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Executive Functions in Young Adults: The Role of Information Processing Speed and Short-Term Memory

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Executive Functions in Young Adults:
The Role of Information Processing Speed and Short-Term Memory

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Executive functions (EF) continue to be one of the more difficult processes to understand, yet researchers agree that they are critical to our ability to successfully negotiate the complex tasks of day-to-day living. Current models of EF exist in the fields of cognitive psychology, development psychology, and neuropsychology, though these models often contradict each other and raise more questions than answers. The current study expands on existing knowledge by investigating the role of the underlying cognitive processes of EF. Specifically, this study examined the influence of short-term memory (STM) and information processing speed (IPS) on inhibition, switching, and planning abilities. Both STM and IPS have been linked to higher-level EF but have not been investigated in a comprehensive study of EF with a non-clinical population. Using hierarchical regression, STM did not predict EF performance above and beyond working memory (WM). Additional analyses were conducted to determine if STM affected EF indirectly by way of WM. Tests of the indirect effect of STM on each EF through WM, supported this claim. These results question the role of a storage system distinct from that which is included in the WM system. Additional hierarchical regressions found that IPS did not significantly predict either inhibition or switching when controlling for WM. However, IPS was a significant predictor of planning ability. This result supports a developmental understanding of EF whereby functions are related to each other in line with their developmental trajectory. Implications of these findings are discussed along with limitations and opportunities for future research.

This dissertation by Elizabeth P. Van Winkle fulfills the dissertation requirement for the doctoral degree in Applied/Experimental Psychology approved by Rebecca L. M. Fuller, Ph.D. as Director, and by Deborah M. Clawson, Ph.D., Marc M. Sebrechts, Ph.D., and James H. Howard, Jr., Ph.D. as Readers.

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Introduction

Executive functions (EF) are interrelated cognitive abilities that allow individuals to perform complex higher-order decisions and formulate appropriate plans to attain goals (Anderson, 2002; Aron, 2008; Blakemore & Chaudhory, 2006; Diamond, 2002; Lezak, Howieson, & Loring 2004; Miyake et al., 2000; Royall, et. al., 2002). These functions include the ability to inhibit prepotent responses, cognitively shift between tasks, and plan future actions towards a goal (Anderson, 2008; Aron, 2008; Blakemore & Chaudhory, 2006). The framework by which to understand EF has changed substantially over time (see Appendix A for a review of theories). Early theories of EF viewed these cognitive processes as a unitary construct (Baddeley & Hitch, 1996; Norman & Shallice, 1986). More recent theories employed latent variable analysis to determine shared and unique contributions of specific EF functions (Miyake et al., 2000; Lehto, 1996; Salthouse & Milles, 2002). Neuropsychological researchers have contributed to this landscape by investigating how the development of the brain from birth to adulthood mirrors the development of EF during this time period (see Appendix B for a review). To date, research on EF has made great advances, yet there is still no agreed upon model of EF and accepted components of EF are still debated (Alvarez & Emory, 2006; Anderson, 2008).

This study begins with a fundamental assumption that higher order cognitions are inherently limited by more basic processing abilities (Blakemore & Chaudhory, 2006; Garon, Bryson, & Smith, 2008; Salthouse, 1996). In trying to understand what functions are considered part of EF, a handful of studies have examined the role of basic functions, such as information processing speed (IPS) and short-term memory (STM), on higher level cognitive functions such as inhibition, switching, and planning (Luciano et al., 2001; McAuley & White, 2011; Mulder, Pitchford, & Marlow, 2011; Salva et al, 2011). However, these studies have been conducted almost exclusively with various clinical populations such as those with schizophrenia (e.g., Dickinson, Ramsey, & Gold, 2007; Salva et al, 2011), persons with multiple sclerosis (e.g., Drew, Starkey, & Isler, 2009), children born prematurely (e.g., Mulder et al., 2011), children with significant deficits in arithmetic (e.g., McLean & Hitch, 1999; Passolunghi, 2011) or the very young (e.g., Gathercole, 2007; McAuley & White, 2011; McLean & Hitch, 1999) or very old (e.g., Deary, Johnson, & Starr, 2010; Gregory, Nettlebeck, Howard, & Wilson, 2009). Despite this limitation, findings from these studies have raised critical questions about the influence of basic cognitive functions, such as IPS and STM, on higher order executive functions. The objective of this study is to expand the current understanding of EF by investigating the role of STM and IPS on EF performance, and to use current theory and research as a guide to better understand these relationships. First, two of the most often cited general theories of EF are presented (additional theories are covered in Appendix A), with an examination of theoretical gaps. Next, the specific roles of STM and WM are described, leading to a summary of the first objective of this study. Finally, the relationship between IPS and EF is reviewed in terms of a theoretical and developmental framework, including an examination of two developmental models of EF. Gaps in this literature lead to a summary of the second objective of this study.

Theoretical Background

EF covers a vast array of higher order cognitive processes including the ability to inhibit prepotent responses, cognitively switch between tasks, and actively plan towards the achievement of a goal (Aron, 2008; Huizinga et al., 2006; Lezak at al., 2004). The theoretical landscape by which to understand EF has been continually expanding. A more extensive review of these theories can be found in Appendix A. For the purposes of this study, two cardinal theories will be reviewed.

Initially, EF was understood as a unitary construct (Norman & Shallice, 1982; Baddeley & Hitch, 1974; De Luca & Leventer, 2008). One of the first models to include an EF construct was Baddeley and Hitch’s model of working memory (1974; Baddeley, 1996). This model is discussed more comprehensively in the next section as well as in Appendix A. In sum, this early model included a “central executive” system and two slave systems: the phonological loop (broadly verbal STM) and the visospatial sketchpad (broadly visual/spatial STM). Baddeley and Hitch’s WM model viewed the central executive as merely part of the full WM system, which ultimately allowed for more “executive” cognitive functions to be possible (Baddeley, 1996; Baddeley & Logie, 1999). Within this model, WM comprises a storage capacity system (audio/verbal and visuo/spatial), a rehearsal system (also audio/verbal and visuo/spatial), and an executive attentional controller that acts as “puppeteer”, using and manipulating the lower level storage and maintenance systems to allow for executive cognition. These systems are related via the construct of “working memory” and only via this construct is EF possible (Baddeley, 1996; Baddeley & Logie, 1999).

As the field progressed, newer models attained the statistical and empirical support earlier models were lacking through more complicated latent analytical computations (Friedman et al., 2007; Huizinga, Dolan, & van der Molen, 2006; Lehto, 1996; Miyake et al., 2000; Miyake & Friedman, 2012). These studies began to uncover diversity in the EF construct and explored models that were less unitary. However, in contrast to earlier models, they were not as concerned with lower level cognitions and were more interested in identifying higher order cognitions within the overarching construct of “EF” (Alvarez & Emory, 2006).

To date, one of the most comprehensive theories of executive function was offered by Miyake, Friedman, Emerson, Witzki, Howeter, and Wager (2000). The authors suggested that three distinct functions were most representative of EF as a whole, though admittedly not the *only* functions included within the construct of EF. These functions are shifting of mental sets (“shifting”), updating and monitoring representations of working memory (“updating”), and inhibition of prepotent responses (“inhibition”). These functions have largely been agreed upon as primary constructs of EF. The authors aimed to determine how these functions worked together, as well as apart from each other, in an attempt to offer a comprehensive model of EF. To accomplish this, they used latent variable analysis to "extract" commonalities and distinctions between constructs. Using a variety of accepted measures, Miyake and his colleagues found that these three constructs were quite distinct and the best fitting model, as measured by the proportion of variance explained in the data, was a model that included three distinct constructs, rather than a "one-factor" model. Additional structural equation analyses, however, did show that all three constructs tapped into an underlying common construct. Miyake and his colleagues contend that this "commonality" may be up for debate. While it could potentially be "executive functioning", it may also be a construct of working memory or inhibition, as has been offered by previous theorists (Barkley, 1997; Roberts & Pennington, 1996). The attraction of this model to researchers is its applicability. It allows for EF to exist as an overarching construct, while also recognizing the benefit of acknowledging distinct functions under this umbrella term. It is no surprise that this theory is the most widely referenced and accepted in EF research.

The results of Miyake and his colleagues have since been replicated and supported by other researchers and many in the field have come to accept this unitary but diverse model of EF (Huizinga et al., 2006). However, there are some limitations. While the model does uncover the unitary and diverse constructs of inhibition, switching, and working memory, it does not delve far into the interrelationships among these constructs. Developmental researchers have found that depending on the age of the participant, the relationship between EF constructs may vary (Best, Miller & Jones, 2009). Constructs included in the model do not account for how each EF comes "online" at a different age, how they rely on more basic cognitive functions, and how to best understand these relationships. Brocki & Bohlin (2004) reviewed current models of EF and found that many have significant drawbacks in their "failure to base the research on theories within developmentally relevant frameworks" (p. 572). Without considering developmental frameworks, there may be significant gaps in our understanding. In addition, this model does not include planning as an EF, despite some indication from other researchers that it should be included (Anderson, 2002; Salthouse & Miles, 2002). Finally, the model does not explore how more basic functions, such as STM and IPS, may impact these functions and whether they deserve consideration as some have proposed (Alvarez & Emory, 2006; Garon et al., 2008; Gathercole, 1999; Salthouse, 1996). This study aims to expand on this literature by including STM and IPS into models of EF to determine how these basic processes impact executive performance.

Short-Term Memory

STM is at the most basic level, a passive "holding" of information online for reproduction, typically through a rehearsal process (Baddeley, 1996; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Gathercole, 1999; Swanson & Luxenberg, 2009). It is one of the most fundamental cognitive processes. In fact, by displaying a stimulus to a newborn for a period of time, and then redisplaying it alongside a different stimulus, researchers have found evidence of STM in newborns who are only a few hours old, who look longer at the familiar stimulus than the novel one (Eliot, 1999; Ross-Sheehy, Oaks, & Luck, 2003). Initially, STM was seen as a unitary construct. Over time, it has become an accepted part of a more diverse cognitive process, working memory (Baddeley, 1996; Conway et al., 2005; Conway et al., 2002; Engle, 2002). However, despite years of research and investigation, there still exists some disagreement about this fundamental process. Some researchers view STM as nothing more than working memory (Baddeley, 1996). Others distinguish between STM and working memory capacity (WMC), with the latter acting as the short-term store for working memory and only activating in the face of interference, and the former acting as a temporary storage for information during basic cognition not requiring inhibitory processes (Conway et al., 2005; Conway et al., 2002; Engle, 2002). While a full review of working memory theory is outside of the scope of this study, it is not possible to discuss STM without a brief review of working memory models and the changing framework by which researchers have understood STM.

Atkinson and Shiffrin (1968) first discussed short-term store as a unitary construct responsible for holding information in temporary storage through rehearsal, with the potential for information to subsequently be input into long-term store (Shah & Miyake, 1999; Baddeley, 1996). This “modal” model was well accepted and supported by early neurobiological evidence. Specifically, patients with amnesia were often found to have intact STM systems, though lacked the ability to store information within long-term memory (LTM). The reverse was also found to be true. Researchers felt this supported Atkinson and Shiffrin's model, which designated STM as a storage system distinct from a more long-term store.

There was one drawback to this binary model of short and long-term memory. The prevailing theory was that short-term storage was necessary to complete a variety of higher cognitive tasks such as reasoning and learning. However, the same patients who showed deficits in short-term memory had intact learning and reasoning ability (Baddeley, 1996). The modal model of STM and LTM subsequently fell out of favor in the 1970's as a result of this conflicting evidence (Ross-Sheehy et al., 2003). The field was relatively open until Baddeley & Hitch (1974) introduced the model of WM that addressed this concern. Their model merged STM into a larger cognitive model that included a central executive system and two, lower level, "slave" systems, the phonological loop and visuospatial sketchpad, that mirrored the cognitive process of STM (Baddeley, 1996). According to Baddeley & Hitch's working memory model, the lower level slave systems made up two distinct types of STM: auditory/verbal and visual/spatial. Both systems rely on temporary, passive, storage of information drawn from available resources including LTM (Baddeley & Logie, 1999). The phonological loop is capable of temporary storage of verbal/acoustic information. This system requires rehearsal for maintenance, often through subvocalization, but there is a limited capacity. Once this capacity is reached, early information fades to make room for more recent information. The visuospatial sketchpad is the complementary system to the phonological loop that temporarily stores visual and spatial information. This system is much more complex than the phonological loop and more than likely requires input from several neurological systems to maintain information (Baddeley, 1996).

