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# Using Information Theory and Elementary Cognitive Tasks to Formally Define Executive Functions

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# USING INFORMATION THEORY AND ELEMENTARY COGNITIVE TASKS TO FORMALLY DEFINE EXECUTIVE FUNCTIONS

by

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# ABSTRACT
# USING INFORMATION THEORY AND ELEMENTARY COGNITIVE TASKS TO FORMALLY DEFINE EXECUTIVE FUNCTIONS

by

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Executive functions (EF) are an umbrella construct in neuropsychology that have received significant attention from both clinicians and researchers in recent years. Despite the wide array of definitions of EF and lack of agreement about such constructs, there seems to be a commonality underlying their theoretical frameworks that has to do with the ability to internally regulate one's behavior. In an attempt to overcome inherent limitations to the construct of EF, the present study used elementary cognitive tasks (ECTs), based on information theory (IT) and a reaction time (RT) paradigm, to establish preliminary feasibility of ECTs to assess behavior regulated by internal rules as a measurement of EF and distinguish EF from non-EF cognitive abilities. Therefore, four ECTs, two putative non-executive direct response tasks (0- and 1-bit non-EF tasks) and two putative executive internal rule tasks (1- and 2-bit EF tasks), were developed and administered in college students. These tasks were given to 30 intact undergraduate students. It was hypothesized that the non-EF tasks would show a linear increase in RT as task complexity increases that follows the Hick's law. Additionally, it was hypothesized that the EF tasks would show an exponential increase in RT as task complexity increases. Results supported the hypothesis showing a linear increase in RT on the 0- and 1-bit non-EF tasks, consistent with past literature, and a nonlinear slope associated with the 1- and 2-bit EF tasks; the dramatic nature of this nonlinear relationship was even better demonstrated when increasing EF complexity (1- to 2-bit EF tasks). This nonlinear increase from direct response to internal rule response was demonstrated by the increased variance explained by the quartic curve fit compared to a simple linear fit. These results strongly support the thesis that the EF bit tasks are qualitatively different from direct response tasks, and puts EF assessment on a firm measurement basis that not only precisely defines the construct, but also measures it at the ratio level of quantification.

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Attention Deficit Hyperactivity Disorder (ADHD)

Elementary Cognitive Tasks (ECTs)

Executive Function (EF)

Information Theory (IT)

International Neuropsychological Society (INS)

Prefrontal Cortex (PFC)

Reaction Time (RT)

Standard Deviation of Reaction Time (RTSD)

Stroop Color and Word Test (Stroop Test)

Supervisory Attentional System (SAS)

Trail Making Test (TMT)

Wisconsin Card Sorting Test (WCST)

# Using Information Theory and Elementary Cognitive Tasks to Formally Define Executive Functions

Executive functions (EF) are an umbrella construct in neuropsychology that have received significant attention from both researchers and clinicians in recent years. EF are generally related to functioning of the prefrontal cortex (PFC), and these control processes have been integrated into various controversial theories and models seeking to define EF. However, lacking a single core construct, it has been difficult to develop measures of EF that correlate well together, to identify individuals with PFC lesions, and to agree upon methods of qualitatively distinguishing between EF and non-EF components of cognitive ability.

Despite the wide array of definitions of EF and lack of agreement about such constructs, there seems to be a commonality underlying their theoretical frameworks that has to do with the ability to internally regulate one's behavior. It is possible to measure this ability through elementary cognitive tasks (ECTs) based on responses according to internal rules. Thus, ECTs may be useful as measures of EF, although they have not yet gained widespread acceptance for this purpose. In an attempt to overcome inherent limitations to the construct of EF, the present study used ECTs, based on information theory (IT) and a reaction time (RT) paradigm, to establish preliminary feasibility of ECTs to assess behavior regulated by internal rules as a measurement of EF and distinguish EF from other cognitive abilities such as perception.

The current project compared the performance on four ECTs, two putative non-executive direct response tasks (0- and 1-bit non-EF tasks) and two putative executive internal rule tasks (1- and 2-bit EF tasks), in college students. In contrast to the currently available EF tests, these ECTs exhibit several advantages such as a clear differentiation between executive and non-executive functioning abilities, a ratio level of measurement based on a RT paradigm, task complexity defined according to bits of information, and a flexible platform that can be adapted to both verbal and nonverbal modalities. Each area, EF and ECTs, has an extensive literature, thus a selective review of these areas follows.

