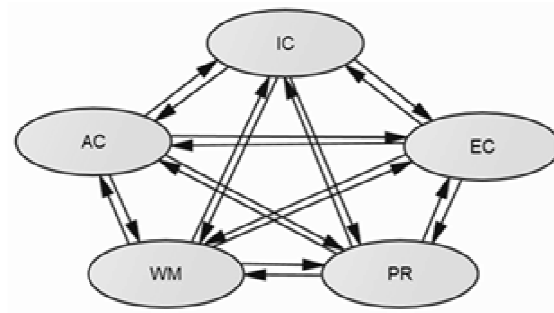
If a measurement model is found to be viable, SEM can also be used to test the structure of the model and its components, via path analysis. Thus, a comparison between two structural (path) models was planned, illustrated below (see Figure 13). These structural models hypothesize that either: a) all EF components interact with each other in a non-hierarchical fashion, or b) certain EF components (e.g., Problem Representation and Updating Working Memory) are engaged more independently in relation to other components (see Figures 13a and 13b, respectively). This latter structural model merely provides an alternative, theoretical model against which the relative utility of INTERACT can be compared. This alternative model was designed to parallel the theory of *PFC* functioning put forth by Miller and Cohen (2001); that the PFC directs activation via an excitatory bias signal. However, rather than the entire PFC emitting a bias signal to more posterior systems, this alternative model suggests that perhaps the Problem Representation component emits a top-down control signal *to the other components of the executive system*, and thus sits at the top of the executive hierarchy. In this way, Problem Representation can easily delegate *how* the other systems will proceed in executing control. In addition, this is theoretically accomplished via the Updating WM component, which holds in mind all relevant aspects of a given problem (representations of the external world as well as information from long term memory storage), which are activated by the current situation. Therefore, this model suggests that perhaps the Problem Representation component interacts with other control systems (via WM) in a top-down fashion. Potential evidence in support of this alternative model stems from a few sources. For example, Owen and colleagues (1996) suggest that a hierarchical

relationship exists between the superior and inferior dorsolateral cortex (associated with the Problem Representation and Updating WM components of INTERACT, respectively). More specifically, Baddeley (2000) previously suggested that the central executive of his model (approximating many of the functions of Problem Representation as per INTERACT) “can influence the content of the store (within WM) by attending to a given source of information, whether perceptual, from other components of working memory, or from LTM” (Baddeley, 2000; p. 421). This suggests that some higher-order function is theorized to exist (e.g., a ‘central executive’ or Problem Representation component), which when activated has the ability to modulate or exert control over an information cache (such as that associated with the Updating WM component).

In addition, Friedman and Miyake (2006) recently used SEM analyses and provided evidence that Updating WM was significantly associated with Inhibition and Shifting (of attention), as well as with measures of both fluid and crystallized intelligence. On the other hand, neither Inhibition nor Shifting were significantly associated with either forms of intelligence. Importantly, INTERACT’s conceptualization of Problem Representation is closely aligned with the concept of fluid intelligence. For example, Friedman and Miyake reference several authors (e.g., Damasio, 1994; Duncan, Burgess, & Emslie, 1995; Duncan, Emslie, Williams, Johnson, & Freer, 1996) and suggest that fluid intelligence may be associated with the ability to reason, execute goals, plan, and make decisions. Furthermore, Problem Representation would be considered vital to explaining performance on those tasks utilized by Friedman and Miyake to capture fluid intelligence (e.g., Raven’s Progressive Matrices). Collectively, this may therefore suggest that the cybernetic components of INTERACT (at least Inhibitory

Control and Attentional Control) may not be directly influenced by Problem Representation, but rather indirectly via Updating WM.

a.



b.

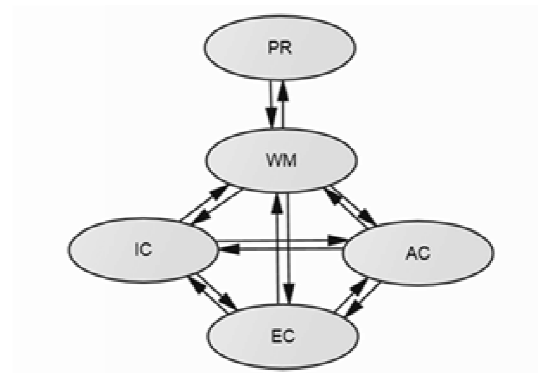


Figure 13. Structural (Path) Models that will be examined to test the relationships between each of the five EF components a) assuming no hierarchical relationships, b) assuming that Problem Representation ‘biases’ other control networks in a top-down fashion.

Hypotheses

In order to provide full support for INTERACT; it was hypothesized that the 5-factor model would demonstrate good ‘fit’ for the observed indicator variables. In part, this should be evidenced by significant factor loadings for each component of INTERACT, suggesting that the chosen indicator variables truly represented their

designated INTERACT components via common variance. In addition, it was hypothesized that the covariance estimates among each of the 5 latent components should represent the degree to which the 5 components are related to one another. According to INTERACT, these relationships should be significant, given that the interactions among executive components are precisely what constitute the emergence of EF. Further, the full 5-factor (INTERACT) model should result in better ‘fit’ when compared to alternative models, using the same indicator variables. Finally, although INTERACT hypothesizes no hierarchical structure among its components, it was hypothesized that this ‘structural’ hypothesis would not be as efficient as the alternative model previously proposed, which specifies a particular hierarchy among the components.

Results

Descriptive statistics for the original 15 indicator variables (n = 218), prior to outlier elimination, are provided in Table 1, below.

Table 1
Descriptive Statistics for the Original 15 Task Variables

	N	Min.	Max.	M (\pm SD)	Skewness (S.E.)	Kurtosis (S.E.)
Go/No-go errors	217	0	80	7.50 (7.56)	7.68 (.17)	70.35 (.33)
Flanker errors	217	.00	.24	.049 (.05)	1.55 (.17)	2.56 (.33)
Stop task SSRT	217	-150.00	1048.80	323.91 (167.82)	1.01 (.17)	2.36 (.33)
Number-Letter switch cost	218	-731.00	2173.73	555.08 (424.85)	.23 (.17)	.67 (.33)
Local-Global switch cost	217	-1296	1704	467.65 (399.67)	-1.04 (.17)	4.15 (.33)
Dual task score	185	-11791	22028	1648.33 (3051.11)	.89 (.18)	13.56 (.36)
Iowa score	216	-44	96	23.10 (26.32)	.75 (.17)	.36 (.33)
E-Face score	201	-496.00	786.00	65.48 (227.82)	.30 (.17)	.77 (.34)
Sternberg score	217	-6565	26382	385.24 (2275.14)	7.09 (.17)	80.94 (.33)
Keep Track accuracy	217	1	11	6.73 (1.98)	-.40 (.17)	.04 (.33)
Letter-Memory accuracy	218	0	16	8.52 (3.81)	-.11 (.17)	-.53 (.33)
Memory-Updating score	213	.0000	.0174	.0067 (.0036)	.67 (.17)	-.07 (.33)
Maze score	218	-89070	48361	12556.49 (9865.68)	-4.46 (.17)	52.14 (.33)
Tower score	213	-55559.20	35638.20	-6156.44 (12724.93)	-1.53 (.17)	4.18 (.33)
Matrices score	214	-165498.00	83731.00	12853.42 (19660.32)	-2.63 (.17)	32.61 (.33)

Missing Data

Only 13 data points were trimmed from the original data set, by way of the outlier methods detailed previously. Nonetheless, outlier elimination contributed to missing data. Of the 218 initial participants, only 1 participant was eliminated entirely from the analysis due to a significant proportion of missing data (75%). This particular participant's data were missing as a result of illness, which prevented her/him from continuing with testing beyond the fifth task. With the exception of this participant, only 2 participants failed to complete the entire set of 15 computerized tasks (due to scheduling conflicts). However, the number of missing data points for these 2 participants was not significant enough to warrant elimination of their data sets entirely. Additional missing data was also evident, typically resulting from computer malfunction (i.e. recording errors). The number of missing data points per participant ranged from 1-5, $M = 1.32 \pm .84$, corresponding with a total of 3% missing data (*after* outlier elimination). However, further analysis revealed that 19.8% of the Dual Task data was missing, and this accounted for 43.4% of total missing data. This was not surprising, given a noted observation by the examiner throughout testing that many participants misunderstood the task instructions for one particular portion of this task. A reliability analysis was subsequently performed on the Dual Task data to help decide whether it should be retained as an indicator variable. A split-half reliability estimate was .73, but overall coefficient alpha was .42. According to the literature there is no consensus "cut-off value" for alpha, although a value of 0.7 or higher is generally acceptable for reliability testing (see Nunnally, 1978). These results therefore suggest that the data obtained for the Dual Task had questionable reliability as a measure of Attentional Control, in addition to

significant missing data. The decision was made to eliminate the Dual Task variable from the analysis.

After elimination of the Dual task, the total percentage of missing data decreased to 1.7%, ranging from 1-4 per participant, $M = 1.44 \pm .85$. Despite the low proportion of missing data, missing values analyses were run to qualify the nature of the missing data. Even after eliminating the Dual Task, the data were not missing *completely* at random (MCAR) ($\chi^2 = 302.52, DF = 230, p = .001$). However, given the explanations previously discussed concerning the remaining missing data (i.e., computer malfunction, attrition, and outlier elimination) it was reasonable to assume that the missing data were unrelated to the underlying values of particular variables themselves, and were therefore missing at random (MAR), despite it being impossible to test this assumption (Allison, 2003). Given that the percentage of missing data was low, and the data appeared to be missing at random, missing data was not a significant issue in the present study. Since a significant proportion of participants had at least one missing data point, the Full Information Maximum Likelihood (FIML) estimation method was selected for the purposes of the SEM analysis.