The central executive system is most similar to Norman and Shallice's supervisory attentional system (SAS). This, in general, views EF as a construct that attends to a goal and inhibits automatic responses when necessary towards achievement of this goal (Norman & Shallice, 1988). The responsibility of the central executive system is to maintain attentional control of the slave systems. This includes higher-level manipulation of information to formulate plans and negotiate goals.

According to Baddeley, the emphasis became less on storage and more on the manipulation of information that is being held online (Baddeley, 1996). Neurological data supported this shift (Kiss, Pazderka-Robinson, & Floden, 2001). Within the field of cognitive psychology, this model redefined STM to a more WM framework. The previous understanding of a unitary "short term memory" became less and less relevant in studies researching cognition.

Baddeley and Hitch's working memory model was and is the most accepted theory of WM. Many researchers, however, did not completely dispose of the more traditional construct of STM. Instead, they viewed Baddeley's slave systems as more a measure of working memory capacity (WMC). The fundamental difference is that WMC stores information in the face of interference while STM constitutes the more traditional definition of a simple storage system (Conway et al., 2005; Conway et al., 2002; Engle, 2002). These researchers contend that STM is very much distinct from

WMC and independently relates to EF as well as other cognitive processes (Conway et al., 2002; Swanson & Luxenberg, 2009). The emphasis is more on controlled attention necessary to manipulate information available in WMC and less on the logistical storage of information (Gathercole, 1999).

Similarly, Engle and his colleagues felt there was a distinction to be made between STM and WMC (Engle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999; Kane & Engle, 2003). They found that when STM was accounted for in models predicting general intelligence, WM significantly predicted intelligence while STM did not (Engle, 2002; Kane & Engle, 2003). However, using structural equation modeling, Engle and his colleagues found that models which included *both* WM and STM fit best to predict measures of general intelligence, indicating an inherent need for both constructs (Engle et al., 1999). Their underlying theory, similar to the previously mentioned models, is that STM is a sole memory function, while WM incorporates a more attentional, executive, function. That is, WMC is less a simple store for data in the face of interference, but more an attentional system to maintain information for use. Engle (2002) clarifies that "[g]reater WM capacity does mean that more items can be maintained as active, but this is a result of greater ability to control attention, not a larger memory store" (Engle, 2002; p. 20). Therefore, STM may be its own construct and, in collaboration with WM, is important to general intelligence and higher cognitive functions. However, these researchers emphasize WM as the predominant factor influencing higher level cognitive functions of general intelligence and EF.

There is some neurological support for a delineation of a distinct STM system. Generally speaking, research has shown that different areas of the brain are responsible for phonological STM (posterior parietal), spatial STM (inferior prefrontal), and WMC (dorsolateral prefrontal; Gathercole, 1999). Activation in the PFC has revealed neural correlates specifically related to the amount of information held online at a time, supporting the assertion that STM construct is viable unto itself (Carpenter, Just, & Reichle, 2000; Miller & Wallis, 2009).

Despite this shift in understanding to make room for a distinct STM apart from WM, research continues to emphasize WM and WMC in all models of EF without investigating the role of STM (Conway et al., 2005). Studies have, however, shown dissociation between these two systems. Research has shown that some individuals had difficulty with the manipulation aspect of working memory (or the central executive in Baddeley & Hitch's model), while performance on STM/phonological loop tasks (such as forward digit span), was within normal ranges (McLean & Hitch, 1999; Passolunghi, 2011). Other research has shown that performance on WM tasks is compromised when the researcher taxes the storage component (Towse, et al 1998, McLean et al, 1999). Studies such as these, though often conducted with clinical populations, raise questions about the unique contribution of STM to EF.

Information Processing Speed

The vast majority of studies on EF that have incorporated IPS tend to view it as a distinct variable in clinical populations, aging populations, or childhood populations.

That is, processing speed is one of many cognitive abilities, along with memory, that is impacted by a variety of disabilities and by age. Researchers therefore account for it more readily within these populations. Rarely is IPS included as a fundamental component in any model of EF in healthy adult populations, yet there is evidence to support its inclusion.

IPS is the speed and efficiency of cognitive processing (Salthouse, 1996; Salthouse, Fristoe, McGuthry, & Hambrick, 1998; Salthouse & Miles, 2002; McAuly & White, 2011). One cannot discuss the impact of processing speed on cognition without discussing Salthouse's processing-speed theory of cognitive aging first posited in 1985 (Salthouse, 1996; Salthouse et al., 1998; Salthouse & Miles, 2002). The basic premise of this theory is that age related declines in processing speed are responsible for declines in higher order cognition and working memory (Deary, Johnson, & Starr, 2010; Nettlebeck & Burns, 2010; Salthouse, 1996; Salthouse & Miles, 2002). It is a "common cause theory" indicating there is a "common" cause for age-related changes in a broad array of cognitive functions, and falls under the umbrella of a global-speed hypothesis that implicate IPS specifically (Span, Ridderinkhof, & van der Molen, 2004). Initially, Salthouse set out to understand the age-related differences widely found in a variety of cognitive processes including reasoning, memory, and spatial abilities (Salthouse, 1996). Salthouse makes two fundamental assumptions in positing his theory. The first is that cognitive functioning is very much susceptible to lower level processing abilities. Constraints on these lower level cognitive functions result in deficits in a wide array of higher-level cognitive functions. Salthouse found support for this in the literature. His own research found not only IPS to impact cognitive functioning, but also elements of dual tasking abilities (Salthouse 1996, Salthouse et al., 1998; Salthouse & Miles, 2002).

The second assumption of the processing-speed theory is that IPS is significantly impacted by age. Much of Salthouse's earlier work contributed to this assumption. He found that as individuals age, the speed with which they can perform a variety of tasks decreases significantly. This is supported by other research in this area (Bugg, DeLosh, Davalos, & Davis, 2007; Kail, 2007; Span et al., 2004; Fisk & Warr, 1996).

The processing-speed theory proposed by Salthouse further includes three hypotheses. First, the slowing of cognition as individuals age is due to broad deficits in general functions rather than deficits in specific localized functions. Salthouse (1996) states that, once accounting for a common speed function, the degree of age-differences in other cognitive variables is significantly decreased. A second hypothesis is that IPS significantly mediates the relationship between age and cognitive function. Salthouse (1996) found evidence to support this hypothesis. Finally, the relationship between IPS and cognition is explained by two mechanisms: the limited time mechanism and the simultaneity mechanism. The limited time mechanism postulates that if an individual has to expend a great deal of attention and energy on the execution of basic operations, the higher level operations will be impacted. This is, inherently, the complexity effect;

the more complex a task is, the larger the deficit will be as individuals get older. The limited time mechanism is one way to understand the relationship between age, IPS, and cognition. A second way of understanding this relationship is through the simultaneity mechanism. The basic premise is that the longer it takes to process information, the more likely information stored for processing decays or becomes lost. This is somewhat similar to Baddeley’s articulatory loop in his working memory model (Baddeley, 1996).

Researchers have also applied this theory on EF more specifically. Salthouse & Miles (2002) used structural equation modeling to determine the impact of time-sharing abilities on EF. They found a significant relationship between age-related declines and time-sharing, though IPS accounted for more of the variability in age-related differences in EF. Fisk and Warr (1996) tested a Salthouse-based model evaluating the role of IPS on age-related differences in EF. In support of Salthouse, they found that age-related differences in EF were significantly explained by IPS.

Salthouse’s processing-speed theory has been widely accepted as a fundamental model of aging and cognition (Kail, 2007; Span et al., 2004; Fisk & Warr, 1996). Other models have expanded on this. For example, Fry and Hale (1996) described the “cognitive developmental cascade” by which to understand how certain cognitions develop in childhood. Specifically, these researchers felt there was a hierarchy of IPS, working memory, and fluid intelligence that each build on the other. That is, advancing age systematically impacts IPS, which impacts the next higher function (WM), which subsequently impacts fluid intelligence. Other researchers support this theory (Kail, 2007, Nettlebeck & Burns, 2010). In particular, Kail (2007) found the cascade model to hold true longitudinally, addressing the concern of cross-sectional studies in developmental research. One concern about the cascade theory is that these models do not take into account neuropsychological development in their methodology. Current theory shows IPS peaking in the very late teens to early 20's (De Luca & Leventer, 2008; Hooper, Luciana, Conklin, & Yargar, 2004). Many studies on the development of EF cap the age of participation too young. For example, Kail's study on childhood development (2007) uses an age range of 8-13 with a "time two" test one year later. Therefore, the oldest participant is 14, well below when neuropsychologists believe IPS "peaks." To state that IPS relates to WM, which then relates to reasoning, may be an empirical jump when IPS has not fully developed (see Appendix B for a review of neuropsychological development of EF).

The relationship between IPS and distinct EF is not well understood for very specific reasons. Researchers who examine EF in nonclinical population tend to be interested in IPS when looking at either the age-related development or age-related declines of EF. Studies that focus on earlier development tend to cap participants well before the age where IPS and EF peak (Anderson, 2008; Brocki & Bohlin, 2004; De Luca & Leventer, 2008; Diamond, 2002) while researchers focus on aging, tend to start at ages near to where many EF have already begun to decline (e.g. Bugg et al., 2007). This research aims to explain age-related differences in EF, but does not offer any general understanding of how EFs relate to the more basic cognitive functions in normal healthy populations who have fully developed EF. This type of research is often referred to as the neurocognitive-change framework. This framework contends that age-related changes in cognitive function must be viewed in terms of age-related changes in the brain (Span et al., 2004). Many researchers study within this framework, as they are interested in the impact of age-related changes in the brain on general cognition (Charlton et al., 2008; De Luca & Leventer, 2008; Diamond, 2002; Hooper, Luciana, Conklin & Yarger, 2004; Lamm, Zelazo, & Lewis, 2006, MacPherson, Phillips & Sala, 2002; Stuss & Alexander, 2000). Unfortunately, while these researchers have uncovered a great amount of information about how the brain develops, they have not applied these frameworks to general models of EF.

Within a neurocognitive-change framework, IPS does not fully develop until very late adolescence/early 20's. Specifically, synaptic pruning and myelination do not complete until into the 20's (De Luca & Leventer, 2008; Diamond, 2002; for a full review, see Appendix B). These processes allow for efficient and effective neurological transmission of signals within the brain. Therefore, the ability to perform tasks quickly and accurately, as measured by IPS, is hypothesized to fully mature when myelination and synaptic pruning has eliminated inefficient and unnecessary connections (De Luca & Leventer, 2008; Diamond, 2002; Luna, et. al., 2004).

In addition to the chronological development of IPS, researchers have also shown later development of planning ability with some reporting planning performance peaks around the same time as IPS (e.g., De Luca & Leventer, 2008; Hooper, Luciana, Conklin, & Yargar, 2004). One way to view this finding is that planning may peak later as it is more reliant on efficient processing of information. This reliance on IPS is less robust for inhibition and switching, which develop much earlier (De Luca & Leventer, 2008; Diamond, 2002).

Considering the emphasis on IPS in developmental models and support from neuropsychological research, surprisingly few models of general EF with healthy normal populations have even accounted for processing speed (Anderson, 2002; McAuley & White, 2011). Yet, it inherently makes sense to do so. As a metaphor, when an individual is attempting to perform a complex function on a computer with a slow processor, it may not be that the computer is incapable of performing the task, but it may require a great deal more time to do so when compared to a computer with a faster processor. Typical EF tasks have time limits. Variability in performance times is assumed to represent variability in the cognitive function the task aims to test. Salthouse and others would posit that rather than only considering this as an inability to perform the higher order cognitive task, researchers should instead question if it is a processing speed issue instead.

There are two current models of EF that can be understood from a developmental framework, though neither of these theories has been empirically validated. Zelazo, Carter, Reznick, and Frye (1997) offered a unique perspective on EF that has not fully been accepted, though its poses some interesting frameworks by which to understand EF through a developmental model. Their theory is a functional theory that views EF from a problem-solving perspective, whereby each EF comes online sequentially over childhood and into adolescence, slowly contributing to a more efficient problem-solving ability (see Appendix A for a review).

