The Integrative Neuropsychological Theory of Executive-Related Abilities and Component Transactions (INTERACT): Best Predictors of Performance Across the Adult Lifespan

by

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BA, York University, 2011

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Supervisory Committee

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Abstract

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Recent neuropsychological research has stressed the sensitivity of the Prefrontal Cortex, mostly the Dorsolateral region, in relation to aging (Darowski et al., 2008). Prefrontal Cortex functions, such as Inhibitory Control (IC), are thought to wane steadily after the ages of 60-65 (Craik & Bialystok, 2006). Little is known about what changes occur between the stages of prefrontal optimal performance (i.e., ages 20-25), and the later periods of functional decline. The present study aimed to investigate performance differences between younger (ages 30-40; n=9), middle-aged (ages 50-60; n=10), and older adults (ages 70 and up; n=13), on five tasks of Executive Functions (EFs); specifically, assessing the abilities of problem representation, shifting, updating working memory, inhibition, and integrating valence and rewards into pursuing a goal. It was hypothesized that (a) quantitative age trends differentiating the three groups on the tasks would be found, (b) IC would be particularly targeted by the hypothesized age trends, and (c) the devolution of IC across the adult lifespan would be linear. MANOVA tests with all tasks of EFs representing the Dependent Variables and age serving as the Independent Variable revealed no significant main effect. Follow-up separate ANOVA tests however, suggested a statistically significant difference between the means of Groups 2 and 3 for the Updating Working Memory task, $F(2,29)=5.374$, $p=.010$, Scheffe ($p=.012$) and Bonferroni ($p=.010$). The contributions of interactions among EFs to the present results, recruitment challenges, and potential age effects are discussed.

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Acknowledgments

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Dedication

This thesis is dedicated to my partner, Peter, my friends and family in Quebec City, and my new friends and family in Victoria, who have provided me with unconditional love and support to see this through to completion.

Introduction

Conceptual Overview of Executive Functions

'Executive Functions' (EFs) represents a relatively new term in neuropsychology. For more than a century however, there has been evidence for the idea of supervisory and 'higher-level' cognitive processes that organize, regulate, and control 'lower level' cognitive and behavioural abilities (Jackson, 1887). These functions were differentiated early on from those of automatic and crystallized nature, which are characterized by practice, repetition, and rehearsal strategies (Burgess, 1997; Shiffrin & Schneider, 1977). The term EFs arose relatively recently from the conceptual need to describe processes that allow for adaptive functioning in response to *change* and *novelty* (Alvarez & Emory, 2006). Also, as they involve a 'top-down' approach, EFs are considered to be capacity-limited 'control operations' (Shiffrin & Schneider, 1977), enabling "intentional processing and adaptive cognitive performance" (Craik & Bialystok, 2006, p.131). Importantly, by placing a greater emphasis on *current* goals or tasks at hand, EFs allow for complex cognition and behaviours *above and beyond* the restrictions of our 'default' abilities. The more efficient EFs are, the richer the learning experience resulting from their underlying course of action will be.

Luria's third functional unit: the executor. The label EFs is *theoretically* rather than operationally based (Burgess, 1997), and primarily originated from a pressing need to promote research and descriptions pertaining to frontal 'higher-level' functions (Lezak, 1983). One of the first refined conceptual descriptions appeared over 30 years ago (Languis, 1992), and was disguised as Luria's third functional unit called the 'executor' of the brain. Luria's brain functioning theory (1973) was one of the first sophisticated explanations of the complexity and differentiation levels inherent to cerebral processes, including an account of the superior role of the frontal lobes' EFs (although EFs were not explicitly named as such). Specifically, Luria proposed a framework comprising three functional units, each responsible for different levels of cognition and behaviour (Luria, 1973). These units were thought to be accountable for regulating cortical tone and awareness (first unit), for encoding, processing, and storing information (second unit), and for programming, regulating, and verifying ongoing mental activity (third unit: modern EFs). Luria described these units as hierarchically organized, with the third unit developing last in the human brain and accounting for "higher-order" associative processes (Luria, 1973, as cited in Languis, 1992). The last unit is called the ‘zone(s) of overlapping’, and appears to be an early description of what is known today as executive functioning. Luria proposed that the ‘zone(s) of overlapping’ are rooted in the frontal lobes, which are responsible for regulating the active state of the cortex, and carrying out plans allowing for guided human behaviours (Luria, 1973). Overall, Luria's advanced conceptualization of the brain's conscious and active cognitive processes, has undoubtedly led to one of the most dynamic topics in contemporary neuropsychology: executive functioning.

It is widely recognized that the neural networks of the executive system originate in the brain's prefrontal cortex (PFC; e.g., Banich et al., 2000; Bechara, Damasio, Damasio, & Anderson, 1994; Cummings, 1995; Daigneault, Braun, & Whitaker, 1992; Fuster, 1989; Hampton, Adolphs, Tyszka, & O’Doherty, 2007; Miller & Cohen, 2001). PFC faculties allow for the brain to focus its attention on relevant stimuli and to ignore irrelevant information (Mahone, Mostofsky, Lasker, Zee, & Denckla, 2009; Murphy, McDowd, & Wilcox, 1999; Stoltzfus, Hasher, Zacks, Ulivi, & Goldstein, 1993) by utilizing distinct frontostriatal pathways specialized in, for instance, goal-directed behaviours, working memory (WM), decision-making, emotional regulation, error detection, and problem-solving (Christakou, Halari, Smith, Ifkovits, Brammer, & Rubia, 2009; Rubia, 2011).

The association cortex. Given their superior managerial role over other brain functions, EFs are thought to be crucial for differentiating complex human intellectual processes from other species' mental abilities (Ardila, 2008). That is, given their highly developed PFC, humans have the ability to interact with their environment in a much richer way than other species, even compared to primates who possess almost the exact same DNA. The implication of associative structures such as the PFC with regards to learning, partly explains the essence of human intelligence (Stout, 2010). The human cortex is composed of more associative regions and complex connections than any other animal (Keverne, 2004). Some of the most multifaceted human functions (e.g., EFs) result from rich interactions among brain pathways involving posterior (e.g., Inferior Parietal Lobe [IPL]) and anterior areas of the brain (i.e., PFC), that are either completely absent or minimized in animals (Ardila, 2008). EFs and their underlying cortical structures (i.e., PFC), increase opportunities for multifaceted learning experiences by the intermediary of speech, which is far more advanced in humans than in any other species. Specifically, speech serves as a cross-modal bridge which facilitates thought organization, closely monitored by the PFC. Thus, speech in conjunction with and via the PFC and associated executive systems, multiplies learning opportunities by promoting human interactions with the environment. In summary, modern advancements in the field of EFs (and research focused on PFC functions) has surely resulted in a deeper understanding of unique human capabilities than we ever thought possible.

Overview of Executive Components

Overall, beneath this rich capacity for learning and interacting lays the notion of an *active* and *conscious* component inherent to all executive demands. Not surprisingly, as they require a deliberate rather than automatic focus on current goals, control processes have often been described as rooted in functions of WM (i.e., which requires active manipulation of information) and/or attention (i.e., top down attention for which awareness is crucial). Thus, some of the first explicit descriptions of executive abilities arose from WM and attention models. The first researchers to overtly depict frontal lobe functions as *executive* were Baddeley and Hitch (1974), portrayed in the "central executive" component of their WM system. The "central executive" is said to be responsible for selecting, initiating and terminating, encoding, storage, and retrieval processes (Baddeley & Hitch, 1974; Baddeley, 1986), thus exerting executive control over other WM functions. This emphasis on executive WM was also supported by Goldman-Rakic ten years later (1996), who discussed the various executive roles of what she called the "WM processor", which she believes to be a central component of PFC functions. The "central executive" is said to be relatively equivalent to Norman and Shallice's Supervisory Attentional System (SAS; 1982), which, as the name suggests, highlights the executive role of attention over other "lower-level" processes. Since Norman and Shallice (1982), numerous other researchers have discussed the supervisory role of attention (e.g., Banich et al., 2000; Barkley, 1996; Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994; Posner & DiGirolamo, 1998; Posner & Rothbart, 2007). Moreover, others have described EFs by emphasizing the rather pragmatic role of frontal lobe processes over social interactions (e.g., Lezak, 1983; MacPherson, Phillips, & Della Sala, 2002; Ozonoff, Pennington, & Rogers, 1991). In 1983, Lezak emphasized the *socially* adaptive core component of EFs, meaning that executive behaviours "are all necessary for appropriate, socially responsible and effectively self-serving adult conduct" (Lezak, 1983, as cited in Jurado & Rosselli, 2007, p.213). Lezak (1983) highlighted EFs' crucial role in achieving successful individual independence and productivity. This relates to Damasio's (1994) notable description of the PFC mechanisms through which *emotions* guide our behaviours and decisions: the "somatic marker hypothesis." Specifically, Damasio stated that humans possess somatic markers which tie emotional and physiological experiences together, and exert a certain level of control over the decisions that we make (Damasio, 1994).

Whether they are described as mediators or moderators of WM, attention, social, or somatic functions, EFs appear to be pivotal in contextualizing "intended actions in light of past knowledge and experience, current situational cues, expectations of the future, and personally relevant values and purposes" (Moran & Gardner, 2007, p.19).

Concepts and dilemmas. Moreover, although there is no apparent consensus yet on the best definition or conceptualization for EFs, three fundamental components seem to dominate current empirical depictions: (a) mental set shifting (*shifting*), (b) information updating and monitoring (*updating*), and (c) inhibition of prepotent responses (*inhibition*; e.g., Baldo, Shimamura, Delis, Kramer, & Kaplan, 2001; Friedman, Miyake, Young, DeFries, Corley, & Hewitt., 2008; Jurado & Rosselli, 2007; Miyake et al., 2000; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). *Shifting* is the ability to alternate between tasks or mental sets with flexibility; *updating* is characterized by the ability to monitor relevance of external information and tying this to the task at hand by updating the content of WM with salient information in a suitable manner; and *inhibition* represents the ability to slow down or hold back outgoing automatic and/or dominant responses (Friedman et al., 2008; Miyake et al., 2000). The work of Miyake et al. (2000) has shed light on these three key elements, by shaping our current conceptual understanding of executive systems and interactions. This conceptualization is unique in that it conveys *both* ideas of unity and diversity, two conflicting themes that are central to a dilemma plaguing other 20th and 21st century EF models (Collette et al., 2005; Duncan, Johnson, Swales, & Freer, 1997; Miyake et al., 2000).

The unity and diversity debate. The aforementioned structural variability among theories is at the heart of an ongoing conceptual debate regarding the unity and diversity of EFs (e.g., Collette et al., 2005; Duncan, Johnson, Swales, & Freer, 1997; Miyake et al., 2000; Stuss & Benson, 1986; Teuber, 1972). A heated argument regarding the single or fragmented nature of executive processes has resulted from the complexity inherent to these systems. Some researchers support a perspective where *unity* (complementarity among subcomponents) is put forth to explain EF processes (e.g., Hedden & Yoon , 2006; Salthouse, 2005), while others support a perspective of *diversity* where subcomponents are independent and separable (e.g., Baddeley, 1996; Bryan and Luszcz, 2000; Burgess, 1997; Duke and Kaszniak, 2000; Duncan et al., 1995; Owen et al., 1995; Stuss et al., 1995; Stuss and Levine, 2002). To solve this quandary, subcomponents of EF models have typically been investigated by means of factor-analytic studies (e.g., Friedman et al., 2008; Miyake et al., 2000). Single factor solutions endorsing *one principal component* such as inhibition (e.g., Hasher & Zacks, 1988; Hedden & Yoon, 2006; Salthouse, 2005), attention (e.g., McCabe, Roediger, McDaniel, Balota, & Hambrick, 2010; Norman & Shallice, 1982; Posner & Boies, 1971) or WM (e.g., Baddeley, 1986; Goldman-Rakic, 1996), support the view that a single focus of activation is common to all EF-related tasks or demands. On the other hand, diversity proponents suggest that EFs are better explained by *multiple factors* which share low communality and high uniqueness (e.g., Collette et al., 2005; Miyake et al., 2000). As neither of these two exclusive conceptual models has the richness to explain the complexity of EFs, an integrative solution binding both unity and diversity was bound to emerge.

Miyake's EFs: resolving the conceptual dilemma. In the year 2000, Miyake advanced the idea that EFs may be divided into multiple complex subcomponents which could share common properties. Hence, Miyake's work was revolutionary as it supported *both* views of unity and diversity (Miyake et al. 2000). Miyake and colleagues' study of EFs, led to the conceptualization of the previously discussed distinct and interactive modules: shifting, updating, and inhibition. More specifically, they undertook a latent variable analysis to investigate the extent to which shifting, updating, and inhibition represented unified or separable elements, and their relative contribution to complex EF tasks such as the Wisconsin Card Sorting Test (WCST), the Tower of Hanoi, and Random Number Generation. Miyake et al. hypothesized and confirmed through Confirmatory Factor Analysis, that components underlying performance on these three tasks were moderately correlated, but clearly separable. Further, they analyzed the relevance of each of the three target EFs (i.e., shifting, updating, and inhibition) in relation to each EF task (i.e., WCST, Tower of Hanoi, and Random Number Generation), and reported that the shifting subcomponent was more highly correlated to the WCST, inhibition to the Tower of Hanoi task, and inhibition and updating jointly to Random Number Generation. This distinction amongst complex tasks and associated target subcomponents further suggested that unity *and* diversity of executive control is likely the most appropriate take on PFC functions.

In 2008, Friedman and colleagues took this dual conceptualization one step further, and used Miyake's model in a twin study, as a means to explain individual differences in executive functioning from a behavioural genetic perspective. Results illustrated the importance of heritability, in explaining convergent and divergent factors in Miyake's approach (Friedman et al., 2008). Moreover, Collette and colleagues (2005) explored the neural substrates of Miyake's three subcomponents with the use of Positron Emission Tomography. By the means of three conjunction analyses (used to isolate cerebral areas common to tasks tapping into the same executive processes), these researchers were able to show that *specific* PFC areas were associated with *particular* EFs, further demonstrating the common and discrete characteristics of executive processes (Collette et al., 2005). More specifically, all tasks seemed to share a common focus of activation in multiple regions such as the left superior parietal gyrus and the left lateral prefrontal cortex, demonstrating the *unity* of EFs; and, illustrating the *diversity* of these functions, specific foci of activation were found: for updating, several areas were recruited such as the orbitofrontal cortices and the cerebellum, for shifting, the left superior parietal region, and for inhibition, the right intraparietal sulcus.