Reliability of the Indicator Variables

The correlation matrix was examined for the remaining 14 task variables (see Table 1, below), to ensure that each indicator was reliably corresponding with the other indicators for a given factor. Inspection of this matrix revealed poor correlations between the Maze task and the other Problem Representation variables. Significantly weak correlations were also noted between the Sternberg task and the other Emotional Control variables. These two variables were further analyzed to determine if they should be

retained for the final analysis. Reliability analyses revealed that the Maze task was quite inconsistent (split-half reliability = .64; coefficient alpha = .37). This is consistent with one previous study that examined a 'route selection' task, in which it was found that performance was associated with a wide variety of cognitive abilities (Salthouse & Siedlecki, 2007). Therefore, based on these results the Maze task was dropped from further analyses. Similarly, despite what appeared to be modest reliability (split-half reliability = .74; coefficient alpha = .68) as an independent measure, the outcome variable derived from the Sternberg task correlated quite poorly with the other EC indicators, and was therefore also eliminated from the analyses.

Of note, a reliability analysis was also performed on each of the remaining indicator variables. On the basis of split-half procedures, modest to good reliability estimates (i.e. minimally > .60) were found for the indicator variables derived from the Stop Signal task, Number-Letter task, Local-Global task, the Emotional Face *n*-back task, the Memory Updating task, the Tower task, and the Matrices task. Such analyses were not performed for the Go/No-Go, Letter Memory, Iowa, Flanker, and Keep Track tasks, which were derived on the basis of single scores.

Table 2
Correlations of All Indicator Variables, After Removing the Dual Task

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. GNG Errors	--													
2. Flanker Errors	.286**	--												
3. SSRT	.293**	.226**	--											
4. N-L Switch Cost	-.041	-.100	.025	--										
5. L-G Switch Cost	-.070	-.122	.101	.211**	--									
6. Iowa Score	-.034	.068	-.017	.127	.138*	--								
7. E-Face Score	.032	-.051	-.040	-.016	-.077	-.164*	--							
8. Sternberg Score	.023	.003	.091	-.006	.062	-.097	.126	--						
9. Keep Track ACC	-.029	-.029	-.195**	-.055	-.040	.046	.001	-.036	--					
10. Lett-Mem ACC	.004	-.034	-.109	-.037	.063	-.008	-.047	.078	.197**	--				
11. Mem-Upd Score	-.047	-.034	-.088	-.088	.019	-.085	.029	-.053	.159*	.204**	--			
12. Maze Score	-.007	-.123	.078	.157*	.061	-.011	-.011	.094	-.014	-.146*	-.200**	--		
13. Tower Score	-.098	-.114	-.085	.128	.044	.023	-.034	-.011	.167*	.048	.113	-.029	--	
14. Matrices Score	-.204**	-.032	-.111	.084	.218**	.055	-.012	.128	.005	.137*	.076	.004	.251**	--

Note. Correlations highlighted in gray denote expected associations among indicators of corresponding latent constructs.

Normality

Descriptive statistics for the final 12 task variables are displayed in Table 2 below. Given that missing data were assumed to be MAR, with significantly fewer missing data points than those addressed by previous studies (see *Data Analysis* section), it was reasonable to assume that ML estimates would be robust if non-normality was not too extreme. Univariate normality for each variable was assessed first. As can be seen in Table 2, skewness estimates ranged from -1.04 to 1.58 (mean skewness = 0.17). Absolute values greater than 3.0 are considered extreme for this statistic (Chou & Bentler, 1995), suggesting that the majority of the data were not significantly skewed (see Crocker & Algina, 1986). Estimates of kurtosis ranged from -0.52 to 4.27 (mean kurtosis = 1.18), and no values were above the critical value of 7 (see Finney & DiStefano, 2006). These estimates therefore provide strong evidence for univariate normality.

Table 3
Descriptive Statistics for the Final 12 Task Variables, After Univariate Outlier Elimination.

	N	Min.	Max.	M (\pm SD)	Skewness (S.E.)	Kurtosis (S.E.)
Go/No-go errors	213	0	16	6.74 (3.10)	.44 (.17)	.17 (.33)
Flanker errors	216	.00	.24	.049 (.05)	1.58 (.17)	2.69 (.33)
Stop task SSRT	213	31.20	808.60	317.05 (147.13)	.59 (.17)	.19 (.33)
Number-Letter switch cost	217	-731.00	1977.00	558.58 (417.60)	.04 (.17)	.46 (.33)
Local-Global switch cost	217	-1296	1704	467.65 (399.67)	-1.04 (.17)	4.15 (.33)
Iowa score	215	-44	96	23.24 (26.31)	.75 (.17)	.36 (.33)
E-Face score	201	-496.00	786.00	65.48 (227.82)	.30 (.17)	.77 (.34)
Keep Track accuracy	217	1	11	6.73 (1.98)	-.40 (.17)	.04 (.33)
Letter-Memory accuracy	217	0	16	8.48 (3.79)	-.12 (.17)	-.52 (.33)
Memory-Updating score	212	.0010	.0174	.0068 (.0036)	.69 (.17)	-.07 (.33)
Tower score	205	-39186.80	13942.40	-4811.14 (9324.87)	-.90 (.17)	1.04 (.34)
Matrices score	210	-10187.00	65317.00	12751.34 (13335.09)	1.16 (.17)	1.83 (.33)

However, the assumption of *multivariate* normality is more critical for the purposes of SEM analyses. Although estimates of univariate normality are informative, they do not always predict the multivariate distribution of the data (see Gao, et al., 2008). Commonly, multivariate normality is assessed by way of Mahalanobis Distances (i.e., the distance between each case and the “centroid” for all cases on all independent variables), and estimates of Multivariate Kurtosis, referred to as Mardia’s Coefficient (Mardia, 1970). In order to obtain estimates of Mardia’s Coefficient and Mahalanobis Distances, additional calculations were necessary given the missing data. First, DeCarlo (1997) provides a macro that can be implemented in SPSS to calculate Mardia’s Coefficient. By utilizing this method, the normalized value for Mardia’s Coefficient for the current data set was 4.60, $p < .001$, suggesting multivariate *non*-normality.

Second, SPSS allows users to calculate Mahalanobis Distances (D^2) for each case using the Linear Regression module. These values are assumed to have a χ^2 distribution, and thus, the probability of each distance from the centroid of all cases can also be calculated. If we assume a χ^2 distribution, and select a very conservative $p < .001$ level of significance (previously discussed) for $df = 12$ (the number of indicators in the model), the critical ratio for D^2 is 32.91. Applying this critical ratio to the obtained D^2 estimates, 2 cases appeared to be multivariate outliers.

Further inspection of these two participants revealed patterns of performance that were overtly indicative of being multivariate outliers. First, a high proportion of their scores were extreme relative to the rest of the sample; almost one-third (27 %) of their scores were above the 95th percentile or below the 5th percentile. In addition, both participants displayed inconsistent performance across the tasks. For example, their

extreme scores were never in a consistent direction (i.e. indicative of either strong or weak performance across the board); nor were their scores consistent within a given latent component (e.g., scoring at the 99th percentile for one IC measure, but at the 9th percentile for a different IC task). This pattern of stark inconsistency likely indicates that some external factor was contributing to these participants' performance across tasks. No behavioural observations were noted for any participant, and therefore inconsistent effort or attention to task instructions cannot be ruled out, nor can it be assumed. Interestingly, responses on the screener questionnaire indicated that one of these participants acknowledged having a history of reading, writing, and math difficulties; while the other participant admitted to consuming alcohol within the past 48hours, but refused to report how much had been consumed. Irrespective of speculation as to the potential implications of these factors, performance of these two participants was nonetheless unusual. Therefore, it was deemed that their performance across tasks was not simply a reflection of normal variability. As a result, the decision was made to eliminate these two participants to decrease multivariate kurtosis (see Yu & Gamble, 2008) and thus bring the sample data closer to a normal distribution. After eliminating these two cases (new $n = 215$), DeCarlo's macro for estimating Mardia's Coefficient was re-run, and the new normalized coefficient decreased to 2.79, $p = .005$. This value, although greater than a critical ratio of 1.96, was reasonable given the intent to preserve variance in the model.

Structural Equation Modelling – Testing the Measurement Model

Using the AMOS 19 software package (Arbuckle, 2010), a latent measurement model was derived for the final sample ($n = 215$), by imposing the five-factor structure implied by INTERACT on the 12 final outcome variables. The model was scaled by assigning a fixed value of 1.0 to one indicator for each latent component.

First, the outcome of the analysis conducted using AMOS indicated that the model was identified. Nominally, this was expected given the structure of the measurement model (i.e. based on the number of free parameters to be estimated, versus the amount of observed data). However, previous research has suggested that such ‘local’ identification does not necessarily indicate that a model will be identified ‘globally’, and ‘empirical under-identification’ is possible (see Kenny, 1979). No signs of empirical under-identification (e.g., multicollinearity, negative variance) were identified in the present analysis. It has also been stated, in general, that for any model with two or more factors, the model will be identified if each factor is associated with at least two indicators (i.e. the “two-indicator rule”; Bollen, 1989), each indicator loads on only one factor, measurement errors are not correlated, and each factor is correlated with at least one other factor (see O’Brien, 1994). Of note, these heuristics do not explicitly state the degree to which a factor must correlate with at least one other factor (i.e. one *non-zero*, non-diagonal element in the covariance matrix). As such, all of the above criteria were met for the current measurement model, and under-identification was not presumed to be an issue. Given that the INTERACT model was identified, model fit was examined.