More recently, Anderson (2002) presented a developmental framework of executive function that combines the unitary and non-unitary aspects of Miyake's model while maintaining foundations in the developmental trajectory of EF across the lifespan. The framework proposed by Anderson is the *executive control system*. Anderson is careful to offer this as a "conceptual framework" due to the lack of empirical validation, but it has nonetheless been one of the few accepted models of EF incorporating developmental frameworks.

In this theory, Anderson's executive control system keeps with the previous theories, which have isolated specific functions known to be "executive" both conceptually and empirically using factor analysis. The functions in this framework are cognitive flexibility, goal setting, attentional control, and IPS. Cognitive flexibility describes the ability of an individual to perform multiple, often conflicting, tasks using divided attention, working memory, and feedback (e.g., switching). Goal setting is the ability to plan, reason, and organize strategies towards a goal (e.g., planning). Attentional control includes traditional inhibition, self-monitoring, and self-regulation (e.g., inhibition). Finally, Anderson introduces information processing which includes the speed of executive processing, fluency, and efficiency (e.g., IPS). The majority of these constructs have been identified in previous models, albeit under different terminology, and each is considered independent of each other. However, they interact to perform specific higher order functions. What is novel about this framework, aside from the incorporation of previous models of EF and the inclusion of developmental theories, is the inclusion of IPS into an EF framework (Anderson, 2002). According to Anderson, it is nearly impossible to assess executive functions without assessing the speed by which an individual performs these functions. From a developmental framework, the question may not be whether the individual can perform a given task, rather whether he or she performs it at a slower and less effective rate. These questions can be applied to both normally developing children as well as individuals who have suffered brain injury or other brain related disorders that impact EF. Impairments and variability in IPS inherently impact the ability to perform EF tasks. In this sense, Anderson's theory falls in line with Salthouse's emphasis on IPS. Yet, Anderson is one of the few who incorporated this into a general model of EF

Given the variability among current models of EF, it is challenging for researchers to come to an agreement on how to understand EF (Anderson, 2008; McCabe et. al., 2010). This study will fill gaps in the current literature by examining the role of IPS on EF. Specifically, if IPS does not peak until later in the brain's development, it makes more sense that IPS is differentially related to planning versus the earlier developing constructs of inhibition and switching. This theory has some support. Gregory et al (2009) evaluated the cascade model in the elderly and found that there was a direct effect of IPS on reasoning that was not impacted by WM. However, the authors did not offer an explanation of this, rather mentioneding this as an unexpected finding in light of cascade theory. This study will attempt to expand on our current knowledge of the relationship between EF and IPS by investigating how IPS relates to individual constructs of EF in healthy young adults.

Present Study

Research that tests the relationship between basic cognitive processes and EF is overwhelmingly conducted on populations who display deficits in these cognitive abilities. Most commonly, research testing these relationships is conducted on clinical populations, childhood populations, or the elderly. Current research has not examined the role of STM on EF in non-clinical adult populations (Gathercole, 1999). Yet, many researchers agree that STM is not simply a construct to be incorporated in WM and deserves distinction (Conway et al., 2005; Conway et al., 2002; Engle, 2002). There is a gap in the literature in determining how IPS relates to individual EF outside of the aging populations. Researchers agree that deficits in IPS play a critical role in later deficits of EF in aging populations (Fisk & Warr, 1996; Salthouse & Miles, 2002). This study will test the extent to which differences in STM and IPS predict performance on EF. This study will use EF constructs identified by Anderson (2002) including inhibition, switching, planning, and IPS, as well as WM (Miyake et al., 2000). The principal strength of this study is the examination of more basic cognitive functions often excluded in EF research. Another strength of this study is the inclusion of planning ability which has been excluded from some of the more prominent EF models (e.g., Miyake et al., 2000). Combining this additional construct and the more base cognitive functions of IPS and STM, this study will attempt to expand on our current understanding of EF.

Objectives & Hypotheses

Objective 1: Examine the Role of Short-Term Memory. The first objective of this study is to examine the relationship between STM and EF, controlling for WM. There are two hypotheses for this objective. The first hypothesis is that STM will significantly predict performance on all EF of inhibition, switching, and planning above and beyond WM. While there is little research on the relationship between STM and EF, STM is a fundamental cognitive construct and should be required to perform tasks of EF, even above and beyond WM. The second hypothesis is that STM will also significantly contribute to EF through its influence on WM. WM is the locus for holding an amount of information online and manipulating this information. A great deal of research has focused on the manipulation aspect of WM, while paying less attention to the amount of information an individual can hold. It would be reasonable to assume that the *amount* of information that can be held — as measured by STM — would impact performance on EF tasks, though potentially indirectly through WM.

Objective 2: Examine the Role of Information Processing Speed. The second objective of this study is to examine the role of IPS in EF performance and to determine if IPS predicts all EFs equally or, as is expected, differentially predicts higher level EFs of planning as would be supported by a developmental model. Developmental models place emphasis on IPS as an integral part of an EF model, though there is no determination of the manner in which IPS relates to other EF. Developmentally, IPS peaks during later development of EF, close in time to the development of planning. The hypothesis in support of this objective is that IPS will predict planning specifically, but will not predict either inhibition or switching, as these develop and peak earlier than both IPS and planning. If this hypothesis is supported by the analysis, it will not only emphasize the role of IPS in models of EF, but will also support a more developmental model of EF whereby there is a hierarchical structure based on the neurodevelopment of these cognitive constructs.

Method

Research Design.

The research design of this study involves the administration of six cognitive tests to measure STM, WM, IPS, inhibition, switching, and planning. In addition, information gathered from demographic assessments will provide controls of education, age, and gender.

In order to better understand the role of STM, a hierarchical regression was conducted to determine if STM predicts EF, above and beyond contributions from the controls and WM. This analysis will test the first hypothesis. To expand on this analysis, and to test the second hypothesis, a test of the indirect effect will be conducted using a mediation model to determine if the contribution of STM can be understood through the relationship between WM and individual EF. These analyses will examine whether STM exerts its influence on EF through WM, whether it contributes by itself, or whether it does both.

To test the role of IPS on EF, hierarchical regressions will be conducted to determine if IPS predicts EF, above and beyond controls, STM, and WM. By analyzing the contribution of IPS on each EF, these regressions will determine if IPS predicts all EFs equally, or only the higher level EF of planning, as is hypothesized.

Measures

Controls. Initially, it was planned that all regressions and tests of indirect effects performed in this study would control for age, education, and gender, where age was defined as the age in years at the time of testing and education was measured as the highest grade completed. For example, freshman were coded as “12”, sophomores “13”, and so on. Gender was coded as 0 = female and 1 = male. Initial correlations indicated a strong significant relationship between age and education ($r = .95$, $p < .000$). Due to this high level of collinearity, age was dropped from further analyses and only education and gender were used.

Executive Function. Executive Function was measured using three tasks from the Delis Kaplan Executive Function System (D-KEFS; Delis, Kaplan, & Kramer, 2001). Use of the D-KEFS has a number of advantages. The D-KEFS provides baseline measures for many tasks which control for base motor abilities, visuospatial abilities, and reading/counting abilities. The D-KEFS also minimizes ceiling effects. Traditional EF tasks aimed at diagnosing brain injury typically have ceiling effects in normal, healthy, populations. The D-KEFS minimizes ceiling effects by constructing tasks of increasing difficulty even for healthy populations.

Switching was measured using performance on the Verbal Fluency Task, switching condition (VerbFluen; Swanson, 2005). This task required the participant to verbally list fruits and pieces of furniture, switching between the two. The individual would alternate by reciting a piece of fruit, a piece of furniture, a piece of fruit, and so on. The total number of correctly cited words was recorded, subtracting out any repeated words or errors in successful switching.

Planning was measured using the Tower Task. This is a well-known task of planning and goal directed, higher level, executive functioning (Delis et al., 2001; Homack, Lee, & Riccio, 2005; Lezak et al., 2004). The Tower Task in the D-KEFS is a modification of similar tasks such as the Tower of Hanoi, Tower of London and Tower of Chicago which have shown similar connections to planning (Lezak et al., 2004; Robbins, 1998). Specifically, the D-KEFS modified these tasks to include five disks and additional trials which require more minimum moves for completion. For example, the final trial of the D-KEFS Tower Task requires a minimum of 26 moves to complete. This modification reduces ceiling effects in the Tower task and lends itself particularly well to healthy educated subjects such as the participants in the current study.

Inhibition was originally to be measured using the D-KEFS Color Word Interference Task. This task is a modification of a traditional Stroop Task which presents participants with color words (e.g. “red”, “green”) which are printed in a different color (e.g., “red” is printed in green ink). Participants are asked to name the ink color while inhibiting the prepotent response of reading the word. While this is a well understood measure of inhibition, a large proportion of the individuals in the sample were students in Introductory Psychology classes. Therefore, there may have been a familiarity that affected overall variability in this sample. Initial analyses indicated no significant correlations between the Color Word Interference Task and any other measure of EF, STM, or WM. As this was not expected, coupled with the reported familiarity with the Stroop task for many participants, an alternative task from the D-

KEFS was used.

The alternative inhibition task used the Trail-Making Task, switching condition, controlling for baseline number and letter conditions (TMT). The TMT contains four conditions, each requiring a “connect-the-dots” type task. The number condition requires the participant to visually search an 11x14 piece of paper to connect numbers 1 through 16. The letter condition has a similar presentation, but requires the participant to connect letters A through P. The switching condition requires the participant to similarly connect-the-dots, but to alternate connecting letters and numbers. Therefore, the participant would have to visually search for, and connect A to 1, 1 to B, B to 2, 2 to C, and so on. The original Trail Making Task B, the equivalent switching condition, randomly assigned letters and number to places on the sheet of paper. The D-KEFS modified this task to provide an element of “capture” (Swanson, 2005). This modification reduces the ceiling effect by placing consecutive numbers and letters in close proximity to one another, thereby requiring an individual to pay closer attention and inhibit the prepotent bias to connect the consecutive numbers and/or letters. While this condition of the TMT was traditionally used as a measure of switching, some researchers have begun to consider it as a measure of inhibition and impulsivity instead (Arbuthnott & Frank, 2000; Latzman & Markon, 2010; Sanchez-Cubillo et al., 2009). This is particularly true for the D-KEFS modified version, which not only takes into account performance on baseline number and letter tasks, but also incorporates capture. Research has shown performance on the original Trails task B not only taps into cognitive flexibility, but inhibition and working memory as well (Arbuthnott & Frank, 2000; Latzman & Markon, 2010; Sanchez-Cubillo et al., 2009). A factor analysis conducted by Latzman and Markon (2010) found that the modified TMT in the D-KEFS loaded significantly on the inhibition factor and not on a switching factor. Rather, VerbFluen loaded significantly on the switching factor. Latzman and Markon contend that this is because the TMT involves external stimulus (letters and numbers on a paper) whereas VerbFluen requires a response to internal representations of responses (e.g., mental representations of fruit and furniture). These researchers contend that this difference, presumably in combination with the additional "capture" component, results in an inhibitory requirement of automatic responses. This supports the use of the TMT as a measure of inhibition. All analyses using TMT were performed using a variable of TMT switching condition which takes into account baseline performance on the number and letter condition.

Memory Constructs. STM was measured using the Forward Digit Span task (FDS; Gathercole, 1999). This task requires participants to verbally repeat back consecutively longer strings of digits until the participant is unable to successfully repeat back two strings of digits in a row. WM was measured using the Letter Number Sequencing task (LNS Haut, 2000). This task requires participants to repeat back strings of letters and numbers, however, the participant must manipulate the letters and numbers so as to repeat them back with numbers in chronological order followed by letters in alphabetical order. For example, the string W-7-3-F would be repeated as 3-7-

F-W. Participants continued until they were unable to successfully repeat back two strings in a row within one trial.

Information Processing Speed. For this study, IPS was measured with the Digit Symbol Task (DST; McCabe, et. al., 2010). This task presents participants with a "key" that matches digits (1-9) with symbols. The participant is then presented with a sheet of numbers, in random order, and requires the participant to write down the corresponding symbols to the digits as quickly as they can. It has been used extensively as a measure of processing speed (Conway et al., 2002; Deary et al., 2010; Dickinson, Ramsey, & Gold, 2007; Howard & Howard, 2001).

Order of Tasks. Participants were either administered executive function tasks first, followed by memory and processing speed tasks, or the reverse order. Alternating task order minimized order effects.