Finally, it is worth mentioning that, when they advanced the ideas of unity and diversity, Miyake and colleagues (2000) did not purport to have created a new model of EFs per se. Rather, the main goal of their article was simply "to provide a necessary empirical basis for developing a theory that specifies how EFs are organized and what roles they play in complex cognition" (Miyake et al., 2000, p.50). Nonetheless, their conceptual endeavours significantly contributed to the literature. Not surprisingly, given the appeal of Miyake's flexible and interactive explanation of EFs, a Google Scholar search for articles citing Miyake et al. (2000) "The unity and diversity of executive functions and their contributions to complex cognition" brought about over 2200 results. And, a Medline search resulted in over 150 articles in which the article was cited.

EF Circuits and Associated Neuropsychology

Frontostriatal networks. Surely, Miyake's contribution to the current topic is inestimable; however, our appreciation of executive processes would be incomplete without a thorough understanding of the underlying neural pathways relevant to them. Alexander, Delong, and Strick, put forth five major frontal-subcortical circuits in 1986, from which three are now generally accepted (e.g., Alvarez & Emory, 2006; Bonelli & Cummings, 2007; Cummings, 1995; Stuss and Benson, 1984). Specifically, there are currently three main distinct parallel frontal-subcortical EF circuits (i.e., frontostriatal system) involved in behaviour, cognition, emotion and motivation which allow humans to interact with and respond to their environment (Alvarez & Emory, 2006; Bonelli & Cummings, 2007; Cummings, 1995). These circuits are (see Figure 1 below): (a) the dorsolateral PFC (DLPFC) circuit, which facilitates responses to external information by permitting cognitive organization of incoming and outgoing information, and which greatly relates to WM demands; (b) the anterior cingulate cortex (ACC) circuit, which is necessary for behavioural motivation and error monitoring/correction; and (c) the orbitofrontal cortex (OFC) circuit, which is crucial with regards to affect and decision-making by integrating emotional and limbic information into behavioural responses (Alvarez & Emory, 2006). These three tracks *mutually* activate specific subcortical structures, while acting in *distinct* manners to produce various behaviours. That is, the frontostriatal EF system creates a loop which travels to the frontal lobes and back, by the intermediary activation of the following important subcortical structures: the striatum, the globus pallidus, the substantia nigra, and the thalamus. Evidently, depending on the faced environmental demands, other structures can also be involved. For instance, *subcortical* areas that play important roles in the emotional valence (amygdala) of encoded and retrieved memories (hippocampus; Masterman & Cummings, 1997), and other *cortical* structures that have effects on, for example, lexico-semantic knowledge (inferotemporal lobes; Collette et al., 2001), and spatial information (parietal lobes; Goodwin, Blackman, Sakellaridi, & Chafee, 2012), may be activated. Direct and indirect routes may lead to inhibition or activation of these circuits, and may result in the expression or extinction of related cognitions and behaviours (Alvarez & Emory, 2006).

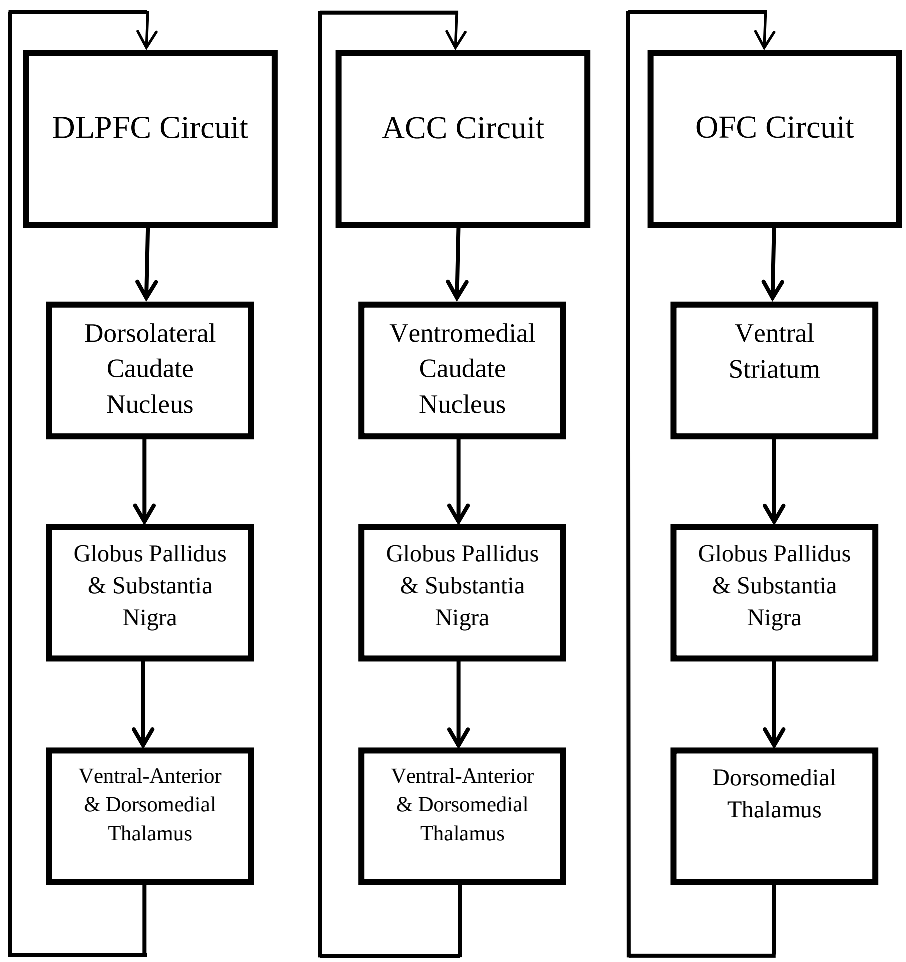

Figure 1. Frontostriatal loops.

Also relevant to the frontostriatial circuitry are two distinct networks which will not be a major topic of review here but which are worth mentioning: the fronto-parietal and fronto-cerebellar pathways. The fronto-parietal network requires DLPFC and intraparietal sulcus involvement (Dosenbach et al., 2007). Actions involved in initiation, error-monitoring, and cognitive flexibility allowing for adaptive executive control based on the task at hand, have been reported to relate to this executive circuit. As for the parietal lobes, the lateral areas have been found to specifically correlate with executive task performance, to a larger extent than other parietal cortices (Seeley et al., 2007). On the other hand, the fronto-cerebellar pathway is involved in automatizing novel cognitions and behaviours, which allows for fluency and efficiency of EFs (Koziol, Budding, Chidekel, 2010). This network has been said to heavily rely on the contribution of the basal ganglia, which is crucial for exerting inhibitory and gating influences. Through its connections with the basal ganglia, the cerebellum allows for analysis and selection of frontal executive plans of action, based on the situation at hand (Koziol et al., 2010; Koziol, Budding, Chidekel, 2012). Koziol et al. (2012) have argued that the cerebellum plays a significant role in training the PFC to execute motor behaviours in a variety of contexts, which allows the frontal lobes to anticipate future outcomes. Overall, the cerebellum's involvement in frontal operations has been argued to be crucial to the *quality* of executive outcomes, by playing a regulatory role over the rate, rhythm, and force of behaviours (Koziol et al., 2010).

Hot and cool pathways. Recent developmental theorists have proposed a classification of EFs different from the previous fronstriatal nomenclature. For instance, two distinct networks, the *cool* and the *hot* pathways, have been used to describe cognitive vs. paralimbic EFs (Metcalfe & Mischel, 1999). According to Rubia et al. (2011), *cool* EFs are characterized by a common cognitive component and are thought to share structural junctions (see Christakou, et al. 2009; Rubia 2011); namely, *cool* EFs are said to be mediated by lateral inferior and dorsolateral frontostriatal and frontoparietal networks. Examples of these *cool* cognitive functions are attention (e.g., attention based on stimulus salience, and visual-spatial attention), WM, planning, timing, goal-directed cognition, cognitive flexibility, control, and inhibition (Rubia, Hyde, Giampietro, & Smith, 2010; Rubia, 2011). These processes are known to be mediated by lateral inferior and dorsolateral frontostriatal and frontoparietal networks. Conversely, *hot* paralimbic EFs are said to have effects on affect, motivation, and emotional regulation. They are thought to be mediated by paralimbic orbitomedial, ventromedial frontolimbic structures, and underlying limbic structures such as the amygdala (Christakou et al., 2009; Fellows & Farah, 2005; Hampton et al., 2007).

EF Neurodevelopment

Understanding *abnormal* executive functioning associated with the previous cerebral networks would be impossible without acknowledging *normal* neurodevelopment. Specifically, a valuable proportion of EF literature has focused on describing early and later maturation. Some of the most important findings related to this topic are outlined next.

Early neurodevelopment. Between birth and early childhood, there is a steep rise in brain volume, grey and white matter development (Giedd et al., 1999). Grey matter decreases after adolescence reflecting synaptic pruning necessary for efficient neuronal transmission (Giedd et al., 1999). In older age however, reduction of connectivity and structural atrophy characterizes the normal progression pattern of cerebral, cognitive, and behavioural functions. That is, as portrayed by Craik and Bialystok (2006): "there is symmetry to our physical lives: we are independent and robust in youth and middle age, but dependent and frail in infancy and old age" (p.131). Interestingly, the vulnerability which typifies both ends of the lifespan is paralleled by the evolution and devolution of EFs. Specifically, the PFC, where EFs are said to originate, is the last cortical area to reach maturation in childhood, and generally the first one to be impaired in aging (Casey, Tottenham, Liston, & Durston, 2005; Craik & Bialystok, 2006; Giedd et al., 1999). Consequently, performance on EF tasks tend to show a similar inverted U-shaped trajectory, of ascent in childhood to early adulthood, with a peak in late teens early twenties, and descent in late adulthood (Craik & Bialystok, 2006; Diamond, 2002). Here are a few examples of important PFC and EF development seen in the first 7 years of life. During the first year of life, arborization, increased dopamine receptor density (important for reward-driven learning; Bäckman et al., 2000; Holroyd & Coles, 2002) is seen in the PFC. At this stage, WM and cognitive flexibility functions can already be seen (Diamond, 2002). From age 1 to 3, prepotent-response inhibition improves (Jurado & Rosselli, 2007), as does performance on matching tasks with an incompatible condition (Holroyd & Coles, 2002). From 3 to 7, as increased task performance related to inhibition (Anderson, 2002), switching (Anderson, 2002), and theory of mind (Perner & Lang, 1999) becomes apparent, neuronal density declines in certain areas of the PFC (Giedd, 1999), reflecting important changes in PFC *efficiency*. Around 6 and 7, an important decrease in grey matter volume (Giedd, 1999) as well as a linear increase in white matter is manifested in processing speed enhancement (Anderson, 2002). At that age, the development of attentional control and inhibitory skills in line with current goals becomes obvious, which is suggestive of cognitive *flexibility* (Anderson, 2002). Again, these abilities peak in the late teens and early twenties, when EFs are at their acme (Craik & Bialystok, 2006; Zelazo, Carter, Reznick, & Frye, 1997; Huizinga, Dolan, & van der Molen, 2006).

Research has shown that neuromaturation can be greatly influenced by environmental variables. For instance, education, health, fitness, bilingualism, and exposure to trauma, can all act as modulating factors. Of note, although many variables may alter someone's developmental path, by elevating or lowering their trajectory, they cannot prevent the degree to which the natural decline associated with normal aging will occur (e.g., Christensen et al., 2001).

Executive dysfunction associated with aging. Whether EFs are approached from a frontostriatal network model or a hot and cool perspective, it is well understood that similarly to *early* development, normal *aging* is characterized by complexity. That is, late development is better described heterogeneously, in terms of continuity (growth), discontinuity (decline), change and stability (Zimmerman et al., 2006). Aging-related discontinuity or decline, affects specific cognitive variables related to fluid intelligence (Craik & Bialystok, 2006). Aptitudes pertaining to fluid intelligence were first defined by Raymond Cattell in the 1970s as relating to mental flexibility and thought abstraction (Cohen & Swerdlik, 2010). Darowski and colleagues (Darowski, Helder, Zacks, Hasher, & Hambrick, 2008) have shown that there is a nearly linear decline from early to late adulthood on such abilities, as opposed to crystallized knowledge (e.g., factual information), which seems to remain stable over time. As explained earlier, fluid intelligence is strongly associated with EFs, as it allow us to adapt to change and novelty, and to derive from the brain's "default" mechanisms (Craik & Bialystok, 2006). Scientific literature is increasingly outlining evidence for the natural decline of particular facets of the executive system, which appear to be more sensitive than others to normal aging (e.g., Carlson, Hasher, Connelly, & Zacks, 1995; Daigneault et al., 1992; Kane et al., 1994; MacPherson et al., 2002; McDowd & Oseas-Kreger, 1991; Mejia, Pineda, Alvarez, & Ardila, 1998). Moreover, this normal decline appears to be particularly prominent after the age of 60 (Craik & Bialystok, 2006), at which time EFs seem to wane with greater intensity than in the years before.

Functional Age-Related Differences

Literature pertaining to age-related functional differences resulting from EF maturation seems to emphasize the *changes* associated with *particular* executive components over time. Specifically, there exists considerable support regarding the effects of aging on inhibitory control and selective attention (e.g., Darowski et al., 2008; Hasher & Zacks, 1988; Jurado & Rosselli, 2007; Murphy et al., 1999), and notable research outlining the changes pertaining to the time of day effect (e.g., Goldstein, Hahn, Hasher, Wiprzycka, & Zelazo, 2006), proactive interference (e.g., Chung, Foong, Hasher, & May, 2002), planning (e.g., Allain et al., 2005), set shifting (e.g., Perry et al, 2009), verbal fluency (e.g., Brickman et al.; 2005), and processing speed (e.g., Keys & White, 2000).