### *Executive functions (EF)*

Theoretical Models. Luria (1973) had an early conceptualization of EF. Although he did not coin the term, the neuropsychological study of EF built on his early reports of patients with damage to the PFC (Stuss & Benson, 1984). Baddeley and Hitch (1974) first described EF as a "central executive" and Lezak (1995) later defined it as a human behavior dimension "necessary for appropriate, socially responsible, and effectively self-serving adult conduct" (p. 42). EF are also generally described as high-level cognitive functions believed to be mediated primarily by the PFC (Stuss et al., 2002). Some hierarchical cognitive models, for example Baddeley's (2002) working memory model and Normal and Shallice's (1986) SAS model, support the existence of a central executive that deals with more complex levels of functioning and that reflect PFC activity; an idea that is supported by neurological literature that describes patients with PFC injury with disorganized and impulsive behavior. Other models, such as Fuster's perception-action cycle (Fuster, 2002), suggest that the role of the PFC is to expand the temporal perspective of the system rather than be an executive interpreter. Moreover, others like Zelazo et al. (1997) reject the approach of the uniqueness of the PFC in the control of EF.

Currently, EF are a multifaceted set of neuropsychological constructs that have received myriad definitions and fractionations into subcomponents comprising a wide range of cognitive processes and behavioral competencies which include, but are not limited to, resistance to interference, working memory, multitasking, sequencing, sustained attention, verbal reasoning, utilization of feedback, planning, problem-solving, cognitive flexibility, and the ability to deal with novelty (Anderson, Northam, Hendy & Wrenall, 2001; Baddeley & Hitch, 1974; Banich, 2004; Borkowsky & Burke, 1996; Burgess, Veitch, de Lacy Costello & Shallice, 2000; Coltheart, 1989; Damasio, 1995; Elliott, 2003; Grafman & Litvan, 1999; Hobson & Leeds, 2001; Lafleche & Albert, 1995; Lezak, 1995; Norman & Shallice, 1986; Piguet et al., 2002; Stuss, 2011; Stuss & Benson, 1984). Sergeant, Geurts and Oosterlaan (2002) listed 33 different definitions of EF, demonstrating the notorious difficulty in precise definition of EF. The wide variety of definitions and subcomponents theorized to make up EF reveals a lack of agreement and even controversy in relation to the true nature of EF (Jurado & Rosselli, 2007; Suchy, 2009); therefore, the construct of EF still awaits a formal definition (Jurado & Rosselli, 2007). Additionally, this confusion of definitions signifies either that the crux of the construct has so far been elusive or that there is no rubric that encapsulates the functions of the PFC. At the 40th Annual Meeting of the International Neuropsychological Society (INS), the president of INS expressed the need to "come to terms with how we define and measure this construct in a reasonable way" (Bauer, 2012). More importantly, having a clear definition of EF that yields a quantifiable measure of the complexity and fractionated components of EF becomes imperative for the field of neuropsychology, not only for the accuracy of neuropsychological assessments, but also for the facilitation of communication among clinicians, the predictability of clinical outcomes, and planning rehabilitation (Chan, Shum, Toulopoulou, & Chen, 2008).

Despite the lack of a formal definition, there exists relative agreement in terms of the complexity and importance of EF to human adaptive behavior (Jurado & Rosselli, 2007). EF are deemed to allow us to alter our mindset in order to adapt to situations while simultaneously inhibiting inappropriate behaviors; that is, they largely allow the organization of thoughts in a goal-directed way in daily living situations (Ardila & Surloff, 2004). By reviewing the different models and theories of EF, there seems to be a commonality among them that has to do with EF allowing internal regulation of behavior. Such an ability could be studied by having the individual follow internal rules to properly adjust his behavior to contextual demands. Therefore, the concept of mental set (e.g., internal rules) seems to be "the only rubric comprehensive enough" (p. 187; Osmon, 1999) under which to heuristically encapsulate the regulatory nature of EF and its subcomponents. Mental set is a concept that also implies holding an internal mental representation, or an internal rule, that connects appropriate actions with concrete environmental aspects, thus allowing us to self-regulate our behavior, so the latter is not subordinated to the mere perceptual features of the stimuli (Osmon, 1999). The following sections provide an explanation to this reasoning.