Participants

This study used 50 participants who were undergraduate and graduate students between the ages of 18 and 35 at The Catholic University of America (CUA). Exclusion criteria included a neurological diagnosis, severe head injury in the previous year, history of strokes/seizures, diagnosis of psychosis for the individual or an immediate family member, drug or alcohol abuse/dependence in the last year, a documented learning or attention disorder, primary language other than English, and/or difficulty seeing with contacts/glasses. See Appendix C for exclusion criteria. IRB approval of the study, notifications, informed consent, and all procedures ensured protection of human subjects.

Recruitment. Participants were recruited from Introductory Psychology classes or through fliers posted at various locations on campus (see Appendix D for flier). Participants in Introductory Psychology class (Psychology 201) received course credit for participation in research studies. Students from these courses sign up for participation on a local bulletin board that contained a sign-up sheet, a description of the study, the informed consent form (see Appendix E), and exclusion criteria. Subjects were also recruited via fliers posted around campus. Fliers included a description of the study, exclusion criteria, and notification of a $25 incentive for participation. Prior to scheduling testing, every student was sent an exclusion form for verification of eligibility. Students either received course credit for the Psychology 101 course or $25 as compensation for the participation.

Data Management

Of the 50 students initially tested, three were later excluded from the study due to extreme outliers in scores. These participants were identified as having confounding issues: the first admitted he/she was under the influence of marijuana, the second reported extreme anxiety as a result of learning he/she was to be expelled from CUA four weeks prior to graduation, and the third reported extreme levels of anger, anxiety, and depression prior to testing. In addition to exclusion for outlying scores, data cleaning was required for certain subjects. Subject EF007 reported familiarity with the Tower Test and was not administered the task. EF043 had to leave testing early for a class, and was not able to reschedule the Tower task. The scores on the Tower Task for these two individuals were set to missing. Subject EF015 and EF026 did not give the day of their birth date. This date was imputed as “15” so as to minimize the degree of error. Subject EF029 and EF043 were familiar with the Verbal Fluency Task. The alternative version of this task was administered for these two subjects which required switching between vegetables and musical instruments.

Recoding of Variables. In order to assist in interpretation, all variables were recoded so that higher scores represented better achievement on the task at hand.

Results

Analyses

The analyses used for this study relied on SPSS Statistics version 18.0 and included descriptives, frequencies, crosstabulations, multiple regressions, and plots to verify assumptions required by multiple regression including homoscedasticity and normal distribution. In addition, tests of indirect effects used the Preacher and Hayes, “Mediate” MACRO for SPSS (available for download at http://www.afhayes.com).

Mediation analysis has gained in popularity since early publications of mediation approaches (Baron & Kenny, 1986; Sobel, 1982). For the first time, these initial publications allowed statisticians to conduct causal analyses where they were otherwise limited by prior strict correlational approaches. As the field of statistics has changed, many feel these older analytical approaches are outdated and lack necessary power (Hayes & Preacher, 2011). Furthermore, and perhaps more relevant to the study at hand, these approaches emphasized the need for a significant relationship between the independent variable (X) and dependent variable (Y), referred to as the “total effect,” as well as emphasis on complete mediation without lauding the relevance of partial mediations (Hayes & Preacher, 2011). Researchers have since found that despite a lack of correlation between X and Y, significant indirect effects may still exist and are valuable to understanding how constructs relate to each other (Bollen, 1989, p. 52;

Cerin & MacKinnon, 2009; Hayes, 2009; Zhao, Lynch, & Chen, 2010). Andrew Hayes explains it well when he states, “[i]f you find a significant indirect effect in the absence of a detectable total effect, call it what you want—mediation or otherwise. The terminology does not affect the empirical outcomes. A failure to test for indirect effects in the absence of a total effect can lead to you miss some potentially interesting, important, or useful mechanisms by which X exerts some kind of effect on Y” (Hayes, 2009, pg. 11). However, it is difficult to conceptualize a traditional mediation when there is no significant amount of variance between the independent and dependent variable by which to “mediate.” This study uses a single mediation approach to test for significant indirect effects between STM (X) and EF (Y) through WM (M). All indirect effects were bootstrapped 1,000 times to account for non-normality of the sample distribution of the indirect effect and held at 95% confidence intervals.

Descriptive Statistics and Correlations

The final sample for this study included 47 undergraduate and graduate students from CUA. Table 1 shows a summary of descriptive statistics for this sample.

Table 1. Descriptive Statistics

	N	Minimum – Maximum	Mean	*SD*	Variance
Age	47	18 – 29	20.23	3.02	9.14
Gender	47	0 – 1			
Educ	47	12 – 19	13.40	1.84	3.38
FDS	47	8 – 17	11.28	2.10	4.42
LNS	47	7 – 18	11.38	2.43	5.89
DigSymb	47	53 – 119	91.11	14.01	196.27
VerbFluen	47	9 – 22	15.60	2.84	8.07
TMT[1]	47	3.45 – 71.59	30.85	13.87	192.28
Tower[2]	45	91 – 260	155.98	40.31	1624.52
Valid N	45				

Note. Gender (0 = female, 1 = male), Educ (Last completed grade), FDS (Forward Digit Span), LNS (Letter Number Sequencing Task), DigSymb (Digit Symbol Task), VerbFluen (Verbal Fluency Task: Category Switching Condition), TMT (Trail Making Task: Switching Condition minus Number/Letter condition), Tower (Tower Task), Valid N (listwise).

[1] The TMT score is the result of the TMT Switching Condition minus the average of the TMT Number and Letter conditions. Therefore, the number represents how much additional time it took in the switching condition versus the baseline number/letter conditions. Therefore, higher scores represent poorer performance. This task was reverse coded for all subsequent analyses.

[2]The tower task represents the total number of moves a participant needed to complete a trial. Higher scores represent poorer planning abilities. This task was reverse coded for all subsequent analyses.

The average age of the sample was around 20 years old. Sixty-eight percent of the sample (n=32) was female and 81% (n=38) were right handed. The vast majority of the sample was undergraduate with 45% of the sample being freshman (n=21), 28% sophomores (n = 13), 11% juniors (n = 5), 11% seniors (n = 5), and 6% graduate students (n = 3). Table 2 shows correlations between all variables.

Table 2. Correlation Matrix

	Age	Gender	Educ	FDS	LNS	DigSymb	VerbFluen	TMT
Gender	-.10	-	-	-	-	-	-	-
Educ	.95**	-.08	-	-	-	-	-	-
FDS	.35*	-.16	.34*		-	-	-	-
LNS	.15	-.01	.14	.54**	-	-	-	-
DigSymb	.29*	-.13	.30*	.38**	.33*	-	-	-
VerbFluen	.34*	-.31*	.29*	.22	.41**	.24	-	-
TMT	.18	.05	.18	.43**	.54**	.38**	.26	-
Tower	.19	.09	.22	.28	.42**	.43**	.33*	.19

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).
Note. Gender (0 = female, 1 = male), Educ (Last completed grade), FDS (Forward Digit Span), LNS (Letter Number Sequencing Task), DigSymb (Digit Symbol Task), VerbFluen (Verbal Fluency Task: Category Switching Condition), TMT (Trail Making Task: Switching Condition minus Number/Letter condition), Tower (Tower Task).

Of particular note is the very high correlation between education and age ($r = .95$, $p < .001$). This is due to the linear effect of higher age relating to higher education. As mentioned previously, education was subsequently used as a proxy for age in all models.

Objective 1: Examine the Role of Short Term Memory

The first objective of this study was to examine the relationship between STM and inhibition, switching, and planning, controlling for WM. There were two hypotheses for this objective. The first hypothesis is that STM will significantly predict performance on all EF of inhibition, switching, and planning above and beyond WM. To test this hypothesis, stepwise hierarchical regressions were done predicting performance on TMT (inhibition), VerbFluen (switching), and Tower (planning) performance, using three steps. Table 3 summarizes the results of these regressions. Step 1 through 3 are relevant for this specific hypothesis.

Table 3. Summary of Hierarchical Multiple Regression Analysis with Short-Term Memory, Working Memory, and Information Processing Speed to Predict Inhibition, Switching, and Planning

		TMT (Inhibition) $N = 47$ $R^2 = .36^*$			VerbFluen (Switching) $N = 47$ $R^2 = .33^{**}$			Tower (Planning) $N = 45$ $R^2 = .29^*$		
		B	*SE B*	*β*	*B*	*SE B*	*β*	*B*	*SE B*	*β*
Step 1	Gender	1.89	4.37	0.06	-1.73*	0.83	-0.29*	9.64	12.72	0.11
	Educ	1.41	1.12	0.19	0.42*	0.21	0.27*	4.93	3.27	0.23
Step 2	Gender	3.57	4.06	0.12	-1.65*	0.85	-0.27	11.62	12.56	0.13
	Educ	0.35	1.09	0.05	0.37	0.23	0.24	2.79	3.50	0.13
	FDS	2.86*	0.96	0.43	0.13	0.20	0.10	5.00	3.21	0.25
Step 3	Gender	2.68	3.78	0.09	-1.84*	0.78	-0.31*	9.36	12.02	0.11
	Educ	0.50	1.01	0.07	0.41	0.21	0.26	3.65	3.35	0.17
	FDS	1.27	1.05	0.19	-0.22	0.22	-0.16	0.03	3.76	0.00
	LNS	**2.44****	0.86	**0.43****	**0.54****	0.18	**0.46****	**6.46***	2.84	**0.40***
Step 4	Gender	3.15	3.74	0.11	-1.83*	0.79	-0.30*	12.00	11.60	0.14
	Educ	0.19	1.02	0.03	0.39	0.22	0.25	2.28	3.28	0.10
	FDS	1.01	1.06	0.15	-0.23	0.22	-0.17	-0.89	3.64	-0.04
	LNS	**2.22***	0.86	**0.39***	**0.53****	0.18	**0.45****	5.21	2.79	0.32
	DigSymb	0.20	0.14	0.20	0.01	0.03	0.04	**0.91***	0.43	**0.32***

**. Coefficient is significant at the 0.01 level.
*. Coefficient is significant at the 0.05 level.
Note. Gender (0 = female, 1 = male), Educ (Last completed grade), FDS (Forward Digit Span), LNS (Letter Number Sequencing Task), DigSymb (Digit Symbol Task), TMT (Trail Making Task: Switching Condition minus Number/Letter condition), VerbFluen (Verbal Fluency Task: Category Switching Condition), Tower (Tower Task).

The first step entered gender and education as controls to account for any variance explained by these constructs. The second step entered FDS (STM). The third step entered LNS (WM). The results of these regressions did not support the first hypothesis. Specifically, FDS did not significantly predict any of the executive functions above and beyond LNS. Examining the partial correlations to calculate the contribution of FDS, FDS explained only 2.3% of the variance in inhibition, 1.6% of the variance in switching, and .0001% of the variance in planning ability. While STM was unable to predict EF over and above WM, STM did predict inhibition when entered alone. Conversely, STM was unable to account for a significant amount of variance in switching or planning when entered alone.

The second hypothesis was that STM would contribute to EF through its influence on WM. While the previous regressions indicated STM does not predict EF directly, it does not expand on the relationship between STM and WM and how STM may contribute to EF by way of WM. To analyze this relationship, tests of the indirect effect of FDS on EF, through LNS were performed. Table 4 summarizes the results of these analyses.

Table 4. Test of the Indirect Effect of Short Term Memory on Inhibition, Switching, and Planning, Through Working Memory

			Bootstrapping (95% CI)			
	Total Effect (c)	**Direct Effect (c')**	**Point Estimate for Indirect Effect (ab)**	**SE**	**Lower**	**Upper**
Inhibition	2.86*	1.27	1.59*	0.77	0.52	3.50
Switching	0.13	-0.22	0.35*	0.13	0.10	0.63
Planning	5.00	0.03	4.97*	2.40	0.44	9.98

**. Coefficient is significant at the 0.01 level. *. Coefficient is significant at the 0.05 level.
1,000 bootstrapped samples used for analysis.
Note. All indirect effects control for Gender and Education. Short Term Memory measured with Forward Digit Span, Working Memory measured by Letter Number Sequencing Task, Inhibition measured by Trail Making Task: Switching Condition minus Number/Letter condition, Switching measured by Verbal Fluency Task: Category Switching Condition, Planning measured by Tower Task.