Inhibitory control age trends. Despite the contradictory results which constitute most of the scarce literature on aging and EF, a *specific* robust relationship between age and inhibition has consistently been portrayed, with increasing age strongly correlating with decreasing performance on inhibitory tasks (e.g., Darowski et al., 2008; Hasher & Zacks, 1988; Jurado & Rosselli, 2007; Murphy et al., 1999). The ability to inhibit irrelevant stimuli while selectively attending to auditory information appears to be particularly affected by age-related changes, and that, to a greater extent than other EFs, impairing older but not younger adults on target measures (e.g., Kane, et al., 1994; Murphy et al., 1999; Stoltzfus, Hasher, Zacks, Ulivi, & Goldstein, 1993). Moreover, Hasher and colleagues (Carlson et al., 1995; Connelly et al., 1991) have put forth the idea that age-related differences in inhibitory processing can lead to difficulty with selective and sustained attention, and thus, with goal-directed behaviours in older adults (Hasher & Zacks, 1988). Darowski et al. (2008) took this theory one step further and hypothesized that the primary determinant for most age-related cognitive deficits is this change in inhibitory processing (what they called "attention regulation ability"). These authors suggested that performance decrements correlated with aging, *only* pertain to inhibitory functions that are necessary to other EFs such as WM. By isolating WM from inhibitory processes, they were able to show that this function appears to be normal in older individuals, and that only the ability to inhibit irrelevant distracters was significantly impaired. McCabe and colleagues (2010) have also proposed the existence of a common executive attentional-control component (i.e., inhibition) to WM and executive functioning. By using a factor analytic approach, they showed that this shared element is strongly predictive of performance on tasks requiring "higher-level" cognition (e.g., using WM on a reading span task, a computation span task, a letter rotation task, and a match span task; McCabe et al., 2010). Others have also supported the inhibition hypothesis (e.g., Kane et al., 1994; McDowd & Oseas-Kreger, 1991; Stoltzfus et al., 1993), some adding that not all inhibitory processes require executive control (Andrés, Guerrini, Phillips, & Perfect, 2008). Andrés et al. (2008) proposed that executive inhibition is the *only* type of inhibition that relies on the frontal lobes, and thus, the only one that should be affected by aging. They tested this hypothesis by combining inhibitory paradigms with different levels of executive control within the same participants, and found that Stroop interference (Stroop, 1935; requires participants to intentionally inhibit or suppress the dominant process of reading a word; i.e., executive inhibition) and stop-signal responsiveness (a task requiring participants to intentionally execute a dominant response [Go condition], and to inhibit a dominant response consciously when prompted by a tone stopping signal [No-Go condition]; i.e., executive inhibition), were affected by age, but *not* negative priming, a task similar to Stroop interference, with the exceptions that it requires automatic, not executive inhibition, and that the color-word which was to be ignored in the previous trials is the same as the ink color which is to be attended to in the current trial. That is, suggesting that tasks for which the executive quality of inhibitory control is high, are more sensitive to aging than those poorly associated with EFs. Given the pervasive role of selective attention and/or inhibition in most measures of EFs, and its strong association with daily living skills and independence, it is not surprising that age-related differences pertaining to these constructs may act as mediators of overall EF performance (Salthouse, Atkinson, & Berish, 2003).

Other age predictors. Other factors are known to influence age-related changes targeting EFs, such as the time of day and proactive interference (Chung et al., 2002; Goldstein et al., 2006). Specifically, it is said that most older adults perform significantly better on various cognitive tasks when tested early on in the day, and that inhibitory deficits such as those of proactive interference, are particularly vulnerable to circadian effects (Chung et al., 2002). Also, the buildup of accumulated knowledge caused by age and life experience, increases older adults' susceptibility to proactive interference (Anderson, Baddeley, & Eysenck, 2009).

Moreover, numerous other executive variables have been associated with cognitive decline in older adults, such as planning (Allain et al., 2005; Robbins et al., 1998; Zook et al., 2006), set shifting (Haaland, Vranes, Goodwin, & Garry, 1987; Perry et al., 2009), and verbal fluency (Brickman et al.; 2005; Crossley, D’Arcy, & Rawson, 1997). Some (e.g., Keys & White, 2000) have also attempted to explain age-related differences in inhibition and other EFs, as an outcome of a deteriorated processing speed. However, ambiguity and contradiction seem to permeate many of these explanations, as most of them fail to account for the *specific* steps through which executive processes change with age. A possible solution may be to take a closer look at brain structures associated with EFs and vulnerable to the effects of aging.

Structural Age-Related Differences

Structural differences pertaining to EF maturation may help better explain the cognitive consequences of age over the lifespan. For instance, although there is evidence for the implication of both anterior and posterior cortices in intact executive functioning (Alvarez & Emory, 2006), there exists greater support regarding the effects of aging on the frontal cortex than any other lobe (Raz, 2005). Specifically, there is extensive support regarding structural aging affecting grey matter volume in the frontal lobes (e.g, Head, Kennedy, Rodrigue, & Raz, 2009; Gunning-Dixon & Raz, 2003; Zimmerman et al., 2006), white matter integrity targeting frontostriatal circuits (e.g., Buckner, 2004; Gunning-Dixon & Raz, 2003; Hedden & Gabrieli, 2004), and changes in the DLPFC (Johnson, Mitchell, Raye, & Greene, 2004; MacPherson et al., 2002; Paul et al., 2005). On the other hand, literature pertaining to the OFC is plagued by important discrepancies; oscillating from decline to stability to improvement (e.g., Lamar & Resnick, 2004; MacPherson et al., 2002; Salat, Kaye, & Janowsky, 2001). Consequently, it appears impractical and difficult to draw robust assumptions with regards to aging and this particular area.

The DLPFC theory of cognitive aging. After the age of 20, the PFC undergoes an average linear decline of about 5% per decade, with the largest loss affecting the lateral regions (Hedden & Gabrieli, 2004). This has an important impact for performance on certain measures of EFs (e.g., WCST; Head et al., 2009; Gunning-Dixon & Raz, 2003), specifically those involving switching, "failure to suppress interfering information" (i.e., inhibition; Hedden & Gabrieli, 2004), and perseveration (i.e., unsuccessful switching and inhibition; Gunning-Dixon & Raz, 2003). Further, a negative correlation has also been established between lateral-frontal grey matter volume, planning and organization abilities in older adults (Zimmerman et al., 2006). As tasks sensitive to DLPFC dysfunction seem to be the strongest predictors of age-related variations, but not those susceptible to OFC dysfunction (e.g., tasks of emotion and social decision-making), a *"specific dorsolateral prefrontal theory of cognitive changes with age*" has been put forth (MacPherson et al., 2002). A significant body of literature supports the claim that frontal deterioration in older adults appears to be *local and specific* (i.e., DLPFC), rather than global and general (Darowski et al., 2008; Hasher & Zacks, 1988; Johnson et al., 2004; Jurado & Rosselli, 2007; MacPherson et al., 2002; Milham et al., 2002; Murphy et al., 1999).

Aging and frontostriatal white matter density. Many studies have shown that white matter density peaks in early adulthood, coinciding with EF culmination, and depletes in late adulthood as a normal part of aging, suggesting that aging-declines affecting frontal myelin may be some of the most significant contributors to age-related differences in EFs (e.g., Buckner, 2004; Gunning-Dixon & Raz, 2003; Hedden & Gabrieli, 2004). Frontostriatal circuits depend on white matter tracts to modulate executive information processing, thereby mediating speed and efficiency of connectivity (Alvarez & Emory, 2006). Age trends affecting this system lead to depletion of the following neurotransmitters: dopamine, noradrenaline and serotonin (Buckner, 2004; Hedden & Gabrieli, 2004), thereby compromising the integrity of EF neural pathways and related processing speed (Gabrieli, 1996). Not surprisingly, the greatest consequences of such changes are seen primarily on tasks loading highly on executive attention and inhibitory control (Buckner, 2004; Oosterman et al., 2008; Söderlund et al., 2006). Moreover, a significant association between executive planning (primarily a DLPFC function) and white matter depletion, has also been found to exist for older but not younger adults' performance on the Tower of Hanoi task (Paul et al., 2005).

Overall, strong evidence supports the specific changes affecting the PFC in older populations, specifically pertaining to the role of the DLPFC and frontostriatal white matter.

Mediators of Plasticity and Cognitive Reserve

Determinants of age declines appear to be better understood than the modulating factors of executive performance in younger adults; that is, it is unclear if it is merely the absence of PFC atrophy and associated executive changes that differentiate younger from older individuals. Nevertheless, particular factors have been acknowledged in the literature as crucial mediators of cognitive deterioration. For instance, low disease probability, high functional and cognitive capacity, and active life-engagement, all appear to be important preserving factors associated with healthy older aging (Rowe & Kahn, 1997).

Alas, there is currently a paucity of literature regarding variables facilitating the *building-up* of cognitive reserve during young adulthood. Most studies in which markers of cognitive reserve and neuroplasticity are assessed, are done amongst older populations, looking retrospectively at possible explanations for executive outcomes (e.g., Richards & Sacker, 2003). "This research design suffers from many limitations including recall bias and misclassification of exposure" (Scarmeas & Stern, 2004, p.374) by the elderly, with regards to potential protective variables. Nonetheless, classic animal studies such as Diamond's (1993), have put forth the idea that early, rich, and stimulating environments play a crucial role in promoting neuroplasticity. Specifically, in Diamond's study (1993), greater social contact and novelty in the types of activities in which young rats were engaged, significantly contributed to neurodevelopment. Similarly, it is believed that comparable effects may be found in adults who engage in novel activities (Vance & Crowe, 2006). Thus, it is possible that increased cortical thickness may lead to subsequent growths and cognitive reserve over time. Moreover, lifestyle variables such as modifiable health factors (e.g., physical activity), social support (e.g., friends and family), positive affect (e.g., adaptive coping mechanisms), stimulating activities, and novel experiences (e.g., learning a new language), are thought to represent some of the strongest sources of executive neuroplasticity and cognitive reserve across the lifespan (Vance & Crowe, 2006). It is important to note that while cognitive reserve did not represent a major focus of the current research endeavour, certain modulating variables have been taken into consideration in addressing this study's questions (see Methods).

INTERACT

Addressing Sensitivity and Specificity Concerns

As seen thus far, there exists incredible variability in findings focusing on aging and EFs. This may be attributable to the lack of reliable measures of *specific* executive components (e.g., Banich, 2009; Burgess, 1997; Collette et al., 2005; Phillips, 1997). Due to the complexity of this construct and its underlying anatomical correspondence, tests purporting to tap onto particular cognitive functions have struggled with accurately isolating them. Additionally, normal aging is associated with *sub*clinical decline in EFs. Thus, executive measures have to be sufficiently precise to differentiate this naturally occurring process in healthy adults, from the executive impairments often seen in psychopathological populations (Bryan & Luszcz, 2000).

Defining executive functioning represents a central obstacle inherent to the aforementioned challenges. The Integrative Neuropsychological Theory of Executive-Related Abilities and Component Transactions (INTERACT; Garcia-Barrera, Frazer, & Areshenkoff, 2012) is a novel approach on EFs and their underlying executive neural systems, which was created as an effort to remedy some of these challenges (see Figure 2 below). As the name suggests, INTERACT emphasizes *interactions* among separate EFs, and the executive cognitive skills and behaviours that arise from them. Precisely, INTERACT supports the existence of five distinct EFs: Problem Representation, Updating WM, Attentional Control, Inhibitory Control, and Reward/Valence Processing. INTERACT was recently validated (Frazer, 2012) with the use of a novel battery of computerized tasks, and examined with a structural equation modeling (SEM) approach. This validation study demonstrated that INTERACT was superior to six alternative theoretically-based measurement models.

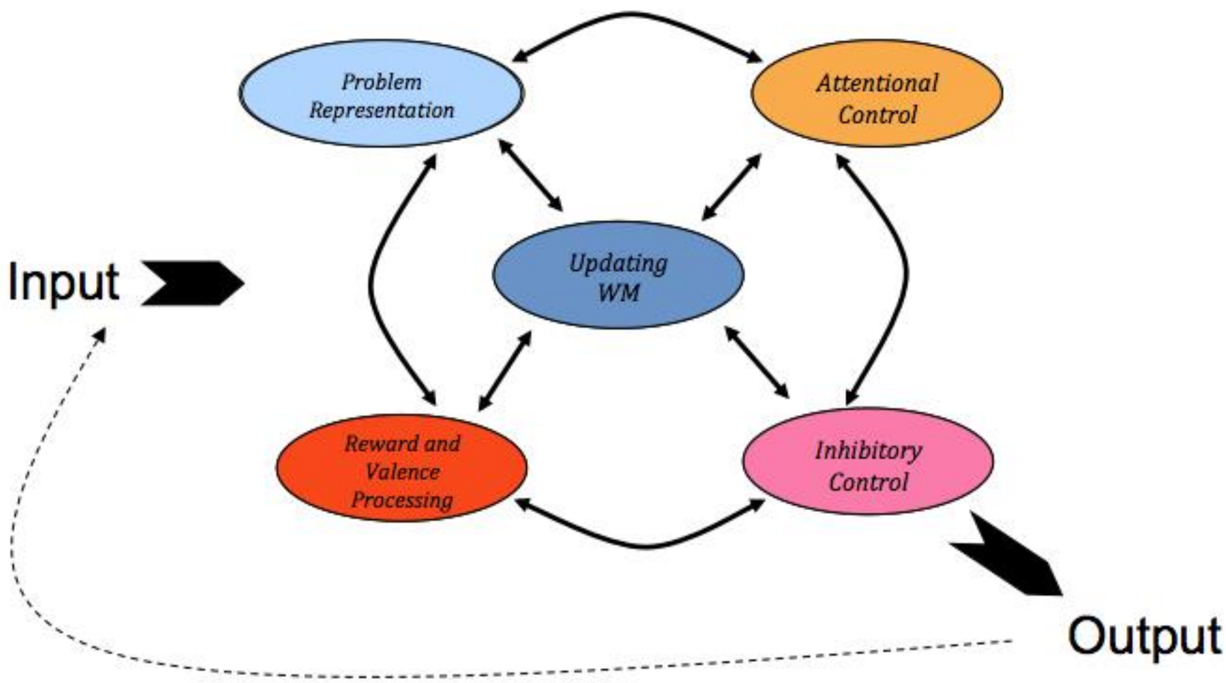

Figure 2. The INTERACT model (Garcia-Barrera et al., 2012).