Operationalization. Along with the difficulties reaching an agreement on the definition of EF is the challenge of operationalizing and assessing EF. A task-based method has been the prevailing approach to the study of EF by identifying impaired cognitive abilities in patients with damage to the PFC (Jurado & Rosselli, 2007; Lezak, 2012; Suchy, 2009). EF tests and batteries such as the Controlled Oral Word Association

Test (Benton, Hamsher, & Sivan, 1994), Trail Making Test (TMT; Reitan, 1992), Stroop Color and Word Test (Stroop Test; Golden, 1978), Wisconsin Card Sorting Test (WCST; Grant, Berg & Heaton, 1993), Behavioral Assessment of the Dysexecutive Syndrome (Wilson, Alderman, Burgess, Emslie & Evans, 1996) and Delis–Kaplan Executive Function System (Delis, Kaplan & Kramer, 2001) are some of the most commonly used assessment instruments that operationalize EF.

Operationalization of a construct is a critical process in science that defines the construct and, therefore, needs to be carried out in a careful, thoughtful manner that fully captures the essence of the process. Although the operationalization of EF has faced many difficulties, only three main issues relevant to the present study will be discussed as follows. First, validating EF tests based entirely on their sensitivity to PFC damage is problematic because of the vast territory of the PFC, making up 30% of the cortical surface (Miller & Cummings, 2007), and because of the PFC's extensive connections to many brain systems, including perceptual, memory, emotional, and procedural systems. As a result, neuroanatomical territories associated with EF have grown well beyond the PFC to include most of the brain. Therefore, the specificity of such EF tests to PFC damage based on a lesion methodology is questionable since both subcortical and posterior lesions can produce PFC test impairments due to the PFC' extensive connections to many brain areas (Royall et al., 2002). Owing to the expanse of PFC cortex and its rich connection to many brain systems, it is likely that EF have many components, which is probably the reason why individuals with PFC damage have such variable profiles across EF test performances. For example, clinical observations demonstrating dissociations in performance among EF tasks (e.g., some patients may fail on the TMT, but not on the Stroop or vice versa; Miyake et al., 2000) along with their low correlation (r=0.40, or less) make some researchers and clinicians doubtful of these tests' true ability to measure and quantify EF (Jurado & Rosselli, 2007). Additionally, classic EF tasks, like the WCST, have been shown to lack sensitivity to PFC damage. For example, a study examining the sensitivity and specificity of the WCST as a measure of PFC damage found that, although many subjects with PFC damage performed poorly, a large number performed within normal limits and many subjects with non-PFC damage failed the test, thus suggesting that interpretation of the WCST performances alone as an indication of the presence or absence of structural damage in the PFC is not supported (Anderson, Damasio, Jones, & Tranel, 1991). These results also suggest that in some sense EF are at the apex of the cognitive taxonomy hierarchy, such that good performance on an EF task is dependent upon intact cognitive abilities lower in the hierarchy. Consequently, impaired perception or memory or any of a host of other cognitive functions will manifest as impairment on an EF task. Thus, impairment on a single task of EF is insufficient to diagnose EF impairment unless a comparative non-EF task that includes all of the cognitive functions lower in the hierarchy is intact. In that instance, EF dysfunction can be inferred by the process of elimination (Schoenberg & Scott, 2011).

Second, another issue with defining EF has to do with the level of measurement extant in psychometrics. Most neuropsychological instruments are based on an interval level of measurement, meaning that direct comparison of performance across cognitive constructs is only partially successful (Furr & Bacharach, 2008; Rao & Sinharay, 2007). Co-norming measures of different constructs is used to partially eliminate the problem of directly comparing someone's memory performance with their language or spatial performance (e.g., the Neuropsychological Assessment Battery by Stern, White, T., & Psychological Assessment Resources, Inc, 2003). Item Response Theory methods have also been used to make further progress in directly comparing performance across different constructs (e.g., Woodcock-Johnson III by Woodcock, Mather, McGrew, Schrank & Johnson et al., 2001). However, these methods are only partially successful because it is difficult, if not impossible, to measure each construct's full range of ability and to center measurement of a construct on the theoretic population mean of that ability, such that task difficulty can be normalized equivalently from one construct to the next (Furr & Bacharach, 2008). Thus, a memory task might be surveying the top end of population performance while a spatial task might be surveying the bottom end of performance. No amount of standardizing performance will correct for this defect of interval level measurement if initial task calibration is skewed, making direct comparison of one cognitive ability with another impossible (e.g., memory and spatial ability; Rao & Sinharay, 2007).