Indirect effects were tested by bootstrapping samples 1,000 times and determining a point estimate for the indirect effect and a confidence interval at the 95% level. “Bootstrapping” involves resampling from the population “k” number of times (in this case 1000) to estimate the indirect effect and develop a confidence interval to test the significance of the coefficient (for a review of this process, refer to Hayes, 2009). These tests of the indirect effect supported the hypothesis that STM exerts a significant amount of influence on EF through WM. Tests of the indirect effect of FDS on TMT, through LNS, showed a significant indirect effect with a point estimate of 1.59 and a 95% confidence interval between 0.52 and 3.5. A similar significant finding was found for the indirect effect of FDS on VerbFluen through LNS, with results showing a point estimate of 0.35 and a 95% confidence interval of 0.10 to 0.63. Finally, FDS had a similar significant indirect effect on the Tower task, through LNS, with a point estimate of 4.97 and a 95% confidence interval of 0.44 to 9.98.

Tests of the indirect effects were conducted on insignificant total effects (e.g., the relationship between FDS and each EF was not significant except in the case of TMT) and insignificant direct effects (e.g., the relationship between FDS and EF after controlling for LNS was not significant). It is important to distinguish what these analyses were intended to address and to cautiously interpret the results. These analyses did not test "mediation" per se and instead simply tested the indirect effect of STM on EF, through WM. That is, a unit change in STM will result in a significant change in WM which will, in turn, result in a change to EF. The initial regression analyses indicated that STM does not contribute to EF directly, when controlling for WM. This is a critical finding in understanding the role STM plays in EF and implies that WM is explaining the most variability in performance across EF. This is in line with much of the research which emphasizes the importance of WM. However, it is known that WM is a combination of capacity and manipulation of information. The regression alone does not offer any explanation as to whether the capacity aspect of WM impacts EF or if it is manipulation alone. A test of the indirect effect can determine this. Inherent in this analysis is an emphasis on the indirect effect (ab) over the total effect (c) or direct effect (c'). Indeed, there was no expectation of significant total or direct effects when conducting this analysis. However, the results should be interpreted with caution as only significant indirect effects, and not as significant "mediations" in the traditional sense of the word.

One potential concern is the range for the confidence intervals in the test of the indirect effects, particularly the point estimate for planning (0.44 to 9.98). The more narrow the range of a confidence interval, the more precise the estimate in terms of representing the population (Field, 2005). This large range does put into question whether this point estimate accurately reflects the sample and these results should be interpreted with caution. This larger range is most likely due to the small sample size. This limitation of the sample size is further discussed in the limitations section.

Objective 2: Examine the Role of Information Processing Speed

The second objective of this study was to examine the role of IPS in EF performance and to determine if IPS predicts all EFs equally or, as was expected, IPS differentially predicts the higher level EF of planning as would be supported by a developmental model. The hypothesis is that IPS will predict planning specifically, but will not predict either inhibition or switching, as these develop and peak earlier than both IPS and planning.

To test this hypothesis, initial hierarchical regressions from Objective 1 were expanded to include an additional third step in predicting EF, which included IPS. Thus, the first step entered controls. The second and third step entered FDS and LNS. The final step entered DigSymb (IPS). The results of these regressions are summarized in Table 3. Findings from these analyses support this hypothesis. Despite the addition of DigSymb, LNS was the primary predictor of TMT ($b = 2.22$, $t(41) = 2.57$, $p = 0.01$) and VerbFluen ($b = 0.53$, $t(41) = 2.91$, $p = 0.01$). While LNS did significantly predict performance on the Tower task when entered in step 2 (*b* = 6.46, *t*(39) = 2.27, *p* = 0.03), DigSymb was the only significant predictor of performance on planning once introduced in step 3 (*b* = 0.91, *t*(2.11), *p* = 0.04).

To better understand the contribution of IPS across EF, it is useful to look at the partial correlations of variables entered at step 4. By squaring these coefficients, the unique contributions of each variable in the final model can be determined. Looking at contributors to inhibition, WM explained 10.2% of variability in inhibition while IPS explained only 3.2% of the variability. For switching, whereas WM explained 13.9% of the variability, IPS only predicted 1% of the variance in switching. For inhibition and switching, it is clear that WM has a great deal of influence on performance, with more than 10% of the variability being explained by WM in both functions. Conversely, IPS explains a small, insignificant, percentage of between 1-3%.

These results are in stark contrast to results for planning. WM explained 6.3% of the variability in planning — a measurable decrease from WM's contribution to inhibition and switching (10.2% and 13.9% respectively). In contrast, IPS explains 8% of the variability in planning performance, which is a measurable increase from IPS's contribution to inhibition and switching (3.2% and 1% respectively).

It is important to note here that while WM was no longer significant in the final model predicting planning, the standardized coefficient was extremely close between WM (*ß* = 0.3195) and IPS (*ß* = 0.3198). While the difference between the two variables can be measured more clearly looking at the partial correlations and explanations of variance, with such a small sample size, it is difficult to say WM does *not* play a role in planning. In addition, a statement such as this would contradict nearly all research indicating the importance of WM to EF performance. It is more likely that the insignificant coefficient was due to “noise” in the data. Notwithstanding, IPS explained a notable amount of variance in planning (8%). This is particularly noticeable when looking at the results for inhibition and switching, which show a relative reversal with WM explaining upwards of 10% of the variability in these constructs and IPS explaining less than 3.5%.

Discussion

The Role of Short Term Memory

The first objective of this study was to better understand the relationship between STM and EF. There were two hypotheses for this objective. The first hypothesis was that STM would significantly predict performance on all EF of inhibition, switching, and planning, above and beyond WM. This hypothesis was not supported. Specifically, once the contributions of WM were taken into account, STM was unable to predict any variability in performance on tasks of inhibition, switching, or planning. These results replicated studies done on WM, STM and general fluid intelligence. In this study, STM was unable to explain a significant amount of variability in intelligence when WM was entered into the model (Engle, 2002: Engle et al., 1999).

The second hypothesis was that STM would contribute to EF through its influence on WM. This hypothesis was supported. Using a pure measure of STM, unencumbered by influences of WM, STM significantly predicted WM, which predicted performance on inhibition, switching, and planning. The indirect effect between STM and each EF measure was significant, indicating that STM exerts a significant influence on EF through its contribution to WM.

Results from the regressions support previous findings that WM, over STM, is the primary construct to predict performance on EF. That is, considering a definition of WM in line with Engle and his colleagues, WM is the sum of a capacity system and controlled attention. The results showed STM was unable to account for a significant amount of variability in EF. Therefore, this would draw attention to the controlled attention aspect of WM as the fundamental predictor of higher-cognitive thought. This would fall very much in line with other research emphasizing the role of interference and attentional control, and minimizing the role of short-term storage of information (Baddeley, 1996; Conway et al., 2005; Conway et al., 2002; Engle, 2002; Engle et al., 1999; Kane & Engle, 2003; Kane & Engle, 2003).

However, the results only show that WM, as a construct, significantly predicts EF. These results cannot expand on this to determine whether the capacity aspect of WM, versus the manipulation aspect, plays a role in EF. Further analysis showed that STM significantly predicted WM, which, in turn, significantly impacted all EF measures. This indirect effect, between STM and EF, by way of WM, was significant. These results do not, necessarily, contradict the aforementioned researchers emphasizing controlled attention as the primary predictor of EF performance, as even Baddeley admits that the WM model is inherently constrained by capacity (Baddeley & Logie, 1999). Fundamentally, a significant indirect effect does not overshadow the lack of a direct effect between STM and EF. WM remains a fundamental predictor of EF, as is accepted in the research (Engle, 2002; Miyake et al., 2000). The results seem to imply, however, that STM contributes to this relationship in small, but significant ways.

The Role of Information Processing Speed

The second objective of this study was to examine the role of IPS in EF performance and to determine if IPS predicts all EF equally or differentially. There has been a great deal of research touting IPS as a key predictor of age-related declines in higher-order cognitive functions (Deary, Johnson, & Starr, 2010; Nettlebeck & Burns, 2010; Salthouse, 1996; Salthouse & Miles, 2002). Yet, research on the development of EF has found that IPS does not fully develop until after most EF has peaked. Using these frameworks as a guideline, it was hypothesized that IPS will contribute to EF, but will differentially predict planning versus inhibition or switching.

Findings from the analyses support this hypothesis. WM was the primary predictor of performance on inhibition and switching tasks while IPS did not predict performance on these tasks. Conversely, IPS significantly predicted planning above and beyond WM.

The interpretation of these results seems to support a developmental framework by which to understand mature EF. There is developmental support for EF building on each other during maturation, which may imply causal relationships between these processes (Best, Miller, & Jones, 2009). Inhibition, WM, and switching develop during early and late childhood. Therefore, it is not surprising that WM would predict these constructs as they come online in a related timeframe and would potentially build off of each other. However, there is a great deal of neurological development during adolescence and the beginning of young adulthood. Specifically, myelination and synaptic pruning in the later teen years and early 20's heighten efficiency of speed of processing. There is a similar trajectory for planning, with heightened performance not culminating until late adolescence and young adulthood. Using this type of neurocognitive-change framework, the results of these analyses make some sense. IPS does not predict inhibition and switching as they come "online" much earlier than IPS peaks. Conversely, IPS plays a significant role in an individual's planning ability, even above and beyond the robust influence of WM, as these functions are the last to fully mature and potentially rely on more interplay compared with the earlier developing functions. These results are somewhat supported by previous research that found IPS predicted reasoning in the elderly, above and beyond WM (Gregory et al., 2009). In addition, applying this developmental framework might also explain why STM predicted inhibition, though not switching or planning. Of these three functions, inhibition comes "online" first — at a very young age. Perhaps STM best predicts inhibition as they are both functions which come on early in infancy. As the additional cognitive functions emerge and begin to build on each other, STM is progressively unable to account for performance on these more complex cognitions.

Limitations

There are a number of limitations to this study that should be addressed for replication and considered when interpreting the results. First, the sample was not only small (n=47), but highly educated and somewhat familiar with psychological testing. The vast majority of participants was recruited from introductory psychology courses and was therefore familiar with basic psychological testing. In addition, the sample was young, nearly 50% college freshman. Considering that there is some debate as to when IPS and planning performance peak, with some researchers indicating that the peak happens well into the 20's, a larger number of individuals in the 20 and older age range would have been beneficial. In addition, small sample sizes lead to instability of estimates when conducting analyses such as the ones conducted in this study. Analytical strategies such as bootstrapping, can minimize this instability, but caution should be taken when interpreting these results until research can be conducted on larger, more representative, samples.

Secondly, this study relied on single task analysis. When measuring cognitive processes, it is often hazardous to rely on one task to measure a cognitive function, particularly with EF tasks where so much is interrelated (McAuley & White, 2011). This issue is often called *task impurity* (Huizinga et al., 2006). It is difficult to say with certainty that the results are not simply measuring relationships between tasks versus the functions themselves. While this study attempted to address this through the use of the D-KEFS, which inherently accounts for many of these concerns, future research would benefit from a wider array of tasks, which measure a variety of audio/verbal capacity and visual/spatial performance.

Related to this was the difficulty measuring inhibition. While there is research supporting the use of the switching condition of the DKEFS Trail Making Task as a measure of inhibition, it is arguably not the most robust measure of inhibition and results should be interpreted with caution. Using a more traditional measure of inhibition, such as the D-KEFS Color Word Interference task, could strengthen this study.

Additionally, using structural equation modeling, Miyake and his colleagues (2000) found a similar Tower task, the Tower of Hanoi, to be best explained by an inhibition factor versus a path from switching, updating, or combination of the three. While this may put into question the use of a Tower task in this study as a measure of planning, there is a great deal of research indicating this is an appropriate use for this task (Delis et al., 2001; Homack, Lee, & Riccio, 2005; Lezak et al., 2004). Further, Miyake at al.'s study is limited as they did not use a planning construct in their analysis and were therefore unable to contend that inhibition explained performance on the TOH task over and above planning. Finally, the Tower task used in the D-KEFS has been modified in a number of ways to increase the complexity of the task. The TOH and D-KEFS Tower task may not be as comparable as they may seem at the outset.

Finally, the analytical approaches used in this study test overt patterns between variables. Research has shown that there is a benefit to using latent variable analysis to determine constructs not easily identifiable using traditional EF measures and to determine interrelationships between functions (Miyake et al., 2000). Future research would benefit from not only including more basic cognitive functions when exploring EF, but also using latent variable analysis to better understand how these functions work together.