In the present analysis, χ^2 was 36.38 ($df = 44$, $p = .786$), suggesting excellent model fit, and especially if non-normal data contributed to an inflated χ^2 estimate. Given

44 degrees of freedom, the relative χ^2 ratio (χ^2 /df) was 0.83 for the specified model, which is exceptional. In addition, a CFI value of 1.00 was obtained, suggesting ideal model fit. In fact, a value of 1 is seldom obtained in practice (Cheung & Rensvold, 2002). Finally, the RMSEA statistic was .000, with a 95% confidence interval falling between .000 and .032 ($p < .001$); once again reflecting ideal model fit. For a summary of these model fit indices, see Table 3 below referring to the full, 5-factor INTERACT model.

Alternative Measurement Model Comparisons

Using the same 12 indicator variables, the latent measurement model of INTERACT was compared against 6 other plausible models; each suggesting different factor structures. It can clearly be seen from Table 3 that INTERACT provided superior (relative) model fit, in terms all noted fit indices. However, many of these indices were not derived or intended to be used for the purpose of model comparison. As such, only AIC and Δ CFI values were assessed for the purpose of these comparisons. Nonetheless, both of these indices revealed a significant superiority of INTERACT above all of the alternative models tested.

Table 4
Alternative Model Comparisons

	χ^2	Df (p)	χ^2 /df	CFI (Δ CFI)	RMSEA	AIC
INTERACT	36.38	44 (.786)	.827	1.00	.000	128.38
4 Factors A	48.66	48 (.446)	1.014	.988 (.012)	.008	132.66
4 Factors B	49.62	48 (.409)	1.034	.970 (.030)	.013	133.62
3 Factors A	61.75	51 (.144)	1.211	.801 (.199)	.031	139.75
3 Factors B	64.17	51 (.102)	1.258	.757 (.243)	.035	142.17
2 Factors	73.18	53 (.035)	1.381	.627 (.373)	.042	147.18
1 Factor	86.24	54 (.003)	1.597	.404 (.596)	.053	158.24

Note: Δ CFI is calculated in comparison to the INTERACT (5-Factor) model.

Regression Weights and Covariance Estimates

Although overall model fit indices were excellent, not all of the indicator variables loaded significantly on their hypothesized latent EF components. As can be seen in Figure 14 below, standardized regression weights ranged from .39 to .61 for Inhibitory Control, .46 to .49 for Attentional Control, .26 to .53 for Emotional Control, .39 to .46 for Updating Working Memory, and .37 to .54 for Problem Representation. Critical ratios for the unstandardized regression weights ranged from 1.36 to 3.10; none of the indicator variables for Emotional Control or Problem Representation were associated with significant regression weights. Of note, Squared Multiple Correlation (SMC) values were all within an acceptable range, from .07 to .38, indicating no significant violations of multicollinearity among the indicators.

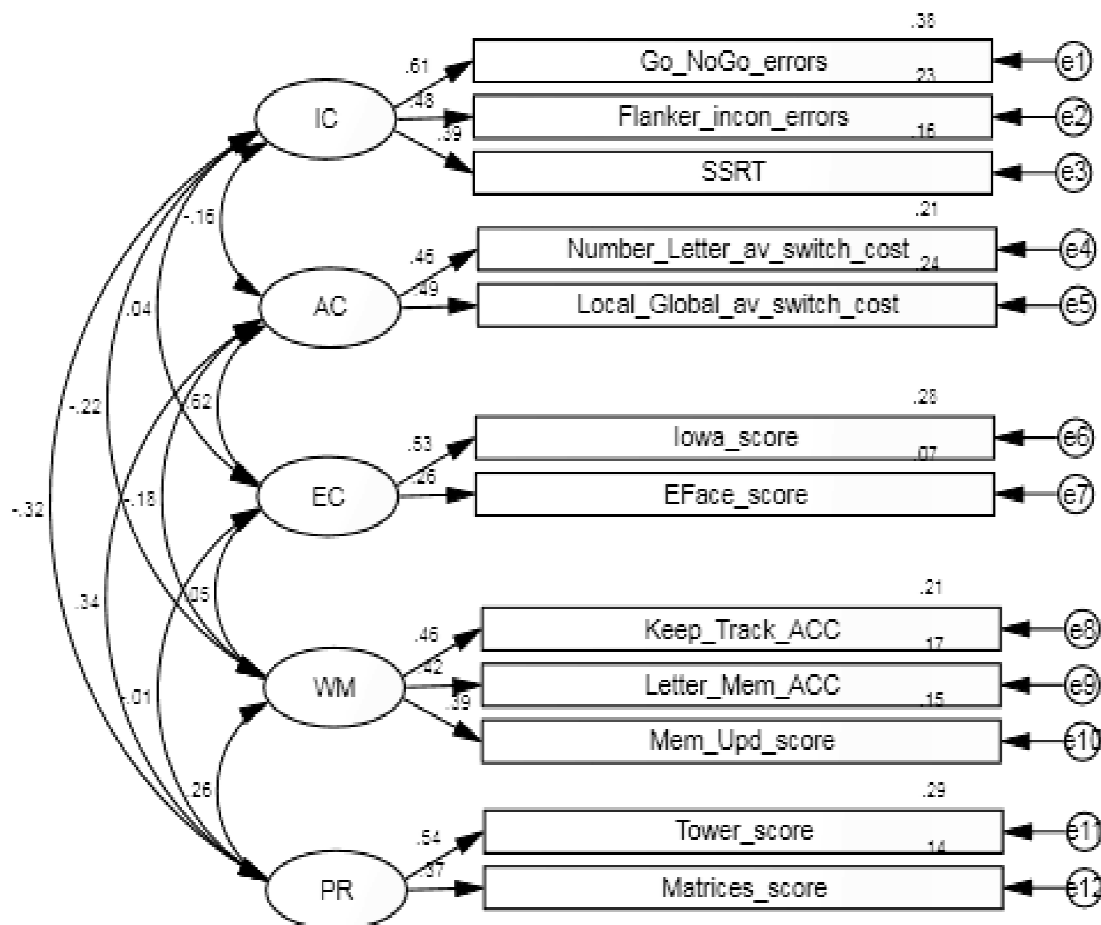


Figure 14. Confirmatory Factor Analysis results testing the latent measurement model of INTERACT; depicting its five components and the 12 specific executive task variables used as indicators for each component. Values attached to single-headed arrows reflect standardized factor weights for each indicator, as well as standardized error variance associated with each indicator (i.e., stochastic error variance, or unique error variance not associated with the latent components of INTERACT); while values attached to double-headed arrows reflect standardized covariances between latent factors (components). IC = Inhibitory Control, AC = Attentional Control, EC = Emotional Control, WM = Updating Working Memory, and PR = Problem Representation.

Finally, covariance estimates between each of the 5 components of INTERACT are displayed below (Table 4). It is noteworthy that in only one case was an association between two components significant; suggesting that the majority of the INTERACT components were un-related to each other, given this set of indicator variables. This finding contradicts the initial hypothesis that significant interactions between latent

components would be represented by significant covariance estimates. This hypothesis was primarily based on those results obtained by Garcia-Barrera and colleagues (2011), which suggested that moderate to high correlations should be expected between the underlying latent constructs because they are strongly related, and are perhaps all “measuring components of the same underlying (and unifying) latent construct, which could be a second order construct in the model” (Garcia-Barrera, et al., 2011, p. 72). Given that INTERACT posits that the interactions between components are precisely what constitute this ‘unifying’ construct, an assumption was therefore made that correlations would estimate this common construct.

Table 5

Unstandardized Covariance Estimates among the Five Components

			Estimate	S.E.	C.R.	<i>p</i>
PR	&	WM	1197.76	910.53	1.32	.188
PR	&	EC	-596.71	14363.47	-.04	.967
PR	&	AC	327155.37	206214.55	1.59	.113
PR	&	IC	-3063.85	1694.83	-1.81	.071
EC	&	WM	.63	2.43	.26	.796
AC	&	WM	-31.70	32.63	-.97	.331
IC	&	WM	-.38	.28	-1.35	.176
AC	&	EC	1623.62	675.24	2.41	.016
IC	&	EC	1.06	4.46	.24	.813
IC	&	AC	-58.32	58.91	-.99	.322

However, this unexpected result led to re-examination of the statistical logic underlying this hypothesis. It was assumed that covariance (correlation) was a satisfactory indicator of interaction; but following this logic, significant covariance estimates should be expected between each and every component of INTERACT. Conversely, INTERACT defines executive functions in terms of a “diversity of *distinguishable* functional systems” (Garcia-Barrera, 2011). That is, significant

covariance between each component of the model would actually suggest significant association, common variance, or ‘overlap’ between components; hence, components would not in fact be perfectly distinguishable (see Miyake, et al., 2000). On the contrary, *non*-significant correlations between INTERACT components should have been expected, in order to support the theory that each of the 5 executive components are unique, and thus distinguishable as independent, diverse functional systems. This would also provide confirmation that the chosen indicator variables were derived successfully; that each indicator was specific to a given component of INTERACT. Therefore, it only became apparent after reviewing these results that the initial statistical hypothesis of the current study did not correspond well with the theory underlying it. On this basis, post-hoc analyses were performed.