Inspired by Miyake. INTERACT arose from Miyake and colleagues' explanation of EFs (2000). Although these authors did not purport to have created a new model of EFs, Miyake's conceptualization was seen as a useful reconciliation between the ideas of unity and diversity, which is what inspired Garcia-Barrera et al. (Garcia-Barrera, Kamphaus, & Bandalos, 2011) to design a model of EFs, which ultimately evolved into INTERACT. Nonetheless, INTERACT expands above and beyond Miyake's theory, in an attempt to contribute to the existing conceptual debate. INTERACT theoretically defines executive processes in terms of *interactions* amongst EFs (i.e., a *unitary* function of EFs). More precisely, according to this model, “EFs emerge as outcomes of multiple interactions between cognitive and emotional control processes. These operations are mediated by basic connections within and between key neural nodes, involved in rule setting and organization of internal representations. The ultimate goal of these interactions is to produce volitional, purposeful, and efficient guided behaviour” (Garcia-Barrera et al., 2012). Therefore, *interactions* amongst the five distinct components on which INTERACT is based, are all necessary to normal executive functioning.

Influenced by Denckla. Furthermore, although all components may interact with one another, INTERACT proposes two aggregated systems in which particular executive processes may be more relevant at certain times than others. That is, the *How* and *When* of INTERACT-interactions, which emanated from Denckla's work on EFs (1996, 2007). As it will be described shortly, Problem Representation reflects the *How* of INTERACT's model of EFs (Garcia-Barrera et al., 2012). The *How* acts as an overarching executive process, allowing individuals to respond to novelty by establishing and initiating plans of action to guide cognitive skills and behaviours (Frazer, 2012). Alternatively, Inhibitory Control, Attentional Control, and Reward/Valence Processing "comprise a ‘cybernetic’ dimension (Royall, et al., 2002) or “When” (Denckla, 2007) of EFs, *which control other non-executive systems in a top-down fashion*" (Frazer, 2012, p.10). The *When* allows for the regulation of behaviours (IC), attention (AC), and reward-based learning (R/V P), resulting in appropriate and desired responses. Overall, *how* we act requires taking goals, plans, and environmental conditions into consideration, particularly in the context of novelty; conversely, *when* we take action, it is crucial that we control our behaviours, attention, and emotions, to adapt to the ongoing demands surrounding us, and so that we may consequently learn from them.

Problem Representation

Definition. INTERACT's first component is named Problem Representation. Problem Representation is crucial to executive planning, goal identification, and initiation of behaviour, in the context of novelty (Garcia-Barrera et al., 2011). It allows individuals to assess external demands, regulate internal states, and control cognition and behaviour accordingly (Frazer, 2012). Specifically, when faced with novel or ambiguous situations, this component facilitates the temporal organization and integration of internal and external information, to enable optimal decision-making (Frazer, 2012). As explained earlier, Problem Representation corresponds to the *How* or syntax of EFs, as it shapes *how* we respond to our environment, *how* we prepare for action, and it is essential for overriding our 'default' mechanisms (Garcia-Barrera et al., 2011).

Neural underpinnings. Problem Representation possesses strong connections with Updating WM, and is crucial to the syntactical organization of thoughts and behaviours. As seen previously, these executive processes are said to require considerable DLPFC recruitment, which is necessary to maintain goals in mind over time (Banich, et al., 2000); specifically, left DLPFC activation is involved when carrying out goals, whereas the right DLPFC is said to play a greater role in initial planning. Additionally, increased task complexity is thought to enhance the DLPFC's engagement (Newman, Carpenter, Varma, & Just, 2003).

Updating Working Memory

Definition. The second component is labelled as Updating WM. Congruent with Miyake et al.'s notion of *updating* (2000), Updating WM lays at the base of executive processes responsible for holding, manipulating and facilitating storage of information, based on current demands (Frazer, 2012). *Control* and *direction* of functions related to WM (i.e., attention and cognition), are essential to INTERACT's second component. Additionally, *storing* and *processing* of WM-stimuli also constitute important operations linked to Updating WM (Baddeley & Hitch, 1974). Furthermore, the role of this executive element is unique as it allows for the syntax formulated by Problem Representation to be carried over to INTERACT's 'cybernetic' dimension. By the means of this interaction, Attentional Control, Inhibitory Control, and Reward/Valence Processing may channel their focus on factors only relevant for carrying out the task at hand. In other words, Updating WM is what unites the *How* (i.e., Problem Representation) and *When* (i.e., Attentional Control, Inhibitory Control, and Reward/Valence Processing) of executive processes, which will be discussed in greater detail shortly.

Neural underpinnings. PFC processes linked to the 'temporal organization of behaviour' (i.e., ongoing updating of information congruent with present goals; Fuster, 1995), are widely recruited during Updating WM tasks. Research suggests that different parts of the PFC may be activated depending on the specific subcomponent(s) needed: *manipulation* of WM-stimuli entails DLPFC recruitment (Levy & Goldman-Rakic, 1999); *rehearsal* requires ventral-lateral PFC involvement, and it seems to be the case that longer delays while holding information require higher levels of PFC involvement (Fletcher & Henson, 2001; Karatekin, 2004); and, the *storage* subcomponent of Updating WM appears to necessitate greater parietal and temporal, rather than frontal recruitment (Fletcher & Henson, 2001), as storing involves greater *manipulation* and *rehearsal* of WM-information than *control* per se (Karatekin, 2004).

Attentional Control

Definition. The third component, Attentional Control (AC), represents those executive processes which exert control over "lower-level" attention functions. AC is multifaceted and may be linked to the control of any of the following operations: selecting, orienting, and maintaining attention (Frazer, 2012).

Neural underpinnings. This “top-down” executive attention (i.e., AC) has been reported to involve early neuronal activation of the frontal lobes, particularly cingulate regions (Posner & Rothbart, 2009), as opposed to “bottom-up” visuospatial attention, which requires early recruitment of the parietal regions (Buschman & Miller, 2007). AC also relies heavily on PFC integrity, specifically on the DLPFC and the ACC, which in turn, depend on dopamine transmission (Frazer, 2012). As it concerns the *cool* network of EFs, AC is thought to be constantly recruited during the execution of goal-directed behaviours, by keeping the brain focused on relevant tasks or demands (Frazer, 2012), thus representing the first facet of the *When* of EFs. AC is responsible for applying Problem Representation's syntax to the ongoing executive activity, by decoding and filtering both internal and environmental stimuli in accordance with relevance levels.

Inhibitory Control

Definition. INTERACT's fourth component is Inhibitory Control (IC). IC represents those executive processes which exert control over "lower-level" motor and cognitive behaviours, thus representing the second facet of the *When*. Moreover, IC may be seen as a complementary function of AC, as it allows for directed behaviours, inhibition of distractive information (Darowski et al., 2008), and for a disregard towards stimuli irrelevant to AC processes.

Neural underpinnings. As seen thus far, executive inhibition (IC) has a particularly strong connection with the DLPFC (e.g., Johnson et al., 2004; Milham et al., 2002). The basal ganglia, cerebellum, and cingulate cortex are also said to be crucial neurosubstrates significant to IC (Frazer, 2012). IC is also part of the *cool* network of EFs (Metcalfe & Mischel, 1999).

Reward/Valence Processing

Definition. Originally referred to as “emotional control” (Frazer, 2012; Garcia-Barrera, et al., 2012), the fifth and final component of INTERACT's model of EFs is Reward/Valence Processing (R/V P). R/V P represents "higher-level" functions exerting control over "lower-level" emotional processes, thus making it the third element of the *When*. R/V P is responsible for regulating the influence of emotions over behavioural outcomes, through reward-based learning (Frazer, 2012); that is, depending on (a) the environmental demands, (b) the syntax allocated by Problem Representation, (c) the efforts granted by Updating WM, and (d) the control permitted by AC and IC, R/V P may allow for socially and contextually appropriate responses, by reinforcing (or not) a given behaviour. Further, given their connection to the *hot* paralimbic circuit (Metcalfe & Mischel, 1999), R/V P operations are said to have effects on initiation, avoidance, and inhibition of affect and motivation (Frazer, 2012).

Neural underpinnings. Just like other INTERACT components, R/V P largely depends on PFC processes, specifically those associated with the ventral-medial PFC, and PFC circuits linked to paralimbic areas such as the amygdala, hippocampus, nucleus accumbens and the hypothalamus (Frazer, 2012). As explained earlier, this frontostriatal network can also impact the emotional valence of memories, by maintaining or neglecting particular cognitions and behaviours (Masterman & Cummings, 1997).

Interactions

Each component represents a distinct system of its own. However, according to INTERACT's model of EFs, an *independent* activation of each system is *not* what results in EFs. Rather, *interactions* amongst them represent the key to complex cognitions and behaviours (i.e., EFs). In other words, executive control does not depend on which individual system is activated during a task; what matters here is *how much* of each component relative to the others, and in parallel with the others, is required.

The Current Study

Studies targeting age-trends for tasks of EFs have been found to typically compare the performance of emerging adults to that of older individuals of ages 60 and over (e.g., Alvarez & Emory, 2006; Braver et al., 2001; Jurado & Rosselli, 1997; West, 1996; Zelazo, Craik, & Booth, 2004). This restricted type of comparison is likely due to what has been systematically outlined in the literature regarding the prime of EFs, which is reached around the age of 25 (DeLuca et al., 2003; Diamond, 2002), and aging-related declines, which appear more evident approximately after the ages of 60-65. It seems surprising however that, as outlined previously, research targeting individuals *between* the ages of 25 and 60, appears to be scarce. Due to this paucity of literature focusing on middle-aged adults, it is difficult to establish whether frontal networks maintain their peak status for a short or longer period of time, possibly plateauing for years, or if the decline observed in older adults begins immediately after having reached the apex of higher-order processes, forming an inverted U-shape (Zelazo, Craik, & Booth, 2004). Also, the precise nature of the association shared by executive components in relation to one another and as a function of age also remains undetermined. As a consequence of these empirical challenges, the following questions remain unanswered: *At what point does the executive system lose its optimal* *efficiency and begin its inevitable descent?* and *Do discrete executive components show differential trends at particular stages of aging?*

Despite the aforementioned uncertainties regarding aging and EFs, one thing seems clear: *inhibitory control* has reliably been found to be affected by the *later* stages of aging, at a more noticeable level than any other prefrontal function (Arbuckle & Gold, 1993; Darowski et al., 2008; Hamm & Hasher, 1992; Hasher & Zacks, 1988; Kane et al., 1994; MacPherson et al., 2002; Tipper, 1991). Speed, capacity, and control of inhibitory information processing, certainly wanes with old age, but what about *mid*-adulthood? Thus, the question that arises is: *Does inhibitory control (i.e., INTERACT's IC component) show earlier signs of change compared to other executive components, or does it remain relatively stable until the later stages of life?*

To address the previous issues, the current study utilized INTERACT's model of EFs (Garcia-Barrera et al., 2012). Of note, the dimensions of EFs and their interactions, proposed through INTERACT, were supported in a study with a population of undergraduate students with a mean age of 21 +/- 3.92 (Frazer, 2012). The current study focused on a sample of young (30-40 years old), middle-aged (50-60 years old), and older adults (aged 70 and older). Assessing these three groups was aimed to allow for a closer look at the *nature* and *timing* of aging-related executive trends.

Hypotheses

The first aim of the present study was to evaluate the existence of performance differences on five tasks believed to tap onto INTERACT's executive components, between the three age groups. Assuming that performance differences would be found, the second goal was to identify if INTERACT's five executive components showed differential trends with age;

namely, as it was found in the literature to be a strong predictor of cognitive aging, the role of IC in relation to the four other components was considered.

It was hypothesized that (a) *quantitative trends in executive processing differentiating the three groups would be found, and* (b) *these age-related distinctions would affect INTERACT's Inhibitory Control component, at a greater level than any other EF.*

Finally, it was hypothesized that if (a) and (b) were found to be true, then contrasting the performance of all participants on the Go/No-Go paradigm (one measure of IC; Donders, 1969) would help clarify the degree to which IC differed at earlier and later stages of aging. As mentioned earlier, Hasher and colleagues have thoroughly investigated the role of IC with regards to aging, and have suggested that there is a *nearly linear decline* from early to late adulthood (e.g., Carlson et al., 1995; Chung et al., 2002; Connelly et al., 1991; Darowski et al., 2008; Goldstein et al., 2006; Hamm & Hasher, 1992; Hasher & Zacks, 1988; Kane et al., 1994; Stoltzfus et al., 1993). It is important to note however, that these researchers have based their assumptions on results involving the performance of younger (e.g., 17-22 years old in Carlson et al., 1995; and 18-32 in Chung et al., 2002) and older (e.g., 62-75 years old in Carlson et al., 1995; and 58-78 in Chung et al., 2002) participants, *leaving out adults of ages lying between these two stages of life*. This further bolsters the recurrent issue of empirical paucity pertaining to IC trends for *most* of the adult life (i.e., ages 20-60). On the other hand, some researchers have investigated the lifespan trends associated with inhibition (e.g., Darowski et al. [2008] looked at the role of distraction control in adults aged 18-87). Regrettably though, they omitted to look at the relationship of this particular element *in relation to other EFs*. Either way, we cannot reliably assume that the executive changes occurring *between* the ages of 30-50 are actually linear and, that the hypothesized decline affecting IC is *above and beyond* aging trends affecting *other* elements of executive processing.

Fortunately, the current study represented an opportunity to address these concerns. Indeed, these last challenges inspired the third hypothesis: (c) *an age-associated linear decline in performance on the chosen executive tasks would be observed; and, although all components may be negatively impacted by age, only performance on the Go/No Go paradigm would be characterized by a significant and linear drop*. At last, confirming (c) would allow for an attempt to bridge the gap between what we know regarding the ascent and descent of executive processes, particularly pertaining to IC changes across the adult lifespan.