Conclusions and Future Directions

This study set out to examine the underlying cognitive processes of STM and IPS on higher-level EF. The results supported a role for each of these processes, though limited. STM capacity does seem to influence performance on EF. Yet, it is clear that it remains in the shadow of WM. IPS seems to play a significant role in higher-level EF of planning, but did not have as much of an impact on those lower-level cognitive functions of inhibition and switching. The findings of this study, as is often the case with research investigating the complexities of EF, pose far more questions than answers. Indeed, despite the wealth of information on EF, we still fundamentally do not have an accepted operationalization of EF constructs (Stuss & Alexander, 2000). Future research should include basic cognitive processes when attempting to understand EF and look at the interactions between them. In line with Salthouse's assertions (1996), it is unreasonable to expect a full understanding of higher-cognitive functions, without consideration for the more basic processes, which are required to perform such executive tasks. There is research indicating sole frontal lobe activation on many simple tasks which measure such basic processes (Stuss & Alexander, 2000). In addition, it has become common practice to look at how deficits in these cognitive subprocesses impact EF in clinical and aging populations, yet this relationship is not often considered when looking at young adults. This is not to say that these basic constructs deserve a place in EF models alongside inhibition, switching and planning. In addition, these lower-level functions may not significantly load on an EF factor in latent analysis. However, when making assumptions about performance on EF tasks care should be taken to ensure that patterns are not explained by more basic functions, or perhaps interactions between these functions, rather than by interrelationships between executive processes alone. As Garon et al. (2008) stated, “EF components are built upon simpler cognitive skills and can be said to be the result of a coordination of simpler skills” (p. 49).

Future research should also investigate how these subprocesses not only impact traditional EF constructs, but also how they may relate to “hot” EF (Blakemore & Choudhury, 2006). Recent research has investigated a potential delineation between “cold” EF, or more cognitive tasks of EF, and “hot” EF, or more affective tasks of EF such as emotional modulation and types of inhibition (Blakemore & Choudhury, 2006). A test of this delineation is outside the scope of this study, but would be an interesting topic for future research.

Additional implications may exist in the treatment for executive dysfunction as a result of trauma to the brain. Cognitive rehabilitation has shown promise in increasing performance on a variety of executive measures in individuals with brain injury, yet is limited by current research and theory (Cicerone et al., 2000 for a review). A more thorough understanding of the interplay between basic cognitive processes of memory, processing speed, and higher-level EF such as inhibition, switching, and planning, may assist in treating these deficits by uncovering innovative ways to increase performance in basic cognitive processes in order to impact performance in higher level functions. Without an understanding of these interrelationships, gaps in the literature will continue to exist.

Appendix A: Models of Executive Function

For many researchers, the birth of executive functions (EF) took place in 1848 in Cavendish, Vermont at a railroad construction site. Phineas Gage, a 25-year old foreman at the site, was involved in an explosion that thrust a 3.5 foot-long, 13 lb rod through his head under his left eye, exiting through the top of his skull near the sagittal suture (Harlow, 1848). From the physical damage observed, it was assumed that this injury resulted in considerable loss of portions of the frontal lobes. Surprisingly, initial assessment of Mr. Gage revealed very few deficits in basic cognition, memory, and perception. However, over time, those close to Mr. Gage identified concerning changes in his behavior (Mesulam, 2002). While these changes were classified as simple personality changes, we now know they represented deficits in abilities that have come to be accepted as EF.

On the most basic level, EFs are the cognitive processes that allow us to monitor and attend to our cognitions and behaviors. Beyond that, the definitions are as varied as the researchers who study them. One could speculate that Freud, with his concept of the *superego*, was one of the first psychologists to attach a name to this set of behaviors. Lezak and her colleagues, in their comprehensive resource book on neurological assessment, define EF as “capacities that enable a person to engage successfully in independent, purposive, self-serving behavior” (Lezak, Howieson, & Loring, 2004). These authors make a very specific distinction between cognition and EF. According to them, cognition involves the “what” and “how much” of human existence: what can the individual do, how much does an individual know: Memory, learning, perception, and sensation are included in this definition of cognition. EF, on the other hand, involves the “whether”, the “how”, and the "when" of human behavior: whether an individual is going to act (i.e., willed action), and, if so, how and when will they perform this action. In line with this, EF includes a variety of higher-order functions including self-control, initiation and inhibition of action, switching between tasks, goal-setting, and planning (Lezak et al., 2004; Royall et al., 2002).

Unitary Theories

Baddeley and Hitch (1974) proposed one of the most accepted models of working memory (WM) and was one of the first to include an executive component. These researchers considered executive functions to be the end-product of a multi-level system which relied on the active manipulation of base-cognitive functions in the form of WM. There were five basic assumptions of their model (as described in Baddeley & Logie, 1999). First, working memory involves the collaboration of specialized cognitive functions working together to permit individuals to represent their environment in such a way as to allow for full comprehension and reasoning, including problem solving and goal setting. Second, these mechanisms involve base memory systems (phonological loop for audio/verbal information and the visuospatial sketchpad for visuo/spatial information) and a higher-level executive system (the central executive), which uses and manipulates information from the base systems to gain full comprehension and reasoning. Third, the base memory systems maintain information via rehearsal. Fourth, the central executive's primary function is to regulate and control the information in the base slave systems. This is primarily done through active maintenance of attention, attentional switching, and activation of information with an end goal of comprehension and reasoning. Finally, this model can be used to successfully explain variations and patterns within normal healthy adults as well as clinical and pathological populations.

The slave systems are described in more detail in the text of this study. However, Baddeley and Hitch's WM model viewed the central executive as a component of the WM system (Baddeley, 1996; Baddeley & Logie, 1999). In this model, WM comprises a storage capacity system (audio/verbal and visuo/spatial), a rehearsal system (also audio/verbal and visuo/spatial), and an executive attentional controller. The latter relies on lower level storage and maintenance systems to ultimately allow for executive cognition. The interrelation among these systems was "working memory" and only via this construct was EF possible (Baddeley, 1996; Baddeley & Logie, 1999). Over time, as research became more and more interested in executive functions, Baddeley allowed for a more open interpretation of the central executive. For example, EF was initially described more unitary construct, though Baddeley later stated this system may well be composed of multiple subparts that interact providing higher executive functions (Baddeley & Logie, 1999).

Emphasis on Inhibition

As theories developed, more attention was placed on inhibitory abilities in the face of interference (Barkley, 1997; Kane & Engle, 2003; Roberts & Pennington, 1996).

The assumption of these models is that EF are required only during tasks that involve interference and therefore require capabilities above and beyond simple basic cognitions (Kane & Engle, Roberts & Pennington, 1996). Kane and Engle (2003) viewed this within a WM framework. That is, EF was possible as a result of WM, which maintains information during tasks involving interference. Roberts & Pennington (1996) take a slightly different, yet innovative, approach by viewing EF as an interaction between WM and inhibition, with inhibition acting as buffer against interference. They contend that all EF are based on this interaction requiring active maintenance and manipulation of information (WM) while managing interference (inhibitory control). For these researchers, EF is seen more as a method to manage interference while making concrete decisions. These theories were not without a great deal of empirical support. For example, early animal studies showed higher WM spans for animals placed in environments with few distractions (Malmo, 1942). Later research showed individuals with lower WM spans tended to have greater difficulty with tasks during interference than those with higher WM spans (Cowan, 2001; Kane & Engle 2003; Engle, 2002).

Another model of EF emphasizing inhibitory abilities was posed by Barkley (1997). The primary focus of Barkley's model, and potentially a fundamental limitation, is that it was constructed to explain attention deficit hyperactivity disorder (ADHD). While the model has a great deal of applicability for healthy adults, much of the empirical support was based on theories and known concepts of ADHD, such as those studies that found children with ADHD did not seem to have deficits in attention per se (see Barkley, 1997 for a review of these studies). Barkley contended that behavioral inhibition was the primary cognitive ability, which allowed for all other EF, and which was responsible for the behavioral manifestations of ADHD. Barkley defined behavioral inhibition as three related abilities: the ability to inhibit an initial propotent response, the ability to cease a response already begun, and the ability to protect this period of time from interference. He posited that EF is a combination of four functions: WM; regulation of one's affect, motivation, and arousal (e.g., self-control); internalization of speech (e.g., reflection, internal problem solving, etc.); and reconstitution (synthesis of information to respond/behave as needed). Barkley believed all of these functions were under the control of an inhibitory system which performed the three aforementioned tasks of inhibition. The end-product of this mechanism was the ability to perform executive functions in both thought and behavior. Barkley contended that the inability of a child with ADHD to properly control the inhibitory process was the primary deficit for this population. Indeed, studies have shown deficits in all three tasks of the inhibitory system in individuals with ADHD (see Barkley, 1997 for a review).

Unitary, But Diverse

The most widely accepted model of EF to date was offered by Akira Miyake and his colleagues (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). In response to research indicating dissociations between tasks of EF (e.g. deficits in the Wisconsin Card Sorting task (WCST) while intact performance on the Tower of London task

(TOL); see Miyake et al., 2000), Miyake questioned if EF were more diverse than originally postulated. In addition, performance on a variety of EF tasks was not strongly correlated, indicating some differentiation between them. Previous research had already begun to question the unitary nature of EF, however this was the first study to empirically test these assertions. Indeed, using latent variable analysis, Miyake and his colleagues found some diversity in how functions related to each other, yet they shared common variance with an overarching construct assumed to be EF. To accomplish this, the researchers focused on three well-accepted Ef: shifting (e.g., cognitive flexibility), updating (e.g., WM), and inhibition. Miyake and his colleagues used latent variable analysis to extract common factors from a variety of tasks tapping into these three functions. Analytically, this method would determine how these functions related to each other without relying on strict task purity, which is inherently difficult as many EF tasks tap into multiple constructs.

Miyake and his colleagues had two primary goals for their study. First, their study aimed to determine whether the three EF are distinct functions, whether they are more unitary, or a hybrid combination of both. A second goal was to determine how these three functions related to tasks that have traditionally been used as general "EF" tasks. Specifically, they tested these functions against the WCST, Tower of Hanoi, (TOH), the random number generation task (RNG), the operation span task (OST), and a dual task (DT).

For the first goal, Miyake and his colleagues used confirmatory factor analysis (CFA) to determine whether a diverse, but unitary, model (distinct switching, updating, and inhibition that also loaded onto a shared "EF" factor) fit the data better than a strictly unitary model ("EF"). The data first indicated that no pairs of functions (e.g., inhibition and switching, switching and updating, or inhibition and updating) measured the same construct. This provided initial support for a diverse, three-function, model. In addition, this model fit the data significantly better than the unitary model. The researchers next tested the diverse, but unitary, model, which contained three distinct functions loading onto a common "EF" construct (i.e., *dependent* functions), to a model of three *independent* functions. As expected, the three-function model that contained a common "EF" factor again provided the best fit to the data. These results supported a model of EF that includes distinct sets of functions under an overarching EF construct.

To test the second goal, the researchers used structural equation modeling to test which functions loaded better on performance for the aforementioned tasks. Miyake and his colleagues found that the performance on the WCST was best explained by a path from switching compared to paths from inhibition, updating, or any combination of the three. Using a similar analytical strategy, the researchers found performance on the TOH task to load best on inhibition. RNG performance was best predicted by inhibition and updating, OST by updating, and DT performance was not predicted very well by any of the three functions.

This study by Miyake and his colleagues expanded the field of EF research by offering an empirically based unitary, but diverse, model of EF. In addition, Miyake shed light on how researchers can better understand the tasks they were often using to measure “general” EF, questioning if the distinction between functions should be applied towards distinguishing tasks. It is important to note that, in terms of an overarching “EF” construct, Miyake and his colleagues contend that this “commonality” may be up for debate. While it could potentially be “executive functioning”, it may also be a construct of working memory or inhibition, as has been suggested by previous theorists (Barkley, 1997; Roberts & Pennington, 1996).

One gap in this study was the exclusion of higher-order EF such as planning (Miyake et al., 2000). Miyake stated that this was done purposely to use the most fundamental operationalization of EF for the purpose of analysis. While this makes inherent sense in terms of the analytical goal of Miyake’s study, the model of EF is limited as it excludes such a commonly accepted function such as planning. Despite this, there is a great deal learned from this study and it is used widely as the primary model by which to understand EF (Royall et al., 2002). One attraction of this model for researchers is its applicability. It allows for executive function to exist as an overarching construct, while also allowing for distinct functions under this umbrella term. It is no surprise that this theory is the most widely referenced and accepted (Anderson, 2002; Garon et al., 2008; Royall et al., 2002).