Testing the Structural Model of INTERACT, and Post-Hoc Analyses

Rather than covariance estimates, it was subsequently hypothesized that *interactions* between latent components would be more akin to the ‘directional’ or ‘causal’ (one-way) pathways connecting latent components in a typical path analysis (see Klem, 1995). These pathways represent the *influence* of one component on another, versus simply a non-directional association (overlap) between components. However, there were two difficulties associated with this new hypothesis. First, the structural model of INTERACT was too complex; i.e., because INTERACT predicts that the interactions between each component of the model is significant, the structural model must include two reciprocal one-way arrows between every component (i.e. bi-directional influences). This increased the number of parameters to be estimated by 10 (given 10 covariance estimates). As a result, the structural model based on the predictions posited by

INTERACT was saturated (full), as well as non-recursive due to the reciprocal influences between components. As a result, testing the structural (path) model for INTERACT was unsuccessful. The model was heavily under-identified and required many additional parameters constraints that were not available with the current data set. Essentially, there was not enough obtained data (“knowns”) to test such a complex model of interactions (“unknowns”). This is not surprising for a non-recursive model (see Klem, 1995). As a consequence, it was also not possible to examine whether a plausible, alternative, *hierarchical* relationship between the components of INTERACT was a better fit for the data than the saturated model.

Despite this limitation, a second difficulty in relation to estimating interactions was theoretical. In particular, INTERACT conceptualizes the ‘unitary’ nature of executive functions emerging as a result of interactions. However, this does not precisely suggest that such interactions are *always* necessary, or likewise that unitary executive function *always* emerges as a result of a given problem. For example, a ‘problem’ for the executive system to solve might only require the interaction of a few executive components (e.g., Attentional Control and Updating WM), but not others. It would be inefficient to always activate all 5 systems, especially for simpler problems in which a specific component might be unrelated to the problem at hand. A perfect illustration of this notion arises when a task is so specific that it theoretically only requires the contribution of one of these systems; as was the intention in deriving the indicators variables for the measurement model of INTERACT. Conversely, it is more likely that the interactions among several executive systems are important for more complex, ecologically-valid problems requiring executive function. To this end, the interactions

between component executive systems should be tested on a task requiring several executive systems. Similar to the statistical analysis performed by Miyake and colleagues (2000), this type of analysis would allow a researcher to examine the relative contribution of separable executive components (derived from an initial confirmatory factor analysis) toward a complex task of executive functions. However, unlike Miyake the prediction of performance on this theoretically more complex executive task should not be based on specific executive components per se, but rather based on their interaction (product) terms (see Kline, 2005).

Unfortunately, this foresight was missing when this study was designed, and therefore no tasks were included on the basis of being complex tasks of executive function. Fortunately, two such *tasks* were included in the current study, despite the fact that the *indicator variables derived from them* were specific to only one component of INTERACT. In particular, the Matrices task has seldom been considered a simple test of executive functioning; most often it is regarded as a measure of visual-spatial reasoning and problem-solving, or more generally ‘fluid intelligence’ (see Wiley, Jarosz, Cushen, & Colflesh, 2011). As such, it is likely that several executive systems are recruited in order to successfully solve each of its puzzles. Likewise due to its complex nature, it has also been speculated that several executive systems contribute to performance on the Tower task (see Miyake, et al., 2000). As such, two separate path analyses were examined. For both of these analyses, the exogenous variables were all possible product (interaction) terms between the factor scores derived from the original INTERACT measurement model, in addition to the factor scores (main effects). Factor scores were calculated in a standardized fashion for each individual on each of the five INTERACT components

Specifically, a given participant's factor scores were estimated by calculating that participant's standard score on each indicator variable, multiplying these scores by their associated factor weights (obtained from the factor score coefficient matrix), and then summing these products (Wahlin, MacDonald, deFrias, Nilsson, & Dixon, 2006). Factor scores were 'centered' prior to creating the product terms (a linear transformation that results in means of zero for all factors); this commonly reduces multicollinearity among interaction terms, and makes interpretation of regression coefficients more meaningful (Cohen, Cohen, West, & Aiken, 2003). Factor scores, rather than latent factors, were used in the path analysis because path analysis requires that all variables be observed. Therefore, this analysis examined a) whether the addition of interaction terms in general to the main effects (factor scores) increased the variance explained in performance on either of these two complex tasks, and b) if the independent effects of any of the interaction terms significantly influenced performance. Incremental variance explained by the interaction terms beyond main effects was assessed by calculating an R^2 change statistic. Covariances were allowed between all exogenous factors.

The results of this novel analysis should be interpreted with caution given its post-hoc nature; however, these preliminary findings appear quite promising. For the Matrices task, the variable that was used to indicate complex EF performance was average reaction time on the first block of the task, in which participants had not yet been informed of the 'rules' of the matrices. Using factor scores for each latent component (derived from the measurement model) and all possible 2-, 3-, and 4-way interaction (product) terms, a path analysis was performed. Indices of model fit ranged from good to excellent ($\chi^2 = 19.04$, $df=11$, $p = .060$, $\chi^2/df = 1.731$, CFI = .996, RMSEA = .058). More importantly, when the

variance explained by this model ($R^2 = .194$) was compared against that of the main effects model (which included no interaction terms; $R^2 = .004$) it was clear that there was substantial additional variance explained by the interaction terms over and above the factor scores (R^2 change = .19). Of particular note, several of the independent effects for these interaction terms were significant (see Figure 15 below).

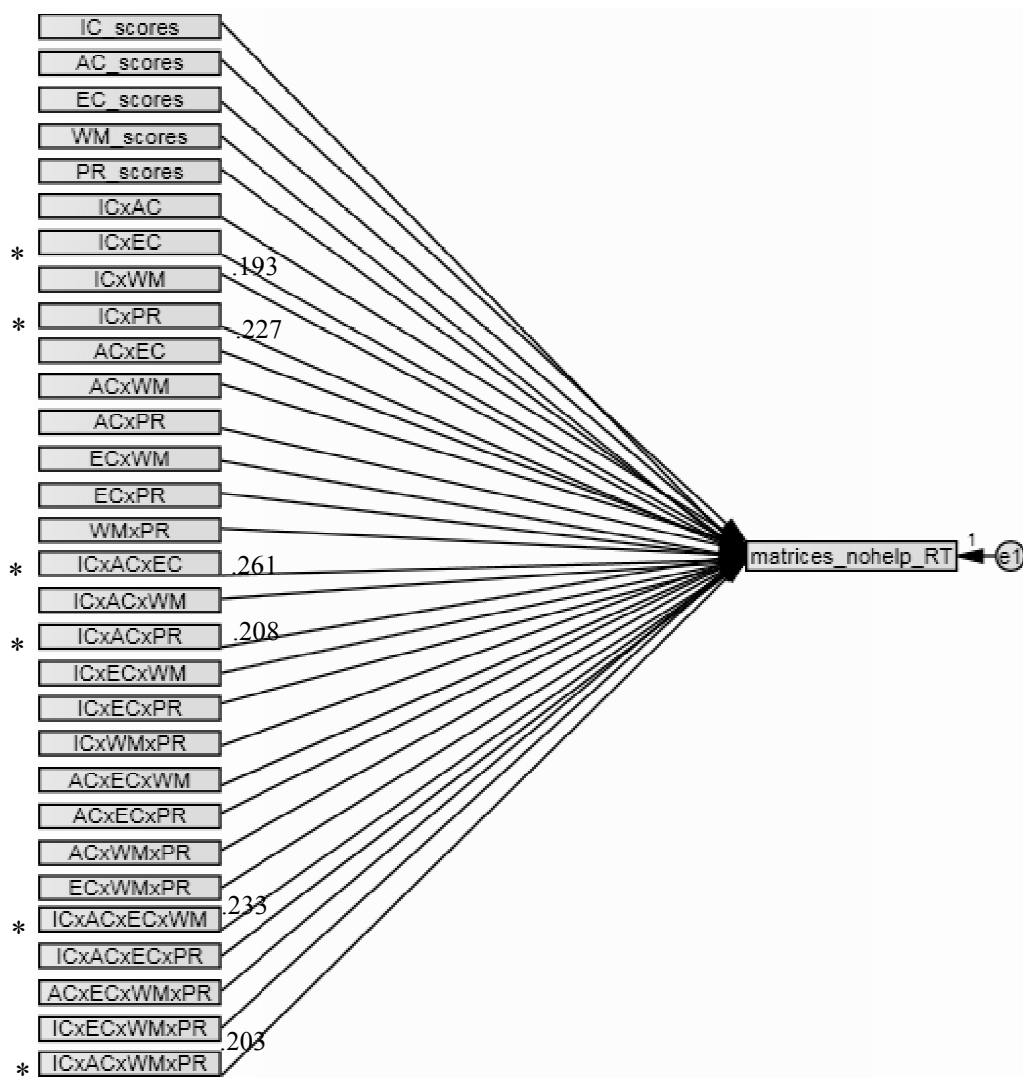


Figure 15. Path analysis model explaining performance on the ‘no help’ task block of the Matrices task, via main effects and interaction effects of the factor scores derived from the measurement model of INTERACT. Significant ($p < .05$) standardized regression weights are labeled, and are denoted by an asterisk appearing to the left of the corresponding exogenous factor.