Methods

Participants

Approval from the Human Research Ethics Board (HREB) was obtained before starting recruitment and then revised upon the changes implemented after the pilot testing. Younger, middle-aged, and older adults constituted this study's research sample. Eligibility for participating in the study was based on the following conditions: no history of significant vision problems, of neurologic disorder, or history of a traumatic brain injury. Additionally, individuals who participate in weekly (or greater) recreational drug use (other than tobacco and alcohol) were excluded from the study. The original aim was to obtain 30 participants per group for each of the three groups (N=90). After running pilot testing with 10 participants, as it will be explained shortly, tasks were re-ordered and modified, taking into consideration the subjects' feedback; these pilot participants were excluded from the present analyses. After pilot testing the tasks, despite our best recruitment efforts, the current sample added up to just over a third of the target size (N=32). Group 1 included 9 adults of ages 30-40 (M=33.333; SD=3.127), Group

2: 10 adults of ages 50-60 (*M*=55.636; *SD*=2.900), and Group 3: 13 adults of ages 70 and older (*M*=80.167; *SD*=9.362) (see Table 1). Participants were recruited from local recreational centers, retirement homes, the University of Victoria, and other community-active establishments. Participants were entered in a raffle for a chance to win a $50 gift-certificate from EBay. Concerns pertaining to power due to the small sample size will be discussed in the next major sections of this document.

Table 1

Demographic data of the 30-40, 50-60, and 70 and above age groups

Variable	Group 1: 30-40	Group 2: 50-60	Group 3: 70 +
Number of participants	n=9	n=10	n=13
Age range	30-38	50-60	72-92
Age (SD)	33.333 (3.127)	55.636 (2.900)	80.167 (9.362)
Gender (M/F)	5/4	2/8	4/9

Procedure

All participants were administered five tasks presumed to measure INTERACT's five EF components. All tasks were administered on a computer; the tasks required minimal knowledge of computers, as performing them only required the use of the space bar or number keys. The order of the tasks was originally planned to be as follow: 1) Problem Representation task, 2) Updating WM task, 3) AC task, 4) IC task, 5) R/V P task. After pilot testing the battery, and due to the notable difficulty of the first task (i.e., Problem Representation), some of the tasks had to be re-ordered, modified, and some instructions had to be added. Specifically, as it appeared to discourage our pilot participants to keep going and to complete the next tasks, the Problem Representation task (i.e., Raven's Advanced Progressive Matrices; Raven, Raven, & Court, 1998) was moved to the end of the battery. Further, as it will be outlined next, a practice trial was included at the beginning of the task, and the matrices' trials in each block were reduced from 8 to 4. Moreover, as pilot participants noted a need for clarification on the Attentional Control task's instructions (i.e., Local-Global 'switching' task; Miyake 2000), the Local-Global task was given a new set of instructions (i.e., more detailed), and participants were required to respond correctly before progressing to the next stimulus (i.e., each stimulus stayed on the screen until a correct response was made); which differed from previous settings.

Testing was done on an individual basis, one session lasting approximately 45 minutes to 1 hour. Participants were informed of the purposes, risks and benefits of the study, and of its voluntary nature. They were also required to provide written and informed consent.

Note. In addition to the outlined procedures, given this opportunity for recruitment, the History Questionnaire found in Appendix A, as well as the UCLA Loneliness Scale-Revised (UCLA-R), a 20-item questionnaire measuring general perception of social connection or isolation (See Appendix B; Russell, 1996; Russell, Peplau, & Ferguson, 1978), were used as estimates of cognitive functioning, reserve, and mediating factors. As cognitive reserve does not represent the focus of this study, data collected to this end was not included in the present analysis; however, as it will be explained later, we plan to use this information in future studies examining the impact of lifestyle variables and individual differences over EFs.

Tasks. Based on Confirmatory Factor Analysis results testing the latent measurement model of INTERACT (Frazer, 2012), and due to their suitable and compelling qualities, the following five tasks were chosen for the present study:(a) the Letter Memory task (see Morris & Jones, 1990), (b) the Local-Global 'switching' task (Miyake 2000), (c) the Go/No-Go paradigm (Donders, 1969), (d) a computerized version of the Iowa Gambling Task (Bechara et al., 1994), and (e) a modified version of the Raven's Advanced Progressive Matrices (Raven, Raven, & Court, 1998). As mentioned previously, the tasks' original order was different from the latter (i.e., the Raven's Advanced Progressive Matrices originally appearing at the beginning of the battery) to adjust to pilot participants' suggestions and complaints.

Updating working memory. The task used to evaluate Updating WM is called Letter Memory (see Morris & Jones, 1990). The standardized factor weight associated with this task as an indicator of Updating WM was identified by Frazer (2012) as 0.42.

For this task, a running sequence of letters randomly varying in length (between 7-12 letters), was displayed on the computer screen. Participants were asked to silently rehearse the last four letters of the series as they were displayed, in a continuous manner. At the end of a sequence, participants were prompted and required to type the target letters (i.e. the final four letters of the target sequence). For instance, if participants were presented with the sequence 'A, D, Z, B, G, H, R, C', they were to rehearse the sequence in a continuous manner, as letters were presented to them, as such: 'A, AD, ADZ, ADZB, DZBG, ZBGH, BGHR, GHRC'. Then, participants had to type 'GHRC' on the keyboard.

There were five trials for which the total number of letters recalled correctly and in the correct order (out of a possible total number of 20 letters recalled), was used as an indicator of Updating WM.

Attentional control. The task used to indicate attentional switching was the Local-Global 'switching' task, which was also used in the work of Miyake and colleagues (2000) to indicate 'switching'. The standardized factor weight associated with this task as an indicator of Attentional Control was identified by Frazer (2012) as 0.49.

For this task, participants were presented with 'Navon figures' (Navon, 1977). Navon figures are geometric shapes which possess local and global qualities. That is, they are composed of multiple individual shapes (i.e., local quality), which may be different from the particular figures that these small shapes represent together as a whole (i.e., global quality). For instance, a Navon figure may be constituted of multiple small triangles (i.e., local), which may be assembled in such a way that, as a whole, they represent a square (i.e., global; see Figure 3 below).

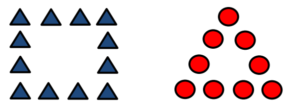

Figure 3. Example 'Navon figures' (Navon, 1977) used in the Local-Global task.

Participants were required to press the following number keys to indicate whether either the local or global geometric figures represented a circle, a triangle, or a square: circle = 1, triangle = 3, square = 4. When presented with *blue* Navon figures, participants had to press on either the number key 1, 3, or 4, to indicate what shapes were represented *globally*. Conversely, when presented with *red* Navon figures, participants had to press on either the number key 1, 3, or 4, to indicate what shapes were represented *locally*. Thus, as they alternated their focus from the global to the local qualities of the figures, participants were required to 'switch' their attention back and forth between stimuli, which is believed to tap onto Attentional Control skills.

There were three trial blocks. The first one consisted of *blue* Navon figures only (i.e., draws from the *global* cue). The second trial block consisted of *red* Navon figures only (i.e., draws from the *local* cue). Finally, the third and final block consisted of randomly presented both red and blue Navon figures, thus alternating between global and local cues.

'Switch costs' were derived by a) subtracting average reaction response time to figures in trial block 1, from average reaction response time to figures in trial block 3 (requiring a 'shift' of attention); and b) subtracting average reaction response time to figures in trial block 2, from average reaction response time to figures in trial block 3 (also requiring a 'shift' of attention)

(Frazer, 2012). An average of these 'switch costs' was used as an indicator variable for Attentional Control.

Of note, the following changes were made to the task after pilot testing. Due to a need for clarification on the task's instructions, the Local-Global task was given a new set of more detailed instructions. Further, to ensure the participants' understanding of the task, each stimulus stayed on the screen until a correct response was made (before moving on to the next stimulus).

Inhibitory control. The task used to indicate inhibition of a prepotent response was the Go/No Go paradigm (Donders, 1969). The standardized factor weight associated with this task as an indicator of Inhibitory Control was identified by Frazer (2012) as 0.61.

On this task, participants were presented with a single letter, which appeared in the center of the computer screen, at a rate of approximately 1 word per 1,400 msec. There were two trial blocks. On the first block, which consisted of the 'go' trial, participants were required to press the spacebar as fast as possible, whenever a letter appeared on the screen. On the second block, which consisted of the 'no-go' trial, participants were also required to press the spacebar as fast as possible, whenever a letter appeared on the screen; however, for this second task block, whenever the letter 'J' appeared on the screen, they had to *inhibit* their prepotent response (i.e. they had to *not* press the spacebar). Of note, the 'no-go' stimulus (the letter 'J') was presented in a random manner amongst the other letters.

As the second block required additional inhibitory control compared to the first one, more errors were expected for this trial. The total number of errors on the no-go trials was used as an indicator variable for Inhibitory Control.

Reward/valence processing. The task used to indicate R/V P was a computerized version of the Iowa Gambling Task (Bechara et al., 1994). The standardized factor weight associated with this task as an indicator of R/V P was identified by Frazer (2012) as 0.53.

For this task, participants were presented with four decks of cards, each deck corresponding to one of the number keys 1-4. They were required to select one card at a time from the decks, for a total of 100 cards, by pressing the number key corresponding to the deck from which they wished to pick a card. Each card was either associated with a reward (i.e., arbitrary gain), or a punishment (i.e., arbitrary loss). Two of the decks were associated with small gains (e.g., $2) and small losses (e.g., $2), whereas the other two decks were associated with larger gains (e.g., $4), but also greater losses (e.g., $10). Participants had to aim to gain as much as possible, and to lose as little as possible. The decks associated with smaller gains and losses resulted in a net profit, as opposed to the decks associated with greater gains and losses, which led to a long-term net loss.

Every time participants picked a card, the associated gain or loss value was displayed on the computer screen, in conjunction with a happy emoticon face (i.e., when there was a gain) or a sad emoticon face (i.e., when there was a loss; see Figure 4 below). The total amount of gains and losses accumulated by the participants was displayed above the emoticon. Participants were expected to learn which decks were more advantageous or disadvantageous across trials, and to make decisions accordingly.

The total number of disadvantageous card/deck selections was subtracted from the total number of advantageous card/deck selections to indicate Reward/Valence Processing.

Figure 4. Sample display screen for the computerized Iowa Gambling Task.

Problem representation. The task used to evaluate Problem Representation was a computerized and modified version of Raven's Advanced Progressive Matrices (Raven, Raven, & Court, 1998). The standardized factor weight associated with this task as an indicator of Problem Representation was identified by Frazer (2012) as 0.37.

To successfully complete this task, participants were expected to organize and sequence novel information, which required the deduction and application of certain rules. A sequence of visual puzzles (or matrices), which were organized in a logical order according to a particular set of unwritten rules, were presented to the participants. Each series appeared as a 3x3 matrix of geometric figures and patterns, in which one piece of the puzzle was missing (see Figure 5 below). Participants were presented with a set of multiple choice options representing the potential missing piece. Participants were required to use deductive skills to select the figure that they thought corresponded to the missing part of the matrix. To indicate their answer, participants had to type in the number associated with their answer.

Four of the rules by which the logical sequence of patterns could be ordered included: "quantitative pairwise progression" (i.e. a constant change occurring 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 was 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 appeared in each of the three cells of a row), and the “distribution of two values” (two values of a categorical feature were distributed through the row, but the value for the third cell was immaterial) (Carpenter, et al., 1990)" (Frazer, 2012, p.41). Two trial blocks were conducted as an attempt to isolate Problem Representation as best as possible. Each was composed of four different matrices (i.e., one matrix for each rule). The participants were presented with 8 matrices in total. Further, between the two trial blocks, the four rules were revealed and explained to the participants. Therefore, when performing on the first trial block, participants were not aware of the rules, which created a higher level of ambiguity and novelty than in the second trial, where participants were informed of the potential solutions allowing them to respond to the problems at hand. Of note, before pilot testing the task, the settings were such that each trial block was composed of eight different matrices, for a total of sixteen matrices. Due to the tremendous difficulty faced by our pilot participants to complete the task, the trial blocks were reduced to half of the original version. Moreover, to further address this issue and to clarify the requirements, a practice trial was included at the beginning of the task.

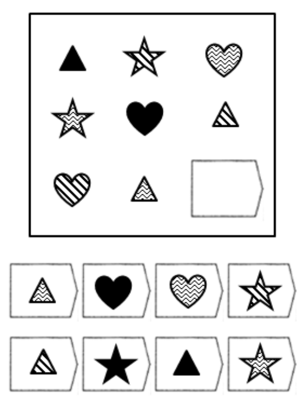

Figure 5. A hypothetical example trial for the Matrices task.

The average time taken to respond to the second trial block's matrices was subtracted from the average time used to make correct responses in the first trial block. It was expected that the first trial block would take longer in average compared to the second one, given that the participants were informed of the four possible rules between the two trials. The difference between the two trials was used as an indicator variable for Problem Representation.

Analysis

Mean performance scores for each of the five tasks for Groups 1, 2, and 3 were compared to determine if the hypothesized between-groups variations were at least partly due to age differences. MANOVA tests were used to address the aforementioned hypotheses, with all tasks of EFs representing the dependent variables (DVs) and age serving as the independent variable (IV); more specifically, these analyses were used to address the first hypothesis which predicted an overall decline of EFs with age, assuming the *global* sensitivity of EFs to aging. Hypothesizing the model predicted a significant amount of the variance in the linear combination of EFs outcomes. Follow-up separate ANOVA tests followed by Scheffe and Bonferroni post hoc tests were used to determine which task(s) contributed most to any potential between-group(s) difference(s). Unlike the first statistical procedure (i.e., MANOVA), which was applied to investigate the *unity* of EFs, these trend analyses (i.e., ANOVAs) served to inform possible interactions between tasks, age and ultimately, EFs as a function of age, assuming the relative independence (i.e., *diversity*) of performance across tasks. As explained earlier, the tasks are thought to tap into *separate* and *dividable* EFs. Thus, ANOVA tests were deemed appropriate to target the second and third hypotheses which concerned the *individual* roles of the components across the adult lifespan. Moreover, as the five tasks of EFs operate on different scales, scores were transformed (i.e., T values) to allow performance comparisons across tasks and between groups. A main effect between groups and between tasks was expected, and the IC task (the Go/No Go paradigm) was predicted to show the greatest effect across age groups.