Third, the lack of understanding of the latent variable that underlies and unifies different instantiations of EF ability on various tasks represents another issue with defining EF. Factor analyses of EF have been limited, but those that exist generally find latent variables emerging that correlate well with each of the component tasks in the analysis (Floyd, Bergeron, Hamilton & Parra, 2010; Miyake, Friedman, Emerson, Witzki, Howerter et al, 2000). However, finding a latent variable and grasping the essence of what that variable means are two different things. For example, the ongoing controversy of the general factor of intelligence (Carroll, 1993) versus the crystallized/fluid conception of intelligence still rages after 100 years of factor analysis (Horn & Cattell, 1966; Keith, 1997). Additionally, there have been many attempts to understand that meaning in the EF literature. For example, Duncan and colleges (Duncan, Emslie, Williams, Johnson & Freer, 1996; Duncan & Owen, 2000) argue that PFC mediates fluid intelligence, marshaling neuroimaging and psychometric evidence that more than 40 point differences between crystallized and fluid intelligence scores exist in frontally lesioned patients and that fluid intelligence performance is associated with marked PFC activation. However, such results do not explain focal PFC activation in various regions associated with more elemental cognitive task performances that do not rely upon complex fluid reasoning ability. Thus, simple working memory tasks activate dorsolateral frontal regions (Smith & Jonides, 1997) while simple resistance-to-interference tasks activate medial frontal areas (Peters, David, Marcus & Smith, 2013), and simple inhibition tasks provoke activation in orbitofrontal foci (Szatkowska, Szymańska, Bojarski & Grabowska, 2007). Given the success of a componential approach to understanding the latent variables of EF, it might be argued that EF as a global construct does not exist; however, that would ignore the empirical fact that latent variables emerge in factor analysis of EF tasks. Therefore, there are no definite answers about the latent variables, so the search continues. Finally, until a formal definition of EF and a better quantifiable measure is found, the study of EF will be plagued by the above problems (Jurado & Rosselli, 2007; Suchy, 2009).

### *Elementary Cognitive Tasks (ECTs), Information Theory (IT), and Reaction Time (RT)*

Construct validity is an ongoing process that accretes from multiple methodologies and cannot be completed by even a handful of studies (Cronbach &

Meehl, 1955). However, one powerful method for defining a construct is to build a mathematical model that predicts the construct with a high degree of accuracy. Prime examples of this process were Shepard and Metzler's (1988) measurement of mental visual rotation and Sternberg's (1969) delineation of memory scanning. Both of these models used precise, ratio level measurement in the form of RT and were able to mathematically describe a cognitive construct. This approach should be useful to delineate the elusive construct of EF and distinguish it from non-EF constructs if executive processing is qualitatively different from other cognitive constructs.

One method of attempting a precise definition of EF is to use IT and the idea of measuring cognition in terms of bits. This approach was used to great advantage to describe the amount of RT associated with each bit of information needed in ECTs (e.g. choice RT tasks) of varying complexity. ECTs represent a range of tasks where individuals perform simple cognitive acts, such as selecting letters or judging line lengths. ECTs require only a small number of mental processes and easily specified correct outcomes, so accuracy is usually very high (Carroll, 1993). Frequently used ECTs measure inspection time (e.g., speed of information intake) or RT (e.g., processing speed; Jensen, 1998). ECTs allow measurement of the number of mistaken responses or accuracy, mean RT, and the standard deviation of RT (RTSD) or processing efficiency over *n* number of trials (Jensen, 1998, 2006; Colom, 2009).