For the Tower task, the variable that was used to indicate complex EF performance was average reaction time on the second block of the task, in which participants were not asked to plan their moves before moving the discs. Again using factor scores for each latent component in addition to all possible 2-, 3-, and 4-way interaction terms, a path analysis was performed. Once again, indices of model fit ranged from good to excellent ($\chi^2 = 19.28$, $df=11$, $p = .056$, $\chi^2/df = 1.753$, CFI = .996, RMSEA = .059). More importantly, there was substantial additional variance explained by the interaction terms over and above the factor scores (R^2 for main effects = .006; R^2 including interaction terms = .127; R^2 change = .121). Again, several of the independent effects for these interaction terms were significant (see Figure 16 below). Of note, there was also 1 regression weight that approached significance (ECxWM, $p = .057$).

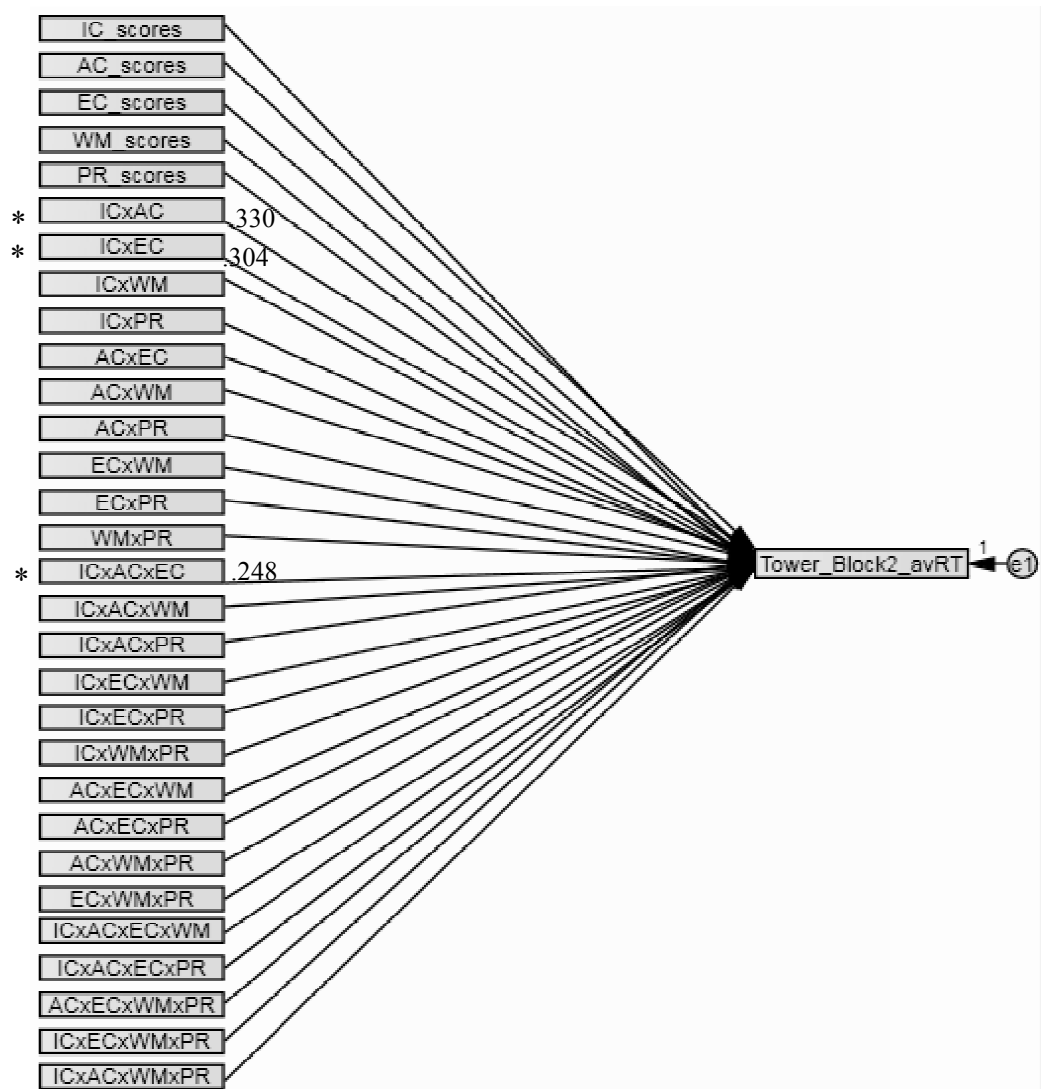


Figure 16. Path analysis model explaining performance on the second task block of the Tower task, via main effects and interaction effects of the factor scores derived from the measurement model of INTERACT. Significant ($p < .05$) standardized regression weights are labeled, and are denoted by an asterisk appearing to the left of the corresponding exogenous factor.

Given that components of both the Matrices and Tower tasks were originally conceptualized as assessing PR, a second path analysis was run for both tasks; whereby the PR factor score and all interaction terms including the PR factor score (e.g., ICxPR) were eliminated from the model. The results of these analyses revealed that the inclusion of PR factor scores and their corresponding interaction terms did not significantly change

the results of the path analyses. This therefore suggests that the significant level of variance explained by the interaction terms was not merely due to including PR in these models.

Discussion

Although the full complexities of INTERACT could not be tested, this study has provided support for several of its predictions. First, confirmatory factor analytic methods supported its five-factor structure. Overall, INTERACT met criteria for excellent model fit; including absolute and incremental estimates of model fit, as well as indices reflecting model parsimony. Unfortunately, it is difficult to compare these results to previous studies for three, notable reasons. First, as noted previously, the literature has not yet provided a *comprehensive* model of EF; incorporating current evidence across multiple domains (e.g., behavioural, neuropsychological, biological, etc.), and accounting for the multitude of phenomena associated with EF (e.g., including both its diverse and unitary nature). Second, many of the indicator measures used in the current study were novel, or were derived in novel ways from pre-existing tasks. Previous studies testing the factorial structure of EFs have continued to use the same classic measures that have been employed as ‘frontal’ tasks for decades (e.g., the Trail Making Test, Wisconsin Card Sort Task, Stroop, etc.; see Table 3 in Royall et al., 2002). However, these tasks are too complex. The cognitive processes tapped by these tasks extend beyond the realm of EF, involve too many functional systems, and a consensus is lacking as to which specific processes or systems are in fact being captured by the resulting data. As a consequence, a third obstacle in supporting INTERACT’s construct validity was that most historical studies (aside from Miyake, et al., 2000) have been forced to take strictly exploratory

approaches, inherently plagued by disadvantages relative to confirmatory approaches. Even Miyake and colleagues, using a confirmatory approach, chose to limit their exploration of EFs to three functions (shifting, updating, and inhibition) specifically because these functions could be operationally defined more precisely than other postulated EFs, and because of the availability of simple cognitive tasks that were presumed capable of tapping them; despite suggesting that these EFs were “certainly not exhaustive and there are other important relatively basic functions that need to be added...” (p. 90). Therefore, the inability to provide evidence of convergent validity from the extant literature arises as a function of the novelty associated with INTERACT and the specific indicators chosen to reflect its latent components, as well as the rarity of the methods utilized to test its predictions. Nonetheless, the results obtained by this study provide initial support for the validity of INTERACT, due of the theoretical strengths of these unique characteristics.

Despite excellent overall model fit, the standardized regression weights associated with the final indicator variables were only modest overall (ranging from .26 to .61). This finding limits the extent to which it can be said that the latent constructs were in fact valid. However, although not ideal, these estimates are relatively consistent with previous studies (e.g., Miyake, et al., 2000). For example, using several similar tasks to indicate ‘Shifting’, ‘Updating’, and ‘Inhibition’ (e.g., local-global, letter memory, stop signal), Miyake and colleagues obtained standardized regression weights ranging from .33 to .63. This consistency likely supports a competing possibility (versus questionable construct validity *per se*); that the constructs were simply measured imperfectly by their chosen indicators. In the current study, it is arguable that this was particularly the case for the

two most novel components of INTERACT, coinciding with especially novel indicators. Specifically, the regressions weights associated with the Emotional Control and Problem Representation indicators were weaker than those associated with the other components. This is perhaps not surprising, again, given that it would be miraculous to create perfect measures of newly-defined constructs on the first try. Nevertheless, these results suggest that either the constructs or the measures used to indicate them were relatively unreliable. However, deciphering the credence of either explanation cannot be addressed without future studies.

Assuming the explanation of somewhat unreliable indicators, there is a plethora of evidence in the literature that suggests that an EC component should exist, and be differentiated from other executive systems. From a biological perspective, purported differences in Emotional Control (assessed by parent reports on the Behavioral Rating Inventory of Executive Functioning) have been associated with *structural* anatomical differences in the amygdala (e.g, Blanton, Chaplin, et al., 2010). Other authors have suggested that the junction of the ventrolateral prefrontal cortex (VLPFC) and the DLPFC may play a crucial role in connecting cognition and emotional processing (see Petrides & Pandya, 2002). For example, increased activation in the VLPFC has been found during emotional induction blocks during tasks of behavioural inhibition (Lamm & Lewis, 2010). Likewise, Emotional Control has been linked with dopamine signalling (Salgado-Pineda, Delaveau, Blin, & Nieoullon, 2005), and the genes underlying dopamine (D2) receptors (Blasi, G., L. Lo Bianco, et al., 2009). Despite the difficulties associated with measuring Emotional Control directly, it has often been inferred based on its impact on other processes. From a cognitive perspective, the impact of Emotional

Control has been examined using a number of different paradigms. For example, in addition to the tasks chosen for the current study, it has been demonstrated that the cognitive control over memory (using a ‘think/no-think’ task) depends on whether information contains negative emotional content (Depue, Banich, & Curran, 2006). Other studies have found an ‘affective Simon effect’ – i.e. faster reaction times when the emotional valence of a stimulus is congruent with the valence of the movement (Eder, 2011). Further, studies examining the process of ‘task-set reconfiguration’ have shown a detrimental impact of fearful faces. From a general behavioural perspective, previous research has shown impulsive emotional behaviours can be strategically overridden via intentions (Eder, Rothermund, & Proctor, 2010). In a related fashion, studies have found a significant relationship between effortful suppression of negative emotion and stress-induced cardiovascular activity (Quartana & Burns, 2010); and between emotional dissonance (perceived discrepancy between felt and expressed emotions) and burnout symptoms, which is moderated by cognitive control deficits (Diestel & Schmidt, 2011). From a clinical perspective, emotional dysregulation has been linked to anxiety disorders (e.g., Kindt, Bierman, & Brosschot, 1997), borderline personality disorder (e.g., Sprague & Verona, 2010; Wingenfeld et al., 2009), and symptoms of depression (e.g., Protopopescu et al., 2008). Finally, research has suggested that the control of emotions increases with age (see McConatha, Leone, & Armstrong, 1997).