Results

Data Preparation

Data cleaning and screening. Before analyzing the data, scores for all 32 individuals were examined. Data was extracted from MATLAB, cleaned and screened for missing data and outliers. The Go/No-Go and Local Global tasks were both screened the same way: mean response times (for correct responses only) faster than 150ms were rejected, based on previously established lower-bound cut-offs (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000), providing a conservative estimate of variability. Reaction times larger than three standard deviations above the mean were also excluded. Data loss in most cases was negligible (<2% of responses). Results for Raven's Advanced Progressive Matrices were screened as follow: mean response times for each block with outliers removed according to the next criteria. Responses faster than 100ms and greater than 200secs were excluded, followed by responses greater than three standard deviations above the mean. Responses in which participants guessed wrong overall more than 8 times were removed (i.e., total number of possible answers per item:8, corresponding to number keys 1-8); suggesting that these participants might have been pressing random keys for each item until they found the correct response. Finally, Iowa Gambling and Letter Memory scores remained untouched as they were found to be unremarkable and analyses only required subtracting the total number of disadvantageous card/deck selection from the total number of advantageous card/deck selection (Iowa Gambling), and adding the total number of letters recalled correctly across trials for the Letter Memory task. Please see Table 2 below for information regarding analysis and participant(s)/data inclusion based on task completion.

Table 2

Number of participants per task[a], and mean T values per task and age group[b]

Task	Group 1:30-40	Group 2: 50-60	Group 3: 70+
Letter Memory	n=9 (51.699, 8.215)	n=10 (56.069, 8.974)	n=13 (44.156, 8.232)
Local Global	n=9 (51.832, 4.832)	n=10 (52.199, 6.465)	n=11 (45.335, 15.227)
Go/No-Go	n=9 (55.181, 11.264)	n=10 (45.147, 4.878)	n=13 (50.147, 9.502)
Iowa Gambling	n=9 (54.787, 9.481)	n=10 (49.403, 10.432)	n=13 (47.145, 7.961)
R.A.P.M.[c]	n=9 (56.138, 6.532)	n=10 (47.822, 6.765)	n=10 (46.922, 12.370)

[a]Refers to the number of participants having completed each task.
[b]Mean T values and SDs in parentheses following the number of participants for each task.
[c]Raven's Advanced Progressive Matrices.

Missing data. There were relatively few missing scores; the only missing data pertained to the third age group. For Local Global, two participants in Group 3 did not complete the task (task error and inaccuracy deemed the task as incomplete); for the Raven's Advanced Progressive Matrices, three participants in Group 3 did not complete all of the task-items. No specific pattern accounting for the missing data seemed to exist; rather, the frustration experienced by participants in the 70 and up age group, and perhaps fatigue, both related to task difficulty, acted as the most plausible explanations for the missing data. No statistical imputation or estimation was needed to replace or deal with the missing data. In future studies, counter-balancing the order in which the tasks are administered could be a valuable approach to overcome some of the challenges associated with task completion, frustration, and fatigue.

Normality and homoscedasticity. Fit between distributions and assumptions were examined. Normality assumptions were confirmed using the Shapiro-Wilk test of normality (appropriate for smaller sample sizes), and Levene's test of homogeneity of variance was used to verify homoscedasticity, given that T tests and ANOVA assume the presence of homogeneity. Testing the assumption that variances of the populations from which the samples were drawn were equal revealed that the obtained differences in sample variances for all tasks but the

Raven's Advanced Progressive Matrices and the Local Global task, were likely to have occurred based on a random sampling of a population with homogeneous variance. Levene's test indicated unequal variances for the Raven's Advanced Progressive Matrices (F=5.096, p=.014), and the Local Global task (F=4.237, p=.025). This resulted in rejecting the null hypothesis which assumed that the error variance of the dependent variable is equal across Groups 1-3 for these two measures. For this reason, considerable caution in interpreting statistical results pertaining to the Raven's Advanced Progressive Matrices and the Local Global task is needed.

Main Effect

MANOVA tests with all tasks of EFs representing the dependent variables (DVs) and age serving as the independent variable (IV) revealed a non-significant multivariate main effect for EFs as a function of age: Wilks' λ =.529 (F=1.576, p=.147), Roy's Largest Root= .510 (F=2.243, p=.086). Included in the MANOVA based on completion of all five tasks were n=9 for Group 1, n=10 for Group 2, and n=9 for Group 3 (see Tables 3-4, and Figures 6-7 below for mean T values). Since our three groups had unequal n's, it is preferable to look at tests other than Hotelling's Trace and Pillai's Trace tests (Anderson, 2003). The present MANOVA tests assessed the overall correlation between executive functioning and age, thus treating EFs as a unitary construct. The observed power on the multivariate tests to detect a main effect was poor <.80: Wilks' λ =.677, Roy's Largest Root=.613; as well as on the tests of between-subjects effects: Letter Memory=.536, Local Global=.228, Go/No-Go==.447, Iowa Gambling=.321, and Raven's Advanced Progressive Matrices=.558. Moreover, to assess the aforementioned diversity of EFs, subsequent to performing the main effect test, separate Univariate tests were conducted.

Univariate Effects

ANOVA tests followed by Scheffe and Bonferroni post hoc tests were used for each task, revealing a non-significant univariate effect for all measures except for the Letter Memory task; suggesting no statistically significant difference for all EF components but Updating WM, as a function of age. The tasks and related results are discussed below in the order of test administration.

Table 3

Mean T values and SDs for each EF task, per age group

Task	Group1: 30-40	Group 2:50-60	Group 3: 70+
Letter Memory	51.699 (8.215)	56.069 (8.974)	44.156 (8.232)
Local Global	51.832 (4.832)	52.199 (6.465)	45.335(15.227)
Go/No-Go	55.181 (11.264)	45.147 (4.878)	50.147 (9.502)
Iowa Gambling	54.787 (9.481)	49.403 (10.432)	47.145 (7.961)
R.A.P.M.[a]	56.138 (6.532)	47.822 (6.765)	46.922 (12.370)

[a]Raven's Advanced Progressive Matrices

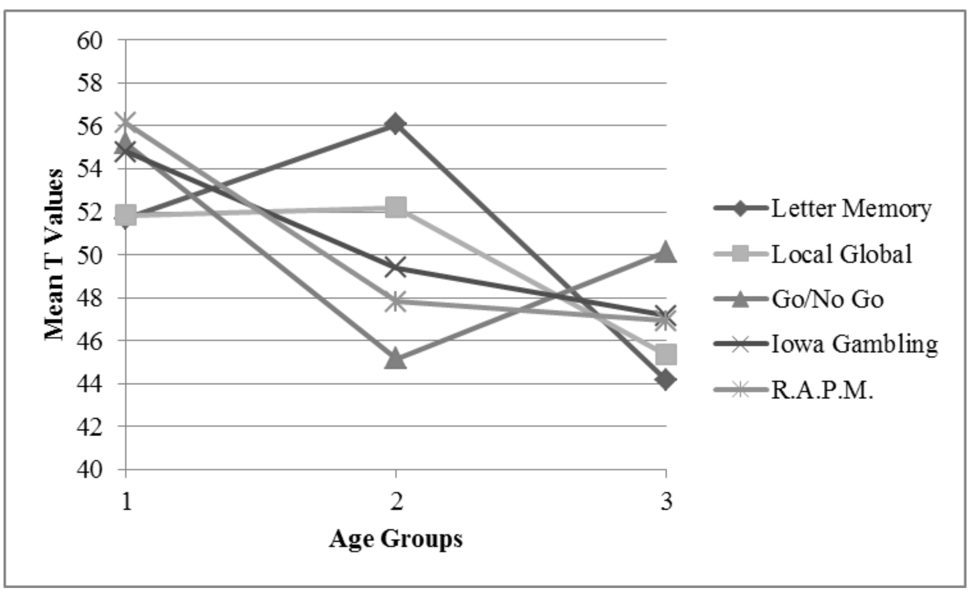

Figure 6. Mean T values for each EF task, per age group.

Table 4

Mean T values and SDs for each age group, per EF task

Task	Letter Memory	Local Global	Go/No-Go	Iowa Gambling	R.A.P.M. [a]
Group1:	51.699	51.832	55.181	54.787	56.138
30-40	(8.215)	(4.832)	(11.264)	(9.481)	(6.532)
Group2:	56.069	52.199	45.147	49.403	47.822
50-60	(8.974)	(6.465)	(4.878)	(10.432)	(6.765)
	44.156	45.335	50.147	47.145	46.922
Group3: 70+	(8.232)	(15.227)	(9.502)	(7.961)	(12.370)

[a]Raven's Advanced Progressive Matrices

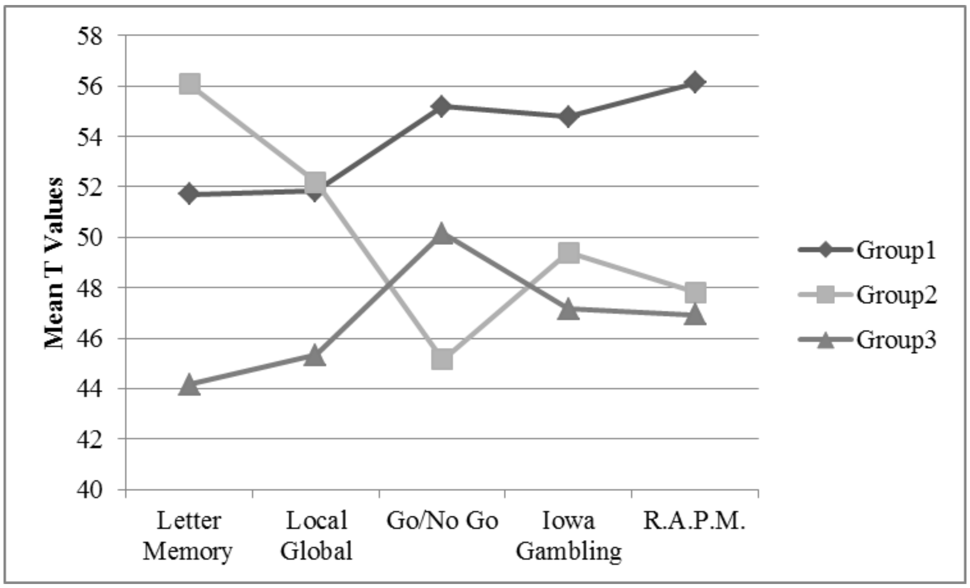

Figure 7. Mean T values for each age group, per task.

Updating WM. Looking at the total number of letters recalled for a possible maximum of 20 on the Letter Memory task, a statistically significant difference between group means as determined by a univariate ANOVA was found, $F(2,29)=5.374$, $p=.010$. Scheffe ($p=.012$) and Bonferroni ($p=.010$) post hoc tests revealed a statistically significant difference between the means of Groups 2 and 3 indicating that the mean number of recalled letters for Group 2 (raw scores: $M=11.417$, $SD=4.769$) was significantly higher than Group 3 (raw scores: $M=5.364$, $SD=4.375$) (see Table 5 and Figure 8 below), and suggesting a statistically significant difference for Updating WM between the 50-60 vs. 70 and up individuals.

Table 5

Mean accuracy scores for Letter Memory

Variable	Group 1: 30-40	Group 2: 50-60	Group 3: 70+
Mean raw scores (SD)	9.778 (4.366)	11.417 (4.769)	5.364 (4.375)
Mean T values (SD)	51.699 (8.215)	56.069 (8.974)	44.156 (8.232)

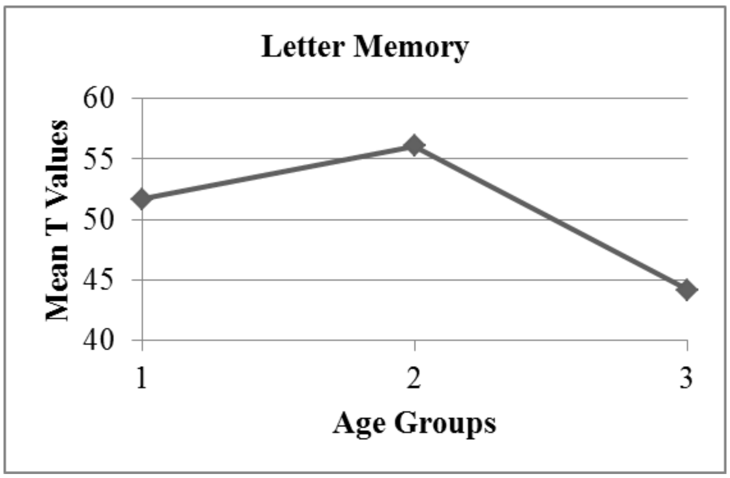

Figure 8. Mean response accuracy T values for each age group on the Letter Memory task.

Attentional control. There was no statistically significant difference between group means as determined by a one-way ANOVA looking at 'switch costs' on the Local Global task, $F(2,27)=1.577$, $p=.225$ (see Table 6 and Figure 9 below); suggesting no statistically significant difference for Attentional Control as a function of age. Given the rather complex method by which 'switch costs' were obtained (outlined previously in the Methods section), raw scores were not included in the table below.

Table 6

Mean transformed 'switch costs' for Local Global

Variable	Group 1: 30-40	Group 2: 50-60	Group 3: 70+
Mean T values (SD)	51.832 (4.832)	52.199 (6.465)	45.335 (15.227)

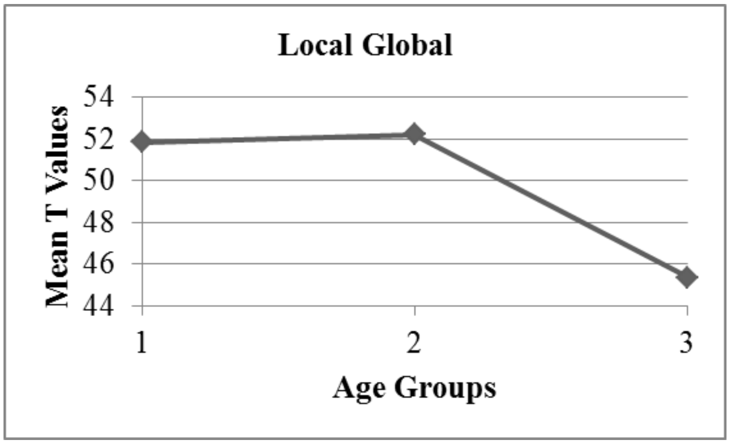

Figure 9. Mean T values for each age group on the Local Global task.