ECTs require people to evaluate and react to simple visual stimuli, but presumably they index the speed and efficiency with which the nervous system processes information (Jensen, 1998, 2006). Jensen (1998; cited by Colom, 2009) argues that "periodic oscillation of the action potentials of assemblies of neurons could underlie the variability in speed tasks" (p. 403). Flehmig et al. (2007) have reported that higher values for RTSD are systematically detected for patients with focal PFC lesions, traumatic brain injury, epilepsy, dementia, mild cognitive impairment, schizophrenia, attention deficit hyperactivity disorder (ADHD), and anxiety-related personality traits. ECT performance has been found to correlate about .50 with varied factor scores on standardized IQ tests (Jensen, 1998, 2006; Sheppard & Vernon, 2008). All ECTs are characterized by demands on motor behavior, but also perception since the speed of perceptual processes represents the speed of cognitive processes quite well (Jensen, 2006).

The time it takes for a person to make a decision as a result of the possible choices available is called Hick's law (Hick, 1952) and it is deemed to assess cognitive information capacity in choice RT task experiments. Based on IT, a bit represents the amount of information required to reduce uncertainty by half (Shannon & Weaver, 1949). According to Hick's Law, the amount of time taken to process a bit is known as the rate of gain of information expressed in the following formula: $\log_2 n$ where $n$ is the number of choices presented. Logarithm to base two explains the relationship because presumably RT is a function of eliminating half of the stimuli perceptually with each bit (Hick, 1952).

Studies have shown a linear increase in RT that follows Hick's law in choice RT tasks that include up to eight stimuli where three bits of information are required (e.g., $\log_2 8=3$), as in the Jensen box (Jensen & Munro, 1979). The Jensen Box includes eight response buttons with a small LED above each and arrayed in a semicircle, a home key in the lower center, and a loudspeaker to play alerting sounds. In this task, the subject should hold down the home key and, when a response button lights up, he or she has to push it. The time to lift off the home key (decision time) and the time to hit the response button (movement time) can be measured separately. Thus, it has been demonstrated that RT slows as a logarithm to base two of the number of choices presented; that is, when there are one, two, four, and eight response buttons available, the Hick's formula applies respectively as follows: $\log_2 1=0$, $\log_2 2=1$, $\log_2 4=2$, and $\log_2 8=3$ (Jensen, 1987).

Additionally, as an example with eight stimuli arranged four on the right and four on the left, the first bit of information can be viewed as eliminating half of the stimuli (four) on the side opposite the target stimulus. The second bit would then eliminate two of the remaining four stimuli while the final bit chooses between the remaining two stimuli. Visual perception accomplishes this process during the decision time aspect of the response, whereas the movement time is a trivial portion of the total response time. Using Hick's law, a precise linear fit to RT data for 0-bit (one response button) to 3-bit tasks (eight response buttons) showed a positive correlation of .97 (Jensen, 1987). Therefore, Hick's law has a logarithmic form because subjects, using a perceptual process, eliminate half of the remaining choices with each bit, thus yielding a linear time increase with each successive bit of information required (Jensen, 2006).

### *Distinction between Automatic and Controlled Cognitive Processing*

It is more crucial to distinguish EF from qualitatively different cognitive functions. In this regard, EF seem to be distinct from perceptual processes, as instantiated in the direct-response and perceptual choice RT tasks described above. Perception is an obligatory and automatic cognitive process while EF are controlled and volitional processes. Such a distinction seems a clear base upon which to differentiate EF from non-EF cognitive processes.

Perceptual cognitive processes are automatic, effortless, reflexive in nature, triggered by particular stimulus events in the environment, and may not require monitoring or consciousness (Palmeri, 2002). EF are controlled, deliberate, attention-demanding, serial, and consciously carried out planned and goal-directed behaviors with flexible responses to environmental demands. The Stroop test (Stroop, 1935) interference condition illustrates the distinction between such processes. In the incongruent condition, words interfere with color naming but colors do not interfere with word naming because word reading is a more highly automatized process than color naming. Word reading happens rapidly and effortlessly, without conscious intention, and cannot generally be suppressed; this would be an example of perceptual processing. Even when the task is to name the colors, and to ignore the words, word reading happens anyways, automatically, and can interfere with color naming. Naming colors requires more attention, conscious intention, and effort, which are requirements of EF types of processing.