Likewise, evidence also suggests that the Problem Representation component should be retained. Although there are clearly difficulties associated with measuring this component, these difficulties are likely a consequence of two specific factors. First, a diversity of similar, complex processes previously discussed in the literature are more

than likely related to each other. However, these constructs rarely fall under a distinct EF category, and have failed to be explained by any specific mechanisms; perhaps leading authors to miss commonalities among them. Examples of such processes include ‘problem-solving’ (e.g., Denney, et al., 1981), ‘reasoning’ (e.g., Miller, Fichtenberg, et al., 2010), ‘decision making’ (e.g., Muri & Nyffeler, 2008), ‘multitasking’ (e.g., Burgess, 2000), ‘organization’ (Seidman et al., 1995), and ‘symbolic cognition’ (e.g., Stocco & Anderson, 2008), among others. Together, these processes might collectively be correlated via the basic properties of the Problem Representation component of INTERACT. However, these basic properties are quite specific in comparison to the relative non-specificity of most measures of EF (i.e. the task impurity problem), including those tasks noted above. For example, the need to identify goals, create a plan, and initiate a response should be inherent in any task of EF that involves a novel problem that needs to be solved. However, this does not mean that it is easy to isolate these specific processes from performance on these tasks. This is illustrated by the finding that a large network of prefrontal (and other) regions is engaged by complex tasks (Cole & Schneider, 2007). Similarly, Duncan and Owen (2000) reviewed a host of imaging studies examining a broad array of EF tasks, and found that a few frontal regions (i.e. the DLPFC, VLPFC, and ACC) were jointly recruited for *all of the tasks* examined. These authors concluded that this specific network of regions is consistently responsible for solving a diverse array of cognitive problems. Nonetheless, the literature also provides evidence that one of these regions in particular, namely the DLPFC, is almost always activated during these types of tasks (e.g., Heekeren, Marrett, Ruff, Bandettini, & Ungerleider, 2006; Krueger, Landgraf, van der Meer, Deshpande, & Hu, 2010; Muri &

Nyffeler, 2008; Polk, Simen, Lewis, & Freedman, 2002; Torriero, Oliveri, Koch, Caltagirone, & Petrosini, 2007). Furthermore, the specific processes of goal identification, planning, and initiation of responses, comprising the precise role of Problem Representation as per INTERACT; all seem to be related to the DLPFC as well. For example, the DLPFC has been linked with goal activation (e.g., Jamadar, Hughes, Fulham, Michie, & Karayanidis, 2010; Polk, et al., 2002), and extensively with planning (Burgess, Veitch, de Lacy Costello, & Shallice, 2000; Cazalis et al., 2006; Kaller, Rahm, Spreer, Weiller, & Unterrainer, 2011; Newman, Carpenter, Varma, & Just, 2003). Other studies have suggested that “the most likely single cognitive function of the DLPFC is to specify a set of responses suitable for a given task and to bias these for selection (sculpting the response space)” (Nathaniel-James & Frith, 2002, p. 1094). This hints at the process of planning, but also suggests that such planning inevitably leads to the implementation or initiation of a response on the basis of this planning. Thus, the precise processes posited to be involved in Problem Representation are unified by the activation of common neural substrate. In addition, the Problem Representation component provides a parsimonious account of common processes involved in all complex tasks of EF. Therefore, the Problem Representation component is theoretically vital to any comprehensive model of EFs, and provides a relatively distinct description for a previously vague set of processes.

In addition to evidence from the literature that Emotional Control and Problem Representation are specific and valuable EF components, the current study also provided evidence that the indicators of Emotional Control and Problem Representation were specific to these components. First, the covariance estimates among the latent

components were minimal and non-significant for the most part. This is inconsistent with previous research (e.g., Miyake, et al., 2000), and could potentially suggest, again, that the construct validity of the INTERACT components is imperfect, or that the indicators were unreliable. However, as discussed in relation to the post-hoc analyses performed here, this divergence from previous research might rather indicate an improvement with respect to the specificity of the indicators employed in the current study. For example, in spite of weak regression weights for Emotional Control and Problem Representation, likely secondary to the novelty of these components, the indicators of these components shared little common variance with indicators of other components. This finding perhaps endorses the prevailing view that EF should exemplify a diversity of functions (i.e. *not* overlap). Likewise, INTERACT fit the data significantly better in comparison to several plausible, alternative-factor models (including alternative model in which Emotional Control and Problem Representation were combined with other components). Relatively speaking, this suggests that the 5-factor structure of INTERACT was best; and subsequently, that the indicators of Emotional Control and Problem Representation should not have been combined with other components. Therefore, the indicators were likely imperfect, and thus led to imperfect regression weights; however, the data also suggest that these imperfect indicators were independent from indicators of other components nonetheless. This lends further support for INTERACT, and bolsters the notion that all five components of INTERACT are necessary, and represent distinguishable, diverse functions.

On the other hand, an exception was found to the observations noted above. In particular, there was an unexpected, significant relationship between Attentional Control

and Emotional Control. This finding may simply be an artefact of less-than-perfect indicators of Emotional Control, given that a significant body of literature distinguishes Attentional Control and Emotional Control as separate systems. However, there is some evidence that supports the validity of this association. First, from a logical perspective, Attentional Control should be crucial for successful EC because it is necessary to attend to information (including emotional information) in order to regulate behaviour on the basis of such information. Some authors have actually suggested that Emotional Control may regulate behaviour *by way of* Attentional Control (Posner & Rothbart, 2007). For example, Peers and Lawrence (2009) found that participants with poor attentional control demonstrated a more pronounced distractor effect for emotional versus neutral distractors. Evidence also suggests that these two systems may share common neural substrate. For example, Pessoa, Kastner, and colleagues (2002) found that emotional faces elicited activation in many brain regions but only when sufficient attentional resources were available to process the faces. In addition, it has been shown that the cortical regions commonly associated with each of these systems are highly interrelated. For instance, Clauss, Cowan, and colleagues (2011) found that individuals with 'inhibited temperaments' displayed greater functional activation in the amygdala, but less activation in the dorsal ACC (*dACC*, more typically associated with the Attentional Control network). Likewise, Sehlmeier, Dannlowski, and colleagues (2011) showed that anxious individuals exhibited sustained amygdala activation and again, reduced *dACC* involvement during extinction of a conditioned response. Electrophysiological studies using ERP evidence have shown that processing task-irrelevant emotional information may compromise attention performance (Dennis & Chen, 2007). Finally, studies

investigating clinical populations have shown that patients' attention must be fully directed towards emotional content during exposure therapy, in order for positive emotional changes to occur, via "prefrontal control over the amygdala" (De Raedt, 2006p. 230). Fales, Barch, and colleagues (2008) demonstrated that patients with depression had enhanced amygdala activation to unattended *fear-related* stimuli (relative to unattended neutral stimuli). Similarly, other authors have shown that even remitted depressed patients can display *attentional biases* toward negative emotional information (Kerestes et al., 2011). Finally, it has been shown that the combination of high anxiety and poor attention control predicts greater processing of emotional information (Reinholdt-Dunne, Mogg, & Bradley, 2009).

However, the previous examples illustrate a difficulty in interpreting the results of these types of studies. For example, can poor attentional control alone account for these findings (i.e. regardless of emotional versus neutral content)? In addition, does the recruitment of the ACC on tasks involving emotion necessarily suggest that Attentional Control is active, especially given that previous studies have shown that functional networks consist of many small, widely distributed components (Pucak, Levitt, Lund, & Lewis, 1996)? Irrespective of the answers to these questions, it appears that it can sometimes be difficult to disentangle the unique roles of Emotional Control and Attentional Control in these contexts. Although many studies have depicted an association between Emotional Control and Attentional Control, very little evidence suggests that significant *overlap* exists between these two components. Rather, the literature seems to suggest that these systems *influence* each other. Therefore, just as an association between these components is expected by INTERACT, via interactions; these

interactions represent directional influence between independent components. Once again, the shared variance found between Emotional Control and Attentional Control is likely due to non-perfect indicators for Emotional Control. However, it is possible that Emotional Control and Attentional Control are more interrelated than has been postulated or discovered thus far in the literature. As a result, future studies should explore the stability of this association, as no alternative model was tested in the current analysis in which these two components were combined.