Inhibitory control. There was no statistically significant difference between group means as determined by a one-way ANOVA looking at the total number of errors on the Go/No-Go task, $F(2,29)=2.639$, $p=.088$ (see Table 7 and Figure 10 below); suggesting no statistically significant difference for Inhibitory Control as a function of age. Interestingly, Group 1 had the lowest mean score compared to both Groups 2 and 3. Raw scores for Group 1 revealed two scores that could possibly account for this surprising difference: one participant made 8 errors, and another subject made 10 errors, the latter representing the highest number of individual errors across the three groups. As these two participants did not qualify as outliers, and due to the small sample size and the experimental nature of the tasks used in this study, caution in interpreting these findings is necessary. Please note that as the scores were based on the total number of errors made across blocks, higher scores should be viewed as indicative of poorer performance.

Table 7

Mean number of errors for Go/No-Go

Variable	Group 1: 30-40	Group 2: 50-60	Group 3: 70+
Mean raw scores (SD)	5.000 (2.582)	2.500 (1.118)	4.273 (2.178)
Mean T values (SD)	55.181 (11.264)	45.147 (4.878)	50.147 (9.502)

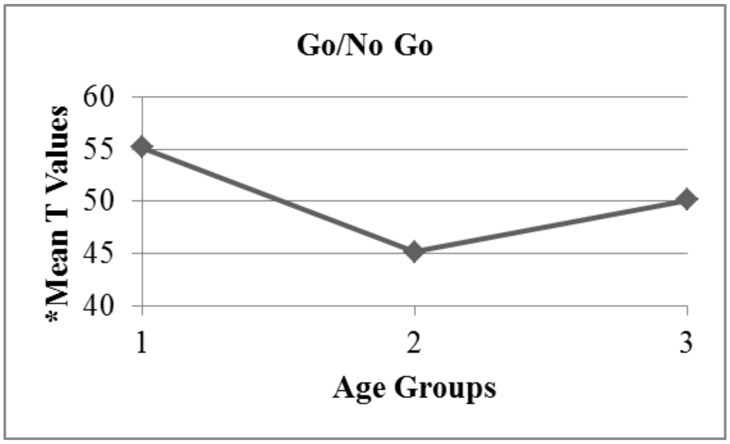

Figure 10. Mean T values for each age group on the Go/No-Go task.

Note. Higher scores denote poorer performances.

Reward/valence processing. There was no statistically significant difference between group means as determined by a one-way ANOVA looking at the total number of disadvantageous card/deck selections subtracted from the total number of advantageous card/deck selections on the Iowa Gambling task, $F(2,29)=1.644$, $p=.211$ (see Table 8 and Figure 11 below); suggesting no statistically significant difference for Reward/Valence Processing as a function of age.

Table 8

Mean difference of good vs. bad deck selections for Iowa Gambling

Variable	Group 1: 30-40	Group 2: 50-60	Group 3: 70+
Mean raw scores (SD)	9.889 (13.892)	-0.167 (15.285)	0.455 (11.665)
Mean T values (SD)	54.787 (9.481)	49.403 (10.432)	47.145 (7.961)

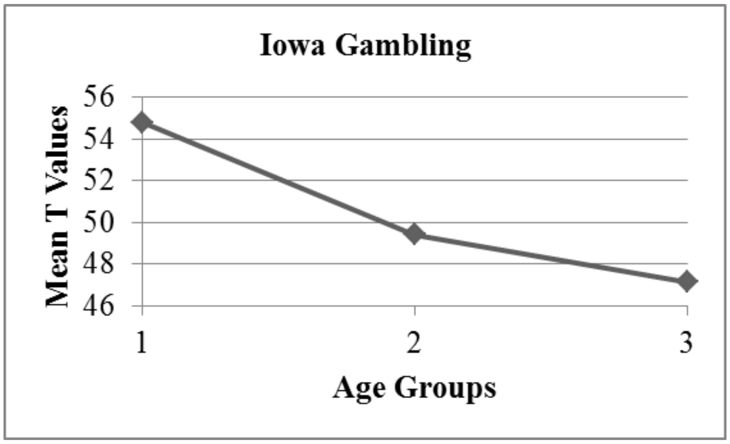

Figure 11. Mean T values for each age group on the Iowa Gambling task.

Problem representation. There was no statistically significant difference between group means as determined by a one-way ANOVA looking at the average reaction time of the second block (help trial) subtracted from the first block (no help trial) on the Raven's Advanced Progressive Matrices, $F(2,26)=2.636$, $p=.091$ (see Table 9 and Figure 12 below); suggesting no statistically significant difference for Problem Representation as a function of age. Please note: this comparison (block 1 vs. block 2) refers to the difference in reaction time between the no help trial and the help trial believed to be indicative of planning and strategizing associated with Problem Representation. As explained earlier, it was expected that reaction time would decrease from the first to the second trial, as the help trial is intended to require less planning. While no significant difference was found, the discussion section will address the potential reasons accounting for the performance patterns between and within groups. In any case, the scores below suggest a greater capacity for learning from rules in a manner benefiting Problem Representation skills for younger adults, compared to Groups 2 and 3.

Table 9

Mean difference for reaction times on block 2 vs. block 1 for R.A.P.M.[a]

Variable	Group 1: 30-40	Group 2: 50-60	Group 3: 70+
Mean raw scores (SD)	19.258 (18.480)	-7.794 (21.500)	-2.656 (36.445)
Mean T values (SD)	56.138 (6.532)	47.822 (6.765)	46.922 (12.370)

[a]Raven's Advanced Progressive Matrices

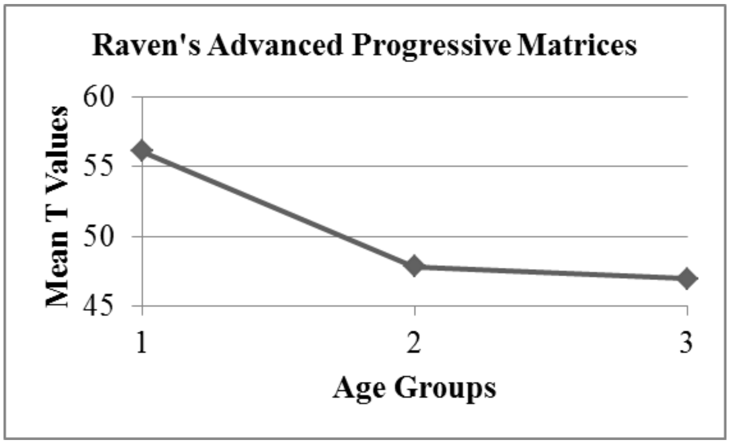

Figure 12. Mean T values for each age group on the Raven's Advanced Progressive Matrices.

Discussion

Age-related decline in EFs is a controversial topic. This debate is based partly in our difficulty to define and conceptualize these abilities, and to create reliable and valid measures to assess them. Topics that have yet to be thoroughly investigated pertain to the next queries. Is there a general decline of EFs as we get older? Do these abilities remain stable between emerging and late adulthood? Can we develop age-sensitive models of EFs? Can we learn from younger and middle-aged adults to create strategies and interventions to improve EFs in the elderly? These questions remain unanswered and the current research was an attempt to explore some of these topics and the puzzling developmental nature of executive functioning in adulthood.

Hypotheses

First and foremost, this study aimed to investigate age-related changes in executive functions across the adult lifespan. To address this, the first objective of the study was to determine whether differences in EFs could be found across adulthood, hypothesizing that looking at younger, middle-aged, and older adults would reveal such trends. Acquiring this type of information could have shown great value given the paucity of research targeting age trends for performance of normal adults between the ages of 30-60 on EF tasks. Unfortunately, perhaps largely due to the small sample size (N=32), the first hypothesis could not be confirmed statistically at this time. Interesting patterns of performance variability however, were observed and will be discussed shortly. Overall, these trends appeared to further confirm the changes occurring across adulthood that have been consistently outlined in the literature (e.g., Craik & Bialystok, 2006; Darowski et al., 2008); that is, despite the low statistical power of this study and even if a significant difference was only found on the Updating WM task, the performance of the three groups *did* differ on *all* tasks, suggesting heterogeneity and/or changes in EFs across the adult lifespan.

As for the second and third goals, which predicted finding age-related distinctions affecting INTERACT's IC component, at a greater level than any other EF and characterized by a significant linear drop, no significant outcome was found either. As noted previously, the unexpected performance of two participants in Group 1 (i.e., representing the lowest scores across Groups 1-3) may have masked any existing significant effect, and leading Group 1 (M=55.181, SD=11.264) to have the lowest mean performance (mean T value) compared to Groups 2 (M=45.147, SD=4.878) and 3 (M=50.147, SD=9.502). Again, please note that for this task, scores were based on the mean number of errors, signifying that higher scores represent poorer performances.

DLPFC and Other Age-Related Effects

Age-related effects on IC. As just outlined, the Go/No-Go task did not reveal the hypothesized age trends. Not only must we acknowledge this study's small sample size in explaining this finding, but also, the role of the aforementioned multifaceted and interactive PFC networks that allow individuals of all ages to do this task. As seen in the introduction, performance on tasks possessing Go and No-Go conditions such as the stop-signal responsiveness (a task similar to Go/No-Go; Aron, 2007) is known to decline with age (e.g., Andrés et al., 2008); thus, greater statistical power would have been anticipated to allow for such age trends to emerge in the current study. Moreover, undoubtedly, measures of inhibition for prepotent responses tap onto IC, which, like other EFs, requires PFC activation. Establishing the *specific* localization of IC processes *within* the PFC however, appears to be a rather complex endeavour and may partially cloud our ability to interpret results such as the ones relevant to this study; that is, drawing conclusions pertaining to functional differences is complicated by the multifaceted brain processes underlying them. Functionally isolating executive inhibition in the brain may depend on the level of task complexity (i.e., the number of stimuli used in the Go/No-Go task design). Indeed, a meta-analysis looking at functional Magnetic Resonance Imaging (fMRI) activation (Simmonds, Pekar, & Mostofsky, 2008) for simple to complex Go/No-Go tasks was able to illustrate how cerebral activation associated with inhibition (i.e., IC) is task-dependent; specifically, the right DLPFC was found to be particularly involved on more complex designs requiring increased working memory demand. This should not come as a surprise given the interdependence of these two functions (i.e., IC and Updating WM) on DLPFC circuits, and the aforementioned importance of executive *interactions*. As it will be discussed next, the potential interactions linking these two EFs and allowing for more complex executive processing, may partly explain aging changes pertaining to the DLPFC and to associated functions. Overall, it appears evident that the complexity inherent to defining IC as a construct, and the presence of various neurocorrelates implicated in creating inhibitory abilities, act as important challenges to measuring and isolating this concept from other components. As pointed out by Simmonds et al. (2008), comparing performance on the Go vs. No-Go trials to indicate inhibition, is "confounded by issues such as task difficulty, attention, different stimuli and maintenance of stimulus-response associations, and as such is not ideal for isolating regions involved in the inhibitory process." (p.225) Acknowledging the limits to seemingly pure tasks such as this one is crucial, especially when one wishes to draw inferences pertaining to their underlying cortical activation. The restrictions of the Go/No-Go paradigm to fully encapsulate IC, and the influence of executive interactions over performance across adulthood are hereby recognized. In future studies, it would be helpful to include additional measures of IC to encompass the multidimensional aspects of this construct.

Age-related effects on Updating WM. Only one ANOVA test revealed the presence of a subtle and specific complex cognitive age decline. Interestingly, a statistically significant univariate effect was only found on the Letter Memory task. More specifically, post hoc tests revealed that the mean T value for Group 2 (M=56.069, SD=8.974) was significantly higher than the mean T value for Group 3(M=44.156, SD=8.232) indicating that the 50-60 year old participants outperformed the 70 and up subjects on the Updating WM task. Although the current study predicted a greater age-related effect for IC above and beyond any other executive age trend, the observed finding for Updating WM is somewhat consistent with current research.

Specifically, as outlined thoroughly earlier, DLPFC functions such as Updating WM (and typically, also inhibition) are known to wane with age (e.g. Craik & Bialystok, 2006; Johnson et al., 2004; Jurado & Rosselli, 2007; MacPherson et al., 2002; Milham et al., 2002; Murphy et al., 1999). Thus, the superior performance of our middle-aged individuals compared to that of the older subjects does not come as a surprise; however, that Group 2 outperformed Group 1 (M=51.699, SD=8.215), while not in a statistically significant manner, is perplexing. Individual scores do not suggest the presence of outliers accounting for this difference. Nevertheless, as it will be discussed shortly, these results may be better explained in terms of the overall variability found in Group 2's performance across the five EF tasks, compared to that of the other groups, which was more consistent throughout.

Age-related effects on executive interactions. Going back to Miyake and colleagues' view on the unity *and* diversity of EFs (2000), and what was later advanced by Garcia-Barrera et al. (2012), results such as the ones outlined above, may be enlightened by a greater understanding of *interactions* among EF components. Despite having a different take than those who suggested that WM is executive processing's *central* element (Baddeley & Hitch, 1974; Baddeley, 1986; Goldman-Rakic, 1996), we also believe that through its interaction with other components, Updating WM *is* crucial to normal functioning. As portrayed in Figure 2 (the INTERACT model: Garcia-Barrera et al., 2012), it is possible that this component rests at the center of the executive system, facilitating communication among other functions, without necessarily being the most important EF. Again, our understanding of Updating WM leads us to think that is not the most crucial element of complex cognition, rather, its role is essential because it allows for the syntax formulated by Problem Representation to be carried over to INTERACT's 'cybernetic' dimension, uniting the *How* (i.e., Problem Representation) and *When* (i.e., Attentional Control, Inhibitory Control, and Reward/Valence Processing). This stance on Updating WM may guide our interpretation of its function over cognitive aging; namely, it can be hypothesized that WM changes in the elderly might be generally more subtle than IC declines. However, as they are both closely linked through their activation of DLPFC networks, aging trends at the WM level may have cascading and exponential effects on IC. Either way, the present findings only allow for speculations on interactions pertaining to this fascinating system. Overall, it is assumed that greater statistical power via larger group sizes could have facilitated our understanding of these mutual connections among EFs. Further research focusing more closely on executive interactions across adulthood is needed.