Developmental Models

As mentioned, the current landscape for the vast majority of research conducted on EF still relies on the premises and assumptions of Miyake and his colleague's study. Other researchers, however, have begun to incorporate the neurological underpinnings of EF (explained further in Appendix B) into developmental models. These researchers think that the development of EF behaviorally and neurologically must be understood in order to understand how individual EF interrelate. Brocki & Bohlin (2004) reviewed current models of EF and found that many have significant drawbacks in their "failure to base the research on theories within developmentally relevant frameworks" (p. 572).

One of the first development models of EF was posed by Zelazo and his colleagues (Zelazo, Carter, Reznic, & Frye, 1997). Their theory is a functional theory that views EF from a problem-solving perspective. Specifically, their model relies on the development of EF to provide the foundations for understanding these functions as a whole. In this model, there are four phases that are separable but work together in a unitary construct: problem representation, planning, execution, and evaluation. According to Zelazo and his colleagues, these functions mirror developmental phases in childhood. Children must first be able to mentally represent a problem prior to solving it (problem representation). Once they have mastered this phase, they can begin to plan how to attain a goal (planning). Thirdly, they can mobilize to execute this goal (execution). Finally, they then have the capability to evaluate the effectiveness of their plan and adjust accordingly (evaluation). According to Zelazo and his colleagues, this process not only describes the advancement of problem solving, but also represents each developmental phases that occurs from infancy into young adulthood. That is, the "outcome of executive function is taken to be the solution of a problem" (p. 200). This innovative approach was one of the first models to incorporate such a developmental perspective. Despite this, Zelazo's model has not been as widespread and accepted as the more general theories that came before him. In fact, of all articles referenced in here, no study used this model as the basis for their research.

A more widely cited model of EF came about five years later with Anderson's developmental model of EF (Anderson, 2002). Anderson presented a developmental framework of executive function that combines the unitary and non-unitary aspects of Miyake's aforementioned model, while maintaining foundations in the developmental trajectory of EF across lifespan. The framework proposed by Anderson is the *executive control system* (2002; Anderson, 2008). Anderson is careful to offer this as a "conceptual framework" due to the lack of empirical validation.

The executive control system keeps with the previous theories that have isolated specific functions known to be "executive" both conceptually and empirically, using factor analysis. The functions in this framework are cognitive flexibility, goal setting, attentional control, and information processing. Cognitive flexibility describes the ability of individual to perform multiple, often conflicting, tasks using divided attention, working memory, and feedback. This is most easily understood in terms of Miyake's "switching" construct. Goal setting is the ability to plan, reason, and organize strategies towards a goal. Attentional control includes traditional inhibition, self-monitoring, and self-regulation, similar to Miyake's "inhibition" construct. Finally, Anderson introduces information processing which includes the speed of executive processing, fluency, and efficiency. The majority of these constructs have been identified in previous models, albeit under different terminology, and each is considered independent of each other (Anderson, 2002; Anderson, 2008; Miyake et al., 2000; Royall et al., 2002). However, they interact to perform specific higher order functions. What is novel about this framework, aside from the incorporation of previous models of EF and the inclusion of developmental theory, is the incorporation of information processing (Anderson, 2008). According to Anderson, it is nearly impossible to assess executive abilities without assessing the speed by which an individual performs these abilities. Impairments and variability in speed of processing inherently impact the ability to perform executive function tasks.

The fundamental assumption of Anderson's model is that cognitive functions, including EF, come "online" at very different rates and are often interrelated as they mature (Anderson, 2002). That is, Anderson suggests that research has shown distinct periods of growth in the frontal lobes which map to development of EF: five years of age with development of attentional control; seven and nine years of age which correspond with initial development of IPS, cognitive flexibility, and goal setting; and 11 and 13 when all attentional control, cognitive flexibility, and goal setting mature and concrete "EF" begin to emerge (Anderson, 2002). Due to these types of trajectories, Anderson contends that while all constructs more than likely relate to each other, attentional control more than likely is not “predicted” by any other construct as it comes “online” first. However, all other constructs interrelate in some fashion.

While this study has garnered some interest (Anderson, 2008), developmental perspectives on EF continue to struggle to become as mainstream as more empirically based models such as Miyake and his colleagues. However, Anderson very specifically challenges current models of EF that do not include some construct of IPS, particularly as this is one of the last cognitive functions to develop.

Given the variability among current models of EF, it is challenging for researchers to come to an agreement on how to understand EF (Anderson, 2008; McCabe et. al., 2010). However, more recent frameworks, such as Anderson’s executive control system, seem to come close to offering a comprehensive view of EF that incorporates the empirically supported ideas presented in earlier studies, as well as more current neurological work on the development of EF and the PFC, into one. The landscape continues to form. With advances in neuropsychological testing and analytical approaches, newer models may emerge with more informed paradigms that continue to expand our knowledge of how we perform these higher level executive functions.

Appendix B: Neurobiological Development of Executive Functions

For the most part, executive functions have become synonymous with the frontal lobe (FL) and, specifically, the prefrontal cortex (PFC). This movement began with Phineas Gage (see Appendix A for a summary) and continues to be a prevailing understanding in the field (Alvarez & Emory, 2006; Brocki & Bohlin 2004; De Luca & Leventer, 2008; Friedman et al., 2006; Hawlow, 1848; Huizinga, Dolan, & van der Molen, 2006; Mesulam, 2005; Miller & Wallis, 2009; Robbins, 1998). However, similar to how models of EF moved from a unitary to more diverse foundation, researchers now dismiss a linear “EF = FL” assumption as being far too simplistic (Alvarez & Emory, 2006; De Luca & Leventer, 2008; Friedman et al., 2006; Stuss & Alexander, 2000). Despite this, there is no doubt that many of the functions considered “executive” are very much reliant on an intact and functioning frontal lobe (Garon et al., 2008; Mesulam, 2005). Research has shown time and time again that patients with damage to the FL show intact basic cognitive functions of perception and memory, while being extremely impaired in EF (Hawlow, 1848; Robbins, 1998). It is not surprising, therefore, to see a direct relationship between the development of the FL and development of EF (Huizinga et al., 2006).

Executive functions are, inherently, what makes us willful, considerate, thoughtful, humans. The alternative is what some have coined the “default mode” (Mesulam, 2005). As described in detail by Mesulm (2005), the default mode is the most simplistic of connections within the subcortical regions of the brain. Linear in nature, these connections represent a stimulus-response reaction with little room for evaluation or reflection, which requires connections to the FL. While this works well for animals, with little need for more cognitive contemplation, humans and primates have far more information to process than can be managed by the default mode. The FL "houses" additional cognitive abilities that allow for selective attention and controlled memory systems to better manage the influx of information. The result is a brain which can not only pull in information, but hold it, store it, retrieve it at will, manipulate it, and use it to inform higher level decisions about actions.

One of the cardinal "players" when discussing EF is the PFC, which is located at the front, or anterior, of the FL. If EF can be seen in terms of a "controller" system, as is often the case (Baddeley, 1996), the PFC is the most appropriate area of the brain for the job, as it connected with every other major region of the brain responsible of all other cognitive functions which EF rely on (De Luca & Leventer, 2008; Miller & Wallis, 2009). In addition, the neurons within the PFC are uniquely equipped to perform these duties, as they are constructed to allow for greater intricacy of interconnections with much higher numbers of dendritic networks (De Luca & Leventer, 2008). In a healthy individual, the only limitation of this system is full maturation of the FL and PFC, and EF development seems to follow in line with this maturation (Huizinga, et al., 2006). Research has shown that this, however, can take much longer than previously believed (Huizinga, et al., 2006; Luna, Garver, Urban, Lazar, & Sweeny, 2004).

Early Development

Development of the FL begins months before birth. Neurons slated for the PFC proliferate and migrate weeks after gestation and this journey is predominantly completed roughly 4 months before birth (De Luca & Leventer, 2008). At birth, the brain is still very underdeveloped in this region as the more subcortical regions, responsible for “default mode”, take on the most responsibility. However, the mapping is in place and it is one of the few areas of the brain that relies on genetics to determine the overall map, but relies on experience to create more fundamental connections (Best et al., 2090; De Luca & Leventer, 2008).

Within the first few years of life, the brain goes through rapid transformations. This is due to two primary processes: synaptic generation and myelination. The brain initially increases in volume as it overproduces synapses (synaptogenesis) to allow for diverse and efficient path construction as needed to connect regions of the brain appropriately (De Luca & Leventer, 2008). The second process is myelination (Blakemore & Choudhury, 2006; De Luca & Leventer, 2008; Luna et al., 2004). Myelination is the process of coating axons to allow signals to seemingly “jump” from one neuron to another. This process not only increases the speed of neuronal signals, reportedly by up to 100 times, but also the efficiency of these communications (Blakemore & Choudhury, 2006; De Luca & Leventer, 2008; Luna et al., 2004). During the first few years of life, the majority of the brain around the PFC becomes myelinated in a very structured sequence from posterior to anterior, dorsal to ventral (De Luca & Leventer, 2008). The result of this process is milestones in language, motor functioning, and other basic cognitive functions come “online” earliest. During this time, the FL and

PFC continues to develop as well. In fact, research has shown the first signs of inhibitory control and working memory between the ages of six months and eight months, with WM coming "online" slightly earlier than inhibition (De Luca & Leventer, 2008; Garon et al., 2008; Richard & Fahy, 2005). These studies have shown that babies at this age are able to complete a simple delayed-response task where the baby is shown the location of an object, it is then hidden from sight for 1-2 seconds, and then the baby is encouraged to identify the location of the object even after this delay (Diamond, 1985).

Through childhood, the brain continues its process of synaptogenesis and myelination. Concurrent with this are ongoing advances in inhibitory control, working memory, and the beginning of cognitive flexibility (Best et al., 2009; De Luca & Leventer, 2008; Garon et al., 2008; Luciana & Nelson, 1998; Richard & Fahy, 2005). Research has shown, as inhibition and working memory abilities continue to improve, there is a developmental "spike" in cognitive flexibility and set-shifting, which is inherently reliant on the lower level EF of WM and inhibition (Garon et al., 2008; Luciana & Nelson, 1998). During this time, there are also the beginning signs of simple planning and goal-directed behaviors (Brocki & Bohlin, 2004). Despite these advances, children under the age of five continue to have a great deal of difficulty managing interference when performing tasks (De Luca & Leventer, 2008). In addition, while children at this age are verbally able to repeat rules, they often have difficulty representing rule sets cognitively in order to be able to selectively control behavior (De

Luca & Leventer, 2008). Further, while simple planning abilities begin to emerge, research has shown children at this age are far from being able to tap into the full gamut of executive abilities in order to complete more complex planning abilities (Luciana & Nelson, 1998). In fact, the circuitry for these early EF are reliant more on limbic connections versus the more efficient PCF connections (De Luca & Leventer, 2008). This period of time in childhood is a playground, of sorts, for EF. It is a time of practicing executive abilities, failing, trying again, and experimenting with cognitive processes to determine what process is most effective and in what circumstance. In this sense, while EF has no doubt emerged during this childhood period, errors are widespread and children at this age are in no way prepared for full execution of executive processes (De Luca & Leventer, 2008).

Pre-Adolescence and Adolescence

Beginning at preadolescence, synaptogenesis and myelination continue, but while the associated white matter increases in the brain, gray matter begins to decrease after years of increasing in volume (Blakemore & Choudhury, 2006; De Luca & Leventer, 2008). This decrease in gray matter is, during this adolescent time period, a result of a process of synaptic pruning. This process, not unlike the name insinuates, is a process by which inefficient dendritic branches and axons of neurons are “cut back” in order to encourage more healthy and substantial growth between the strongest and most effective “branches” (Bishop, Misgeld, Walsh, Gan, & Lichtman, 2004; De Luca & Leventer, 2008). This process, in combination with myelination, continues to fine-tune the brain allowing for an increase processing speed. In line with this, EF continues to improve with inhibition now allowing for multiple rule sets to be managed and selectively inhibited towards a goal (Brocki & Bohlin, 2004). In addition, set-shifting abilities and cognitive flexibility continue to increase during this time allowing for more complex multi-dimension tasking.