Thus, one would expect a different relationship to hold between choice RT task performance, which traditionally relies on perceptual processes, and ECTs based on EF of increasing complexity. Perceptual processes can eliminate half of the information with each bit, and the time taken to do so is equal from one bit to the next without regard for the number of stimuli processed in each bit (e.g., about 27ms/bit; Jensen, 1987) as previously mentioned. It might be expected that EF processes would be slower, showing a much different slope from one bit to the next or even have an exponential slope with greater "processing times" with each successive bit.

However, what would distinguish EF from perceptual processing on ECTs? The answer to this question seems to turn on the automatic versus controlled processing distinction. One way to adapt ECTs into the automatically driven format is to have choice RT based upon natural responses in the case of automatic tasks (e.g., respond to a left or right stimulus with a left or right button press, respectively) or an unnatural internally-mediated rule in the case of controlled, EF tasks (e.g., respond to a left or right stimulus with a right or left response, respectively). Such a procedure also maps onto a bit measurement process. For example, each internal rule would reduce uncertainty by half. In the prior example, an internal rule that controls behavior through the verbal statement “respond with the button opposite the stimulus” would require one bit to reduce uncertainty. A second bit could be added with the internal rule “alternate from an opposite side response to a same side response with each trial.” If executive functioning processes are qualitatively distinct from perceptual, automatic processes then different slopes should characterize performance on the two types of tasks.

### *Advantages of Executive Functions (EF) based on Elementary Cognitive Tasks (ECTs).*

EF measured with ECTs offer several advantages over the currently available EF tests. First, they make a clear differentiation between non-executive and executive abilities. In this case, a distinction is made between obligatory and automatic cognitive processes that rely on perception versus controlled and volitional cognitive processes that are supported by EF. For this study, the four ECTs were composed of two non-executive direct response tasks (0- and 1-bit non-EF tasks) that require the subject to produce an automatic response to a tangible external stimulus similar to traditional choice RT tasks (e.g. press a button anytime that a stimulus shows up or lights up). On the other hand, the other two tasks are executive internal rule tasks (1- and 2-bit EF tasks) in which subjects’ responses are determined by intangible internal rules that are recursive or self-referential in the service of regulating behavior. As an example of their recursive nature, on the 2-bit EF task (described further below in the Methods section) a self-repeating pattern is defined by the rules, but applying the rules requires keeping track of how the rules are being applied. Thus, one presses a button on the same or opposite side as the stimulus depending upon an alternating pattern, such that one has to keep track of each trial relative to the prior trial. Having automatic/stimulus-driven versus effortful/internal-controlled tasks provides a clear distinction between non-executive and executive tasks that circumvents the difficulties in imprecise definition of the executive nature of a task.

Second, these ECTs were based on a RT paradigm that has a ratio level of measurement because of the true zero point inherent in RT measurements, thereby allowing absolute scores and truly direct comparison between and within subjects' performance across tasks. Thus, by assessing performance with ratio level measuring instruments like RT, EF scores can be directly compared to non-EF scores (or scores among different EF components) and problems of identifying EF impairment are ameliorated. Third, task complexity according to bits of information necessary to determine a response represents another advantage of these ECTs, since it provides a mathematical specification of the executive nature of the ECTs; a powerful and precise mathematical method to describe and delineate the elusive construct of EF and distinguish it from non-EF constructs if the former is qualitatively different from other cognitive constructs.

Third, a flexible computerized platform is used that can be adapted to both verbal and nonverbal modalities. Studies have shown a distinction in performance between verbal fluency and design fluency in patients with PFC lesions compared to controls, although results have been controversial about the brain lateralization of such functions. In general, studies have found that verbal fluency is most sensitive to left frontal lesions (Baldo, Shimamura, Delis, Kramer, & Kaplan, 2001; Janowsky et al., 1989; Perret, 1974;) although some studies have found that right frontal patients show disturbed verbal fluency as well (Baldo & Shimamura, 1998; Miceli, Caltagirone, Gainotti, Masullo, & Silveri, 1981; Miller, 1984). Additionally, other studies reported that patients with right frontal and right frontocentral lesions were significantly impaired on a design fluency task (Jones-Gotman & Milner, 1977; Ruff et al., 1977) whereas other researchers have shown that design fluency rely on both right and left frontal cortexes (Baldo et al, 2001; Elfgren & Risberg, 1998). Moreover, patients who might have either verbal or spatial deficits that compromise their assessment through a specific cognitive modality could benefit from having complementary tasks that can be adjusted to their intact cognitive abilities (Lezak, 2012). Also, cognitively normal individuals might have an asymmetric performance on verbal and non-verbal tasks due to a greater talent in either of these domains, which could be assessed independently with complementary tasks assessing both modalities. Therefore, having a flexible, computerized platform would be useful to make further distinctions and hypotheses on right and left PFC functioning as well as allow the assessment of patients under different cognitive modalities, and the characterization of cognitively normal individuals' verbal and design fluency skills.