Age-related effects on the unity and diversity of EFs. Also relevant to the current discussion are the links between executive components, interactions, and the conceptual debate on the unity and diversity of EFs. Mostly, as seen in the section describing the development of EFs, we have strong reasons to believe that the evolution of EFs across the lifespan is marked by unity in the early stages of life, with more global executive processes, and then, a fragmentation of PFC functions as we reach adulthood and as these abilities become more specialized and refined. What is uncertain, and remains a question, which this study attempted to but was incapable of answering, is whether aging brings us back to higher-order unity; that is, more unified, less divided, executive capacities. Tables 3-4, and Figures 6-7 depict patterns of performance in the three age groups that do not suggest a return to unitary executive functioning in old age per se. Rather, the presence of more closely clustered and consistent scores for the younger (Group 1) and older adults (Group 3), compared to the middle-aged subjects (Group 2) which showed a more divergent performance across tasks, suggests that different stages of adulthood might be accompanied by a reorganization of abilities and a change in strategies.

Some of the previously outlined mediators of cognitive reserve may possibly justify these trends and play different roles over EFs at distinct stages of life. For instance, it is possible that mediators of cognitive reserve affect consistency and account for some of the heterogeneity in performance in middle-adulthood. Also, perhaps it isn't that middle-aged adults present with significantly different lifestyle variables that could inform their performance as such; maybe, instead, it is simply that factors facilitating cognitive reserve at this stage of life manifest differently than earlier and later on. Other reasons shedding light on the rather harmonious executive skills of Groups 1 and 3, as tested on INTERACT's tasks, contrasted with the rather dispersed performance of Group 2, could make for a very interesting discussion that is beyond the scope of this paper. As indicated earlier, in addition to the five INTERACT tasks, a History Questionnaire and the UCLA-R were administered with the goal of using information drawn from these measures in future studies where mediating factors of cognitive reserve will be addressed; and thus, data collected to this end was not included in the present analysis. It is possible that including this information in the current study would have elucidated some of the performance differences between the three groups (i.e., statistically significant and non-significant findings). Nevertheless, a preliminary exploration of these measures does not suggest the presence of factors that could help explain some of these differences. Consideration of demographic information collected from these two measures with the addition of greater statistical power via a larger sample size will be necessary to clarify the role of potential individual differences (i.e., mediators of cognitive reserve) over EFs in future studies.

Limitations

Recruitment. As outlined thus far, multiple variables have limited the capacity of this study to take greater proportions and for particular lines of inquiry to be investigated. The greatest impediment to exploring EF interactions and the role of IC over other components for instance, was mostly attributed to the poor statistical power of our analyses, which in turn, was a result of the incredible difficulty encountered in recruiting subjects. Recruiting volunteers from the community proved to be particularly challenging, especially for individuals of ages 30-40 and 50-60. It appears recruitment problems may have been rooted primarily in the occupational status of the target groups. Indeed, the majority of eligible subjects for these groups are members of the working population, unlike individuals of ages 70 and up. This was an important obstacle to scheduling visits, despite the possibility for the research team to do on-site testing. Older (70 and over) adults' occupational status generally allows for easier access to populated sites where on-site testing can be done (e.g., retirement homes), and for this reason, individuals belonging to this age group typically have more flexible schedules than Groups 1 and 2. Also, offering larger monetary incentives could have yielded greater enrollment in the study. Nevertheless, we are extremely grateful for the involvement of all participating community, recreation, and retirement centres in assisting with scheduling our visits and aiding our recruitment efforts.

Demographics. Another potential limitation to this study pertained to the demographic characteristics of homogeneity which typify the city of Victoria's population, and thus, the present sample. Higher education levels among the target population represent a contributing factor to homogeneity. The majority of Victoria residents are well educated; for instance, in the entire population of individuals aged 35-64 living in Victoria (i.e., 31, 185), only 2, 865 do not possess a certificate, diploma, or degree; the remainder possessing at least a high school diploma, 6, 210 possessing a college or other non-university diploma or degree, and 10, 380 possessing a university certificate, diploma, or degree (Statistics Canada, 2007). As mentioned previously, education can act as a mediator of cognitive reserve. Sampling from a population of mainly Caucasian individuals possessing high school diplomas or more, may have limited our ability to detect effects normally present in more diverse (in terms of education levels) populations.

Moreover, as outlined in Table 1, gender was unevenly distributed across the three groups. A previously cited study by Friedman and colleagues (2008) looking at the genetic contributions of individual differences in the three EFs supported in Miyake's seminal research and which inspired the present study (i.e., shifting, updating, and inhibition; Miyake et al., 2000), did not find gender differences to significantly impact task performance. Nevertheless, it is possible that uneven gender ratios may account for performance differences in the current sample. After all, some studies have found EFs to emerge differentially between boys and girls in the early stages of life (e.g., Anderson, Anderson, Northam, Jacobs, & Catroppa, 2001); thus, it is possible that gender patterns underlying higher-order performance across adulthood exist, which may have influenced our findings.

Overall, we can assume that the influence of homogeneous educational characteristics and gender imbalances across the three groups would most likely have been minimized if the statistical power had been greater and if the sample had been more diverse; this needs to be addressed in our future endeavours.

Age-related effects on task completion. Another shortcoming pertains to an issue previously underlined in the Methods and Analysis sections; that is, apparent age-related effects on task comprehension and completion. The current study included a group of older individuals (i.e., ages 70 and up) which was included for comparative purposes, given what we *know* on age-related declines in EFs affecting the elderly (i.e., ages 60-65 and over), and what is *unknown* about younger adults (i.e., under 60). This group was necessary to the present analysis; however, testing these individuals was accompanied with particular challenges. As outlined previously, pilot testing unveiled issues concerning the ambiguity of the tasks' instructions, particularly for the Local Global task. Raven's Advanced Progressive Matrices also presented with notable issues, for instance, the difficulty inherent to particular items was perceived as frustrating to the extent of task-termination for some older adults. Clarification and addition of instructions on the Local Global task, and shortening (i.e., Raven's Advanced Progressive Matrices items reduced to half of the original set) and re-ordering the tasks (i.e., Raven's Advanced Progressive Matrices placed at the end of the set to prevent discouragement) led to significant improvements. Participants tested after these changes were made encountered fewer obstacles and were in great majority able to complete the entire battery. What is important here is that during and after pilot testing, complaints leading to incomplete task items were expressed by and limited to the third age group. Subjects belonging to Groups 1 and 2 expressed frustration related to their performance on certain tasks, particularly the Raven's Advanced Progressive Matrices, but only verbalized such comments *after* completing the battery. It appears that the abbreviated and final task on the battery was the greatest obstacle to this study's analysis, as failure to complete it was noted for 3 participants. It is important to note, however, that motivation did not seem to be associated with task completion. Indeed, participants in Group 3 appeared to be generally highly motivated to perform the tasks. Many of them verbalized concerns related to the outcome of their performance on these tasks and expressed feeling worried that the study would shed light on their declining abilities. The principal investigator and the research assistants did explain to the elder participants that looking at *individual* scores would not yield such findings regarding their abilities. Regardless, it appears that the fear of discovering personal cognitive deficits was a great motivator for the older subjects to give their best effort on the tasks, as opposed to the middle-aged and younger subjects who did not express these concerns as much. Nevertheless, it is possible that a larger sample and fewer incomplete Matrices would have allowed for an effect to be found, particularly one pertaining to Problem Representation and the difference between Groups on the two trial blocks. As explained earlier, between blocks 1 and 2, participants were given rules as a means to foster planning, strategies, and ultimately, Problem Representation. This was intended and did lead to increased performance for all, but particularly for younger adults, suggesting that younger individuals benefited from help on the Problem Representation task in a way that differed from the middle-aged and older subjects. In other words, it appears Problem Representation skills became more efficient for Group 1 across blocks, more so than any other group. This was perhaps a manifestation of their younger brains' high flexibility, plasticity, and capacity to learn from cues in the environment efficiently (Mahncke, Bronstone, & Merzenich, 2006). Also, it is possible that greater deliberate efforts to implement strategies on the first block were made by the younger subjects, which in turn, may have resulted in a drastically faster performance on the second block and thus, a wide gap for reaction times between sets; that is, resolving the second block's matrices was made easier by their careful planning on the first block and the addition of rules between sets.

Overall, a richer understanding of Problem Representation skills across the adult lifespan is needed, especially targeting the processes underlying planning and strategizing of complex information.

Conclusion

Many obstacles were encountered in the current study, thereby obscuring our ability to draw robust inferences at this time. Contrary to Darowski et al. (2008), this study was unable to support an IC aging hypothesis. Nonetheless, Updating WM, which is compatible with Miyake et al.'s notion of *updating* (2000) and closely linked to inhibition, was found to be susceptible to aging effects, particularly for the transition characterizing middle to late adulthood. As suggested earlier, it is likely that the interactions among EFs and the role that each component has in relation to others, have reciprocal and lateral effects. Thus, intervening at the WM level (e.g., implementing strategies facilitating the development or conservation of these skills) could be a valuable approach to increase most or all EFs in aging, even inhibition. In other words, the decreased ability to constantly update the content of one's WM may have a ripple effect on other EFs with age. Fortunately, recent studies have reviewed and pointed to the beneficial value of WM training on performance increases in WM tasks (e.g., Klingberg, 2010; Morrison & Chein, 2011), as well as transfer effects on other tasks such as reasoning (Basak, Boot, Voss, & Kramer, 2008; Borella, Carretti, Riboldi, & De Beni, 2010), and finally, it is important to note that performance growth has also been found in both younger and older *healthy* adults (Bastian, Langer, Jäncke, & Oberauer, 2013). Despite some of the current limitations, a DLPFC theory of aging still shows great appeal, with its complex and nuanced nature further reinforced by our findings.

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Appendix A. Screener Questionnaire

Name:________________________ Participant Number (*provided by researcher*):_________________

Age:____ Gender: M F

Handedness: Right Left Ethnicity: _________________

Do you have normal/corrected vision? Yes No

Do you have normal hearing? Yes No

Has a professional ever diagnosed you with a Traumatic Brain Injury (not including a concussion)? Yes No

Has a physician ever diagnosed you with any neurological conditions (e.g., epilepsy)?
Yes No

Previous Diagnoses? (Please circle all that apply)

Depression	Yes	No
Anxiety	Yes	No
Any Other Psychological Disorder Please specify:	Yes	No

Are you currently taking any prescription medication? Yes No

- If YES, which type of medication:
- How often do you take it:
- How much do you take each time:

Have you consumed any alcohol in the past 48 hours? Yes No

- Please Specify approximately how much:

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:				

Screener Questionnaire (Continued)

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 Formal Learning	Informal (Y/N)	Duration of Informal Learning
L2:			<1 yrs 1-5 yrs 6-12 yrs >12 yrs		<1 yrs 1-5 yrs 6-12 yrs >12 yrs
L3:			<1 yrs 1-5 yrs 6-12 yrs >12 yrs		<1 yrs 1-5 yrs 6-12 yrs >12 yrs

Physical Activity Levels

We are interested in finding out about the kinds of physical activities that people do as part of their everyday lives. The questions will ask you about the time you spent being physically active in the last 7 days. Please answer each question even if you do not consider yourself to be an active person. Please think about the activities you do at work, as part of your house and yard work, to get from place to place, and in your spare time for recreation, exercise or sport.

Think about all the vigorous activities that you did in the last 7 days. Vigorous physical activities refer to activities that take hard physical effort and make you breathe much harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

1. During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, digging, aerobics, or fast bicycling?

_____ days per week **If you performed no vigorous physical activities, skip to question 3.*

2. How much time did you usually spend doing vigorous physical activities on one of those days?

_____ hours per day _____ minutes per day _____Don’t know/Not sure

Think about all the moderate activities that you did in the last 7 days. Moderate activities refer to activities that take moderate physical effort and make you breathe somewhat harder than normal. Think only about those physical activities that you did for at least 10 minutes at a time.

3. During the last 7 days, on how many days did you do moderate physical activities like carrying light loads, bicycling at a regular pace, or doubles tennis? Do not include walking.

_____ days per week **If you performed no moderate physical activities, skip to question 5.*

Screener Questionnaire (Continued)

4. How much time did you usually spend doing moderate physical activities on one of those days?

_____ hours per day _____ minutes per day _____Don't know/Not sure

Think about the time you spent walking in the last 7 days. This includes at work and at home, walking to travel from place to place, and any other walking that you have done solely for recreation, sport, exercise, or leisure.

5. During the last 7 days, on how many days did you walk for at least 10 minutes at a time?

_____ days per week **If you performed no walking, skip to question 7.*

6. How much time did you usually spend walking on one of those days?

_____ hours per day _____ minutes per day _____Don't know/Not sure

The last question is about the time you spent sitting on weekdays during the last 7 days. Include time spent at work, at home, while doing course work and during leisure time. This may include time spent sitting at a desk, visiting friends, reading, or sitting or lying down to watch television.

7. During the last 7 days, how much time did you spend sitting on a weekday?

_____ hours per day _____ minutes per day _____Don't know/Not sure

Appendix B. UCLA Loneliness Scale (Russell, Peplau, & Ferguson, 1978)

INSTRUCTIONS: Indicate how often each of the statements below is descriptive of you.
O indicates “I often feel this way”
S indicates “I sometimes feel this way”
R indicates “I rarely feel this way”
N indicates “I never feel this way”

1. I am unhappy doing so many things alone O S R N
2. I have nobody to talk to O S R N
3. I cannot tolerate being so alone O S R N
4. I lack companionship O S R N
5. I feel as if nobody really understands me O S R N
6. I find myself waiting for people to call or write O S R N
7. There is no one I can turn to O S R N
8. I am no longer close to anyone O S R N
9. My interests and ideas are not shared by those around me O S R N
10. I feel left out O S R N
11. I feel completely alone O S R N
12. I am unable to reach out and communicate with those around me O S R N
13. My social relationships are superficial O S R N
14. I feel starved for company O S R N
15. No one really knows me well O S R N
16. I feel isolated from others O S R N
17. I am unhappy being so withdrawn O S R N
18. It is difficult for me to make friends O S R N
19. I feel shut out and excluded by others O S R N
20. People are around me but not with me O S R N

Scoring:
Make all O’s =3, all S’s =2, all R’s =1, and all N’s =0. Keep scoring continuous.