Unfortunately, due to statistical limitations consequent to the complex interactions among its components, INTERACT's *structure* could not be definitively tested. Specifically, no support was gained for the theory that each of the five components of INTERACT exerts a reciprocal, causal influence on all other component systems. This will require a creative solution given currently available statistical techniques. For example, it may be possible to use a Bayesian approach in future studies, as the implementation of this type of analysis has been supported for structural equation models with non-linear effects and non-recursive influences between latent factors (Li & Wang, 2010). It was also unfortunate that the structural model of INTERACT could not be tested against a plausible, *hierarchical* structure via path analysis techniques. This analysis could have provided novel insights into the relationships between those neural networks thought to underlie each of the five executive components, during tasks of executive function.

However, a feasible alternative for future exploration was offered. On the basis of past insight (i.e. Miyake et al., 2000), a novel method was introduced to capture the uniqueness of INTERACT's predictions, which revealed the value and significance of

examining interactions to explain performance on complex tasks of EF. Specifically, interactions involving all five components of INTERACT predicted performance on the Matrices task. Similarly, several interactions among Inhibitory Control, Attentional Control, and Emotional Control were significantly explanatory in terms of predicting performance on the Tower task. No specific hypotheses were formulated prior to conducting this analysis, regarding which interaction terms might theoretically explain variance on either of these complex EF tasks. Although previous studies have examined the contribution of specific EF constructs (e.g., Inhibitory Control) to complex EF task performance (e.g., Miyake, et al., 2000), no previous research has examined the explanatory power of interaction terms on such tasks. Consequently, there was no strong theoretical basis for explaining why unique interaction terms predicted the two tasks utilized for these analyses. However, these results make intuitive sense in terms of how we conceptualize performance on these complex tasks, thus supporting the face validity of this analysis. In addition, and perhaps more importantly, these findings support the proposition that a unitary flavour of EF emerges as a result of these interactions. In brief, this method revealed preliminary, yet supporting evidence for INTERACT using two different complex tasks of EF, and should be utilized again. Future studies should address the relative contribution of these interactions toward performance on other complex measures of EF as well.

Potentially, these findings also suggest that executive control is in fact *efficient*, evidenced by the mere fact that not every factor or its interaction terms significantly predicted performance on these complex EF tasks. That is, to be efficient, components should only be recruited (and interact) when necessary, given the demands of a particular

‘problem’. This hypothesis has certainly been addressed in the literature. For example, many authors discuss cognitive processing efficiency (e.g., Dennis & Chen, 2007). Some authors have suggested that reaction times alone can be used to quantify processing efficiency (i.e. assuming accurate performance, faster is better; e.g., Fan, et al., 2002). Other authors have suggested that efficiency relates to the functional connectivity among neural systems (e.g., Kamijo, Takeda, et al., 2011; Liston, Watts, et al., 2006). However, even if greater functional connectivity is apparent, it is still logical to assume that activating five functional systems would be less efficient than two systems, for example. In line with this suggestion, the processing-efficiency hypothesis (Eysenck & Calvo, 1992; Eysenck, Derakshan, Santos, & Calvo, 2007), predicts that anxious individuals require greater activation of brain systems (e.g., DLPFC) in pursuit of cognitive control, to perform at par with non-anxious subjects. Similarly, several other clinical populations have been examined for efficient recruitment of neural systems. For example, Fama, Pfefferbaum, and colleagues (2004) found that alcoholics recruited more demanding and thus less efficient cognitive systems than those demonstrated by controls on a basic task of perceptual learning. Likewise, average intelligence (versus higher intelligence) has been associated with greater PFC activation during tasks requiring response selection, despite comparable performance (Graham, Jiang, et al., 2010). Skilled (versus less-skilled) readers have demonstrated greater neural efficiency by activating the right hemisphere on language tasks on an “as needed basis” (Prat, Mason, et al., 2011). Patients with diffuse axonal injury have shown greater recruitment of PFC regions to accomplish task performance equivalent to controls (Turner & Levine, 2008). Finally, schizophrenia has been associated with excessive recruitment of cortical systems during

logical reasoning tasks (Ramsey, Koning, et al., 2002). Therefore, in light of the proposed evidence of neural efficiency in executive systems from the current study (i.e. that only *some* interactions are necessary to explain performance on a given complex EF task), it may be particularly informative to test the *structural* validity of INTERACT in future studies. For this same reason, it would be especially important to compare INTERACT's structure against *hierarchal* arrangements of the components. For example, Braver, Gray, and Burgess (2007) have suggested that reduced cognitive efficiency might result on the basis of changes in DLPFC recruitment; which is congruent with placing PR at the top of the hierarchy (as per the alternative structural model proposed in this study). Thus, efficiency might depend on the initial stages of goal identification, the creation of an adequate plan, and the successful and expedient initiation of a viable response.

Limitations

In spite of the evidence that has been put forth on behalf of INTERACT, several limitations should be addressed. This is not surprising, given that equivocal evidence from the extant literature (e.g., Alvarez, & Emory, 2006), based on the many limitations associated with studying executive functions, was precisely the motivation for the current study. First and foremost, more research is needed to fully support the construct validity of INTERACT's components, given that only modest regression loadings were found for some of the indicator variables in this study. Conversely, but perhaps more likely, this finding might suggest that the reliability of some of the indicators was imperfect. As noted previously, this was expected, to a degree, for novel measures of relatively novel constructs. Unlike other studies in which the construct validity of a measure can be ascertained by comparing performance to a previously-validated measure of the same

construct (e.g., Schiavetti & Metz, 2006), or by testing performance in a population with a known deficit related to the construct (e.g., Anderson, V. A., P. Anderson, et al., 2002); these executive measures of Emotional Control and Problem Representation have never been previously used, nor have these definitions been applied to clinical samples. As a result, no comparisons with other measures are possible (i.e. concurrent validity cannot be established), and there is no available information regarding how populations with specific EF deficits should perform on these tasks. In short, novel results are expected for novel measures. Similarly, several studies assessing the construct validity of novel measures within the domain of EF have struggled to find definitive support (e.g., Leeds, Meara, et al., 2001). Nevertheless, future studies might also address this issue by examining intra-individual variability on these tasks, and across the components of INTERACT. This variability could be inherently due to the limited reliability of the tasks themselves, or might rather reflect normal variability in performance for healthy individuals across multiple EF tasks. As discussed previously, EF tasks often involve novelty, and novel problems typically require novel responses. Given that the current task battery involved 15 different EF tasks, each involving a novel problem ‘to-be-solved’; one might argue that only highly efficient and ‘non-fatiguing’ EF systems would be capable of exhibiting perfectly consistent performance across such a battery of tasks. Stated differently, perhaps any relatively lengthy battery of EF tasks, in which all of the tasks are found to be perfectly reliable, may not be an ecologically-valid reflection of EF performance *per se*. For this reason, intra-individual variability is likely an important avenue to explore in the domain of EF.

Next, results from the screener questionnaire suggest that several unique population characteristics were included in the sample (e.g., ADHD). For the most part, it was hypothesized that the omission of exclusion criteria for the sample would provide the most ecologically-valid 'normal' sample. Provided that the proportion of these characteristics in the sample echoed average prevalence estimates for the population, it was assumed that including unique population characteristics should represent richer variance in EF performance. Nonetheless, it is possible to speculate that there might have been an impact of including such diversity. First, it is noteworthy that the relative proportion of clinical diagnoses endorsed by participants largely reflected what is to be expected in the normal population. For example, participants reporting a history of depression or anxiety comprised approximately 8% of the current sample, compared to approximately 5-12% in the normal population (Public Health Agency of Canada, 2006; Offord, Boyle, Campbell, Goering, Lin, Wong, et al., 1996). A diagnosis of ADHD was reported in roughly 2% of our sample, versus approximately 4% in the normal population for adults between 18-44 years of age (e.g., Kessler et al., 2006). In addition, the proportion of participants in the current sample with a history of learning disorders (1.4%), learning assistance (5.5%), and speech/language difficulties (1%) was relatively low. However, there were a few other demographic characteristics worth noting, which have been associated with EF deficits in the literature, and thus might be worth further investigation in future studies. For example, the literature suggests that alcohol consumption has profound effects on the PFC (Abernathy, Chandler, & Woodward, 2010). Many studies have reported negative long-term effects of chronic alcohol abuse on EF (see George, Rogers, & Duka, 2005), but even modest doses of alcohol have been

shown to negatively impact EF (e.g., Montgomery, Ashmore, & Jansari, 2011). Similarly, a history of multiple concussions has been associated with possible EF deficits (see Belanger, Spiegel, & Vanderploeg, 2010). Conversely, bilingualism has demonstrated an advantage in terms of EF performance (Bialystok, 2010; Bialystok & Viswanathan, 2009; Carlson & Meltzoff, 2008). Again given the novelty of the current study, it is uncertain as to what impact, if any, these diverse sample characteristics might have had on the results. Although the five components of INTERACT might be reliable across all mature adults, it is possible that healthy EF systems are distinct from those that develop in the aforementioned populations. As such, it would be interesting to examine model invariance in future studies, comparing normal control samples with specific populations associated with unique EF strengths and weaknesses.

Although the novel post-hoc analysis of the derived interaction terms was seemingly successful, one potentially concerning issue was not addressed previously. That is, main effects were not found any of the factor scores, on either task. Minimally, it was expected that PR factor scores would predict performance on these two complex task variables, given that indicators of PR were derived from these tasks. However, it is important to note that the indicators variables derived from these tasks were quite distinct (i.e. more specific, theoretically, to the PR component), in comparison to the complex variables that were used for the post-hoc analyses. As such, it is not entirely surprising that PR main effects were not found. In fact, this may provide further support for the theoretical hypothesis that the interactions among components capture a unique aspect of EF performance, which cannot be explained by way of any particular component alone, or via a summation of individual components. Nonetheless, especially in light of the

relative novelty of this analysis, future studies should examine the reliability of this finding.