During adolescence, between the ages of 13 and 19, the FL is near to full maturation. Teens typically are much more successful at understanding rules, cognitively switching between tasks, engaging in goal-directed behaviors, and have optimally functioning working memory systems (De Luca & Leventer, 2008). However, the connections between the PFC and the rest of the brain are still not complete. Research has shown that the teen years mark the final transition from more primitive connections relying on the amygdala-circuitry, to the PFC circuitry (Luna & Sweeny, 2004). This transition is not without “growing pains”. During this age, there is often a disconnect between what the teen brain “knows” and what it “does”. Seemingly, it is still lacking a Freudian *superego* to keep it in check. As a result, teens are notoriously risky in their behavior, impulsive, and much more influenced by their emotional world than mature adults (De Luca & Leventer, 2008). Cognitively, performance on a variety of tasks is at their peak and most all EF are considered at “adult” levels.

Maturation of Executive Functions & Logistical Problems in Research

While most all cognitive tasks show peaks by adolescents, researchers also know the last developmental milestone is the final myelination of the newer connections between the PFC and all other regions of the brain. This seems to occur somewhat later than expected, into the early 20's and coincides with the final maturation of planning abilities which occurs after other EF peak (De Luca & Leventer, 2008; Huizinga, et al., 2006). Therefore, while cognitive performance on tasks is relative stable, the speed and accuracy by which these tasks are processed do not reach full completion until full myelination occurs. It seems only once this occurs that planning and goal-directed behaviors can reach fruition (De Luca & Leventer, 2008; Huizinga, et al., 2006). While research is uncertain when, exactly, this ends, there is support for it happening much later in life (De Luca et al., 2003).

While the height of EF is reached in the 20's, this is not long lasting. In fact, research has shown brain weight declines beginning in the 30's and continues into old age, dropping by 10% by the age of 90 (De Luca & Leventer, 2008). This presents an increasingly difficult model to test and questions whether an understanding of EF is necessarily taping into EF at a variety of developmental stages depending on the age of the sample. In order to appropriately understand EF, a researcher would have to test individuals at the height of brain development and maturation while cognitive abilities are at their peak, around young adulthood. However, no one can say with certainty when this is specifically, as it seems to vary slightly between individuals and the window of opportunity is so small. Assuming a researcher could investigate EF right at this peak of functioning, what would it necessarily tell us about EF considering this time of peak performance is so short-lived? This is a question researchers must address when conducting research in this area. Are we necessarily interested in EF as a construct, or, due to neurological limitations, only able to understand EF on a developmental sliding scale? Future research should employ a variety of statistical and neurological techniques to better understand how EF develop and whether cognition is inevitably a moving target which can only be understood on a continuum.

Appendix C: Exclusion Screening Form

Please exclude yourself if you answer yes to any of these questions:

1. Are you younger than 18?
2. Are you older than 35?
3. Do you suffer from a documented neurological condition (such as MS, Asperger's, Autism, etc.)?
4. Have you had any significant head injury due to an accident within the past year?
5. Do you have a history of stroke or seizures (epileptic or otherwise)?
6. Do you or a family member have a history of psychosis (such as bipolar disorder or schizophrenia)? Depression and anxiety are not forms of psychosis.
7. Do you have a history of drug or alcohol abuse in the past year?
8. Do you have a documented learning or attention disorder such as Attention Deficit Disorder (ADD), Dyslexia, or Attention Deficit Hyperactivity Disorder (ADHD)?
9. Do you consider any other language (besides English) as your primary language?
10. If you wear glasses or contacts, do you have any trouble seeing when you are wearing them?

By signing this form, I confirm that none of the above criteria apply to me.

______________________________ __________________

Signature Date

Appendix D: Posted Flier

Volunteers Wanted for Psychology Experiment

$25 Compensation or Research Credit

Executive Functions in Young Adults: The Role of Information Processing Speed and Short Term Memory

Purpose of Study

To evaluate the development of executive functions in young adults and to determine if this development is impacted by information processing speed and short term memory.

Who can volunteer

The study will include healthy males and females between 18-35 years of age. Contact Elizabeth Van Winkle for additional criteria.

Where

The research will be conducted in the Psychophysiology Lab or the Cogni tive Science Lab at the Catholic University of America. The psychological testing may require up to 2.5 hours.

Additional Information:

Participation is purely voluntary. If you are currently enrolled in PSY 201 you can earn research points. **If you choose not earn research credit, you will receive compensation of $25 upon completion of testing.**

Contact

Please contact Elizabeth Van Winkle by e-mail at ____________________________

Appendix E: Informed Consent Form

CUA The Catholic University of America	Page1 **RESEARCH CONSENT FORM**

Participant Name: ________________________________ **Date:**____________________

Title of Study: Executive Function in Young Adults: The Role of Information Processing Speed and Short Term Memory

Principal Investigator: _Elizabeth P. Van Winkle and Rebecca Fuller, PhD

INVITATION TO PARTICIPATE

This study is interested in the cognitive functioning of healthy young adults. Thus, males and females, between the ages of 18 and 35, will be invited to participate. There will be no exclusion criteria based on race, ethnicity, or gender. Participants will be excluded for the following reasons: history of severe psychiatric illness (psychosis), strokes, seizures, or neurological disease; documented learning/attention disorder; family history of severe psychiatric illness (psychosis), vision impairment, significant head trauma or substance abuse in the past year.

PURPOSE

To determine how executive functions, as measured by the Delis Kaplan Executive Functions System (D-KEFS), develop throughout young adulthood. This not only includes the accuracy of executive function performance, but also the speed of processing, as measured by the Digit Symbol Test. These results will be viewed in relation to individual short term memory capacity, as measured by the Forward Digit Span Test (FDS), to determine if this simple memory capacity can explain individual differences, above and beyond working memory, as measured by the Backward Digit Span Task and Letter-Number Sequencing Task.

DESCRIPTION OF THE PROCEDURES

The research will be conducted in the Psychophysiology Lab at the Catholic University of America. The psychological testing requires approximately two hours.

Initial Assessment: This form will ask questions relating to the participant's current state and mood as well as substance use in the past 24 hours and medical and psychiatric history. These factors have been found to impact performance on executive function measures and therefore, needs to be controlled for. Due to the sensitivity of this information, it will be safeguarded in a locked file and will not be attached to your name or identifying information.

The D-KEFS is a paper and pen neuropsychological test that measures overall executive function. It is a compilation of nine individual, stand-alone, tests, which measure a variety of verbal and nonverbal cognitive functions. Administration will occur for seven of the nine tests and will include a brief review of task instructions and then administration. During administration, participants will be seated in a comfortable chair and will be given ongoing instructions and prompts as provided in the D-KEFS stimulus booklet. The six tests include a Trail Making Test, Verbal Fluency Test, Design Fluency Test, Sorting Test, Twenty Questions Test, Color-Word Inference Test and Tower Test. Scoring will take place concurrent with administration and then later compiled. The total time frame for the D-KEFS is 75 minutes.

The Forward Digit Span (FDS) is a paper and pen memory task, which measures short term memory. This is the maximum amount of information an individual can remember and repeat back without error. This task requires participants to listen to a series of numbers and repeat these back after a brief delay. Individuals are asked to remember progressively longer strings of digits until the individual is unable to accurately repeat back the series. The maximum number of digits accurately repeated is recorded. This task takes approximately 5 minutes.

The Backward Digit Span (BDS) is a paper and pen memory task, which measures working memory. This task requires participants to listen to a series of numbers and repeat these back, after a brief delay, in reverse order. Individuals are asked

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Protocol 10-016

Participant's Initials________ Date________ **CUA FORM – December 2002**

Participant Name: ______________________________ **Date:**____________________

Title of Study: Executive Function in Young Adults: The Role of Information Processing Speed and Short Term Memory

Principal Investigator: _Elizabeth P. Van Winkle and Rebecca Fuller, PhD

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to remember progressively longer strings of digits until the individual is unable to accurately repeat back the series. The maximum number of digits accurately repeated is recorded. This task takes approximately 5 minutes.

Letter-Number Sequencing Task (NLS) is a paper and pen task, which measures working memory. The participant is given a series of numbers and letters (e.g., 2-K-9-F-5). Participants are instructed to listen to the numbers and letters and then repeat back the numbers first in ascending order and then the letters in alphabetical order. The maximum number of digits and letters accurately repeated is recorded. This task takes approximately 5 minutes.

The Digit Symbol Task (DST) is a paper and pen task, which measures speed of processing. The participant is given a key that matches digits to symbols. They are then asked to go through a series of digits and write down the appropriate matching symbol based on the key provided. The total number of correct symbols within a given time frame is recorded. This task takes approximately 5 minutes.

Confidentiality, Data Storage and Analysis: These data will be de-identified and stored for later analysis. This study is part of a larger on-going project in Dr Fuller's Psychophysiology Lab. We would like to consider participating in the study by Dr. Fuller, Contralateral Delay Activity and Working Memory.

☐ If you check this box I will pass your information on to Dr. Fuller.

The two studies will share identifiable data in order to combine the datasets; for example your name will be the link. Once the data are merged into a single dataset the data will be de-identified for all subsequent analyses. You must sign a separate Informed Consent Form for Dr Fuller's study before you can participate in her study and before I will share any data with Dr Fuller.

DISCOMFORTS AND RISKS

The study presents minimal risk to the participants. Some participants may experience frustration during the tasks, however, prompts, time limits, and discontinuation rules are in place in the D-KEFS in an attempt to minimize such experiences. The additional tasks are each under 5 minutes in duration and should therefore limit this type of response. The principal investigator will serve as the data monitor for the study and will provide interim reports as required to the IRB. Serious adverse events will be reported to the IRB, according to IRB established guidelines

As with all research there is the potential risk of breach of confidentiality. This risk will be minimized through the following steps: Your information is kept in confidence and you are given a unique personal identification number for association with your information. Your name or location will not be published. Any information that identifies participants by name will be kept in a locked file cabinet in the Psychophysiology Lab.

EXPECTED BENEFITS

Participants will not benefit directly from participation in the study, although information from the study will contribute to the knowledge of the variability in executive functions within a normal population. In addition, participants who complete testing will be compensated with $25.

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RESEARCH CONSENT FORM

Participant Name: ________________________________ **Date:**______________________

Title of Study: Executive Function in Young Adults: The Role of Information Processing Speed and Short Term Memory

Principal Investigator: _Elizabeth P. Van Winkle and Rebecca Fuller, PhD

WITHDRAWL FROM THE STUDY

You can withdrawal from the study at any time. If you are a CUA student this will not affect your grade in any class.

COSTS AND PAYMENTS

There is no cost to participate. If you are an introductory psychology (PSY201) student, you will receive one research point for each half hour of participation, as indicated in the course syllabus. Aside from the earning of research points, you understand that class standing or grades will not be affected by your decision to participate in or withdraw from this study. Participants who do not wish to receive research credit, but complete the testing, will be compensated with $25 cash.

CONTACTS

Elizabeth P. Van Winkle, Psychology Department, Catholic University, 703.501.0473, 79vanwinkle@cardinalmail.cua.edu

RESEARCH SUBJECT RIGHTS: I have read or have had read to me all of the above.

____________________ has explained the study to me and answered all of my questions. I have been told of the risks or discomforts and possible benefits of the study.

I understand that I do not have to take part in this study, and my refusal to participate will involve no penalty or loss of rights to which I am entitled. I may withdraw from this study at any time without penalty or loss of benefits to which I am entitled.

I understand that any information obtained as a result of my participation in this research study will be kept as confidential as legally possible. The results of this study may be published, but my records will not be revealed unless required by law.

NOTE:

If I have any questions about the conduct of this study or my rights as a participant in this study, I have been told I can call The Catholic University of America Office of Sponsored Programs at (202) 319-5218.

I understand my rights as a research participant, and I voluntarily consent to participate in this study. I understand what the study is about and how and why it is being done. I will receive a signed copy of this consent form.

________________________________ ____________________

Participant's Signature Date

________________________________ ____________________

Signature of person obtaining consent** Date

________________________________ ____________________

Signature of Principal Investigator Date

****Only required if not investigator.**

APPROVED
CUA IRB 00000082

Expires: FEB 23 2012

Protocol 10-016

Participant's Initials________ Date_________

CUA FORM – December 2002

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