### *The present study*

The present study sought to investigate whether performance on automatically-driven versus internally-mediated rule ECTs is characterized by qualitatively distinct slopes (e.g., linear versus exponential respectfully). It operationalizes EF as the ability to regulate one's behavior according to internal rules that can be precisely measured by using ECTs. ECTs that base responses on internal rules as opposed to traditional choice RT tasks driven by automatic response to external stimuli were developed. This study used a within subjects design with two automatic, perceptual tasks (0- and 1-bit non-EF tasks) and two controlled, EF tasks (1- and 2-bit EF tasks) that required one or two internal rules to respond correctly. This was not a concurrent validity study, since no correlations between the ECT performance and other currently available EF measures was conducted. Instead, determining the pattern of responses to stimuli associated with, and thus establishing if there was a difference in performance (e.g., linear versus exponential increase in RT) between, non-executive and executive ECTs represented the first step toward finding a way to make a clearer fundamental distinction between non-EF and EF processes. To this end, the two non-EF tasks and two EF tasks, which can be differentiated by using direct responses to stimuli versus an internal rule to respond respectively, were administered to college students. The following hypotheses were generated:

1. The non-executive direct response tasks (0- and 1-bit non-EF tasks) would show a linear increase in RT as task complexity increases. As previous studies using the Jensen Box and up to three bits of information, it was expected that subjects' performance on the 0- and 1-bit non-EF tasks, which relied on a perceptual cognitive process, would resemble a linear increase in RT that follows Hick's law (Jensen, 1987; Jensen, 2006).

2. The executive internal rule tasks (1- and 2-bit EF tasks) would show an exponential increase in RT as task complexity increases. In contrast to the aforementioned linear increase, it was expected that subjects' performance on the 1- and 2-bit EF tasks would show an exponential increase in RT.

## METHOD

### *Participants*

30 college students in psychology classes were recruited as participants (18 women, 12 men, *M*age = 24.2 years, age range: 18–30 years). Participants received an informed consent sheet (see Appendix A) to read and sign and were allowed to ask the undergraduate research assistants (RAs) questions about the nature of the experiment. Participants were treated in accordance with university regulations regarding human research subjects. Participants eligible to participate must have been 18 years old or older and had no past history of a psychiatric or neurological condition, and no diagnosis of learning disabilities or ADHD.

### *Materials*

The four ECTs, two non-executive direct response tasks (0- and 1-bit non-EF tasks) and two executive internal rule tasks (1- and 2-bit EF tasks), defined in complexity according to the number of bits necessary to determine a response were programmed using Direct RT Research Software (Jarvis, 2008). The stimulus presented in each task consisted of a black circle randomly appearing either on the right or left side of a box centered on the screen on a white background; except for the 2-bit EF task, which had a pseudo-random order. Each task also had 20 practice trials and 120 testing trials; except for the 0-bit non-EF task, which had only 5 practice trials. Participants indicated their choice by pressing the space bar key for the 0-bit non-EF task or by pressing either the F key (left-sided key) or J key (right-sided key). The 0-bit non-EF task was a simple RT task where the subject had to press the space bar key when either a left- or right-sided circle appeared. The 1-bit non-EF task required a direct response by doing a same side response to the circle by pressing a right/left-sided key. The 1-bit EF task required one decision according to an internal rule: doing an opposite side response to the circle by pressing a right/left-sided key. The 2-bit EF task asked the participant to do a same side response followed by an opposite side response and keep alternating these responses throughout the task. Thus, the 2-bit task required two decisions according to an internal rule: alternating same/opposite side from one trial to the next. Feedback upon incorrect responses was given during practice trials and the 2-bit EF task during testing trials for the subject to get back on track on the alternating pattern.