Finally, it is debateable as to whether the non-normality of the current data (albeit minimal) biased the parameter estimates obtained. Without revisiting this debate in its entirety; the literature has yet to provide a succinct, “one-size-fits-all” procedure for handling non-normality, especially in light of missing data. As a result, the tools available to researchers for dealing with these issues are limited, and somewhat subjective.

Nonetheless, given the extent to which measures were taken in the current study to examine and account for non-normality as best as possible given the available literature, there is little reason to believe that it was not dealt with most diligently. Further, this thoroughness has certainly not been exemplified by the majority of studies reporting SEM results (see Schreiber, Nora, Stage, Barlow, & King, 2006). Finally deviations from normality were minimal for the current data set. Therefore, by treating non-normality conservatively, it is likely that the need to make adjustments for non-normality was well-balanced by the need to preserve normal and important variance in participants’ performance. As a final note, even if non-normality was more serious than the results revealed, model fit would have been even more ideal, as an *inflated* chi-squared is the most commonly-reported repercussion of non-normality in the literature.

Implications

In summary, it was hypothesized that the current study would provide evidence that would help to clarify the ongoing *conceptual* debate regarding EFs. To this end, the results of this study supported many of the theoretical underpinnings of INTERACT, and provided initial evidence that it is a viable model of EF. Importantly, the current results

appear to suggest that INTERACT accounts for the dual nature of EF – i.e. its diversity of distinguishable functions *and* its unitary nature when appropriate (and efficient).

Although modest, the results of the current study might also suggest that we have moved one step closer toward resolving the *measurement* debate. Specifically, it became evident during the course of the analyses of this model, that a successful new method for capturing EF was potentially born. Further, given the novelty of the model and the nature of SEM, novel and precise indicators of each component of INTERACT were necessary. Collectively, the results of this study provided some evidence for the validity of the battery of EF tasks that was selectively created for these analyses, with the aim of minimizing task impurity. This battery was relatively successful in terms of differentiating between distinct EF systems; although work still needs to be done to perfect the indicators of Emotional Control and Problem Representation - the most novel components of INTERACT.

In addition to these findings, the questions left *unanswered* by the current study have nonetheless paved the way for future enquiry. Notably, valuable avenues for future research should involve testing the *structural* validity of INTERACT; particularly in comparison to alternative, hierarchical arrangements of INTERACTS' components. These alternative arrangements may or may not prove to be more *efficient* in pursuit of overall executive control; but, as it was argued here, efficiency should be an integral element of any model of EF. In addition, future studies should examine a greater number of complex executive tasks, to test the reliability of INTERACT and the methods used to explore the importance of interactions among its components. This will also allow for a

better understanding of those tasks that have traditionally been used to represent EF in research, and in clinical applications.

For example, traditional tasks of EF used for the purpose of neuropsychological assessment have previously been criticized for lacking ecological validity (e.g., Burgess, Alderman et al. 1998). A better understanding of the underlying processes contributing to performance on these traditional measures would not necessarily improve their ecological validity. However, it would allow clinicians to convey, more precisely than previously possible, those cognitive processes contributing to impaired or improved performance, and the functional systems underlying such processes. For example, given a client presenting with diffuse axonal injury resulting from a head trauma; it would be typical to test the integrity of their executive functioning abilities in the aftermath. On one hand, the use of traditional tasks could lead to the interpretation that the client ‘perseverated’ on the Wisconsin Card Sorting Task (when he or she should have figured out that they needed to switch how they were sorting the cards), and this likely indicates that either their ‘switching’ ability, or their ‘inhibition’ was impaired. However, the specificity of these interpretations of performance is limited by the tasks used to obtain such results, and by the current availability of theoretical descriptions of EFs. Therefore, given a precise and (relatively) comprehensive model of EFs, and tasks reliably reflecting this precision, it might be possible to provide more informative interpretations to other clinicians, or more importantly the client’s family. For example, atypically reduced significance of the interaction among IC and updating WM on a given complex task of EFs (theoretically established with a normal sample) could perhaps suggest damage to the white matter tracts specifically connecting the DLPFC and the orbitofrontal cortex. As a consequence,

this could impact the efficiency with which these systems now communicate (interact); for example, leading to an inability to hold in mind the rules for when it is necessary to inhibit one's behaviours (practically leading to impulsive social behaviours). Despite the theoretical nature of this example, in short it is much more difficult to explain what neuropsychological results mean, when there is no consensus in the literature. Without a valid model of EF s, descriptions of performance on executive tasks rely on literal interpretations of performance, versus theoretical foundations.

Furthermore, INTERACT might provide very useful information for other clinical purposes. For instance, it would be informative to decipher whether the typical development of functional EF systems follows an aberrant trajectory in populations with known EF deficits, and thus leads to a distinct factorial structure in terms of the EF components comprising INTERACT. For example, for disorders considered 'developmental' in nature (e.g., ADHD), do EF systems perhaps develop in a fundamentally different fashion compared to normal controls, leading to more or less 'fractionated' EF systems? On the other hand, perhaps such populations merely portray normal variance (yet identical structure) in relation to the abilities underlying the five components of INTERACT.

Given the integrative nature of INTERACT; it could also be useful in bridging the gap between experimental and clinical domains of scientific inquiry. If future validation studies support the reliability of INTERACT, these domains might finally have a common means of communicating results, via common constructs. This would enhance the ability to inform clinical practice by way of experimental research, and vice versa; potentially providing an important link between seemingly disparate avenues of research

(e.g. EEG studies and clinical interventions). For example, it would be revolutionary to link evidence that suggests that inadequate functioning of the *dACC* might be responsible for a reduced “No-Go P300” ERP component in ADHD samples (e.g., Fallgatter, et al., 2004; Liotti, et al., 2005), with an applied cognitive intervention on this basis. Although this link is not yet established, and seems a lofty goal, common constructs to both of these realms is a necessary first step in creating such a bridge. In brief, it has thus far been an impossibility to ‘translate’ information across these disciplines without common terms, and more importantly without a common model.

For the future, it is essential to test INTERACT in novel ways in order to deepen our understanding of EFs, given the evidence that INTERACT appears to be a more comprehensive model of EF than others proposed before it. For example, computational modeling techniques could be utilized to discover the directional flow of neural activity among executive systems. In conjunction, the use of cutting edge experimental neuropsychological techniques (e.g., ERP, fMRI, DTI, MEG, etc.), would certainly enrich our understanding of EFs *if provided with a model from which to base predictions*. In addition to simply testing the structural validity of INTERACT, these methods could together provide useful insights regarding the *temporal* dynamics of executive systems. As a result, a better understanding of the functional interplay between the brain systems associated with the components of INTERACT would be gained. In turn, this would advance the exploration of INTERACT from a *cognitive/behavioural* level of analysis, to a biological level of analysis; which should be the next step in the development of a viable model of EFs, from a neuropsychological perspective.

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Appendix A: Screener Questionnaire

PARTICIPANT #:

****Please note that any information that you choose to voluntarily provide in this questionnaire will remain confidential.**

1. Age:
2. Gender: male female
3. Handedness: right left
4. Previous Diagnoses? (Please circle all that apply)
 - a. Attention-Deficit/Hyperactivity Disorder (ADHD/ADD)
 - b. Fetal Alcohol Spectrum Disorder (FASD)
 - c. Autism
 - d. Any Other Developmental Disorder (Mild Intellectual Impairment, etc).
 - a. Please specify:
 - e. Learning Disorder
 - a. If you answered 'Yes' to 3e, please specify which type of Learning Disorder:
 - f. Have you ever received learning assistance or extra accommodations at school?
 - a. If you answered 'Yes' to 3f, in which area(s) did you receive assistance (e.g., Math, Reading, Writing)?
 - g. Have you ever had any speech/language difficulties?
 - h. Any Neurological Conditions (e.g., Epilepsy)? Please specify:
 - i. Any Psychological Conditions (e.g., Depression, Anxiety, etc.) Please specify:
5. Have you ever been knocked unconscious/suffered a concussion? YES NO
 - a. If so, how many times?
6. Do you have normal hearing? YES NO
7. Do you have normal/corrected vision? YES NO
8. Are you currently taking any prescription medication? YES NO
 - a. If YES, which type of medication:
 - b. How often do you take it:
 - c. How much do you take each time:
9. Have you consumed any alcohol in the past 48 hours? YES NO
 - a. Please Specify approximately how much:
10. Have you consumed any non-prescription drugs in the past 48 hours? YES
NO
 - a. Please Specify approximately how much:
 - b. What was taken:

Appendix A: Screener Questionnaire (Continued)

11. Are you Bilingual? Yes / No
If yes, please respond to the questions below.

What is your native language? _____

Please list any other languages that you know below. For each, rate how well you can use the language on the following scale:

Not Good 1 2 3 4 5 Close to Native

Languages	Speaking	Understanding	Writing	Reading
L2				
L3				

For the languages you listed, please indicate below the age at which you learned them, and if applicable, whether you learned them by formal lessons (e.g., at school or a course), or by informal learning (e.g., at home, at work, from friends, living in another country/province).

Languages	Age	Lessons (Y/N)	Duration of lessons	Informal (Y/N)	Duration of Informal
L2			<1 year 1-5 years 6-12 years >12 years		<1 year 1-5 years 6-12 years >12 years
L3			<1 year 1-5 years 6-12 years >12 years		<1 year 1-5 years 6-12 years >12 years