### *Procedure*

Participants went over the informed consent document and filled out a demographics questionnaire with the help of RAs (see appendix B). All participants were tested in the Adult Neuropsychology Research Laboratory at the University of Wisconsin-Milwaukee. The four ECTs were administered to each participant according to the following order: 0-bit non-EF task, 1-bit non-EF task, 1-bit EF task, and 2-bit EF task. Participants were run individually. The number of mistaken responses (accuracy), mean RT of correct responses (from target onset until participant's response), and the RTSD of correct responses were measured. The ECTs were administered on a Hewlett Packard computer, with 18 inch monitor and standard keyboard and computer console, positioned in a standardized distance of five inches from the edge of the table.

### *Statistics*

Raw data were stored and analyzed on Microsoft Excel (2010) and JMP Pro 11.0 (SAS Institute, Inc., 2013). Data were initially entered into a Microsoft Excel (2010) database and double-checked by RAs in order to eliminate keying errors then data were analyzed in JMP Pro 11.0 (SAS Institute, Inc., 2013). That is, demographic data per participant along with their respective RT data collected on Direct RT Research Software (Jarvis, 2008) were entered weekly by RAs in the database. Once data collection was completed, all the data were double-checked by RAs and descriptive statistics were run in order to ensure further accuracy before transferring the data into JMP Pro 11.0. For all RT analyses, participants' data were trimmed as outliers for any RT less than 150ms (physiological limit; Jensen, 2006), or greater than two *SD* of the ipsative mean, since the former is considered quicker than physiologically likely and RT distributions tend to be typically positively skewed. Therefore, correct responses used for time data analyses were those between RT greater than or equal to 150ms and less than two *SD* above the ipsative mean. In the case of error data, participants making more than two *SD* of group mean errors were deleted because they likely did not complete the task faithfully. Incorrect responses, such as responses less than 150ms and responses contrary to the predetermined instructions, were used for error analysis.

To determine the pattern of responses to stimuli associated with each ECT, group RT averages based on correct responses per task were calculated. For hypothesis 1 and 2, which predict a linear versus an exponential increase in RT on the non-EF and EF tasks respectively as complexity increases, curves showing the best fit to the group averages per task were used. Curve fitting analyses were conducted as an aid for data visualization, a means to test the study hypotheses, and to summarize the subject's performance on both the non-EF and the EF tasks. However, given the fact that there were two non-EF tasks producing only two data points each, they would show a linear increase by definition. Therefore, a comparison between the ECTs' group averages and previous results from the literature (e.g., 300ms for the 0-bit, 324ms for the 1-bit, 355ms for the 2-bit and 381ms for the 3-bit using the Jensen Box in college students; Jensen, 1987) was required. Additionally, since there were two EF tasks, the exponential increase was extrapolated from the participants' performance on the non-EF tasks and the literature. To do so, results from the 0- and 1-bit non-EF tasks' group averages as well as the continuation of the linear relationship shown in previous literature were considered. One-sample - t-tests were conducted to compare the 0- and 1-bit non-EF tasks and results from the literature (Jensen, 1987).

## Results

*Elementary Cognitive Tasks (ECTs) Descriptives*. Table 1 shows the basic group-level descriptive data on the ECTs based on the trimmed data; less than 5% of the data were trimmed as described above. Evident in Table 1 is the 25ms/bit difference between the two direct response ECTs (0- and 1-bit non EF-tasks), while the difference between the more complex direct response and simplest internal rule ECTs (1-bit non-EF and 1-bit EF tasks) is much greater at 74ms/bit. Likewise, the difference is even greater between the two internal rule ECTs (1- and 2-bit EF tasks) at 591ms/bit. Figure 1 shows a comparison between subject's performance on the four ECTs and previous results from the literature (Jensen, 1987). As can be seen in the error data shown in table 1, the ECTs are generally easy when given practice trials with feedback, as done in this study, with only 2 or 3 errors in 120 trials on average.

Table 1 *ECT group performance*

| Task | Mean (*SD*) RT | Mean (*SD*) Errors |
|---|---|---|
| 0-bit non-EF Task | 285 (52) | 3 (6) |
| 1-bit non-EF Task | 310 (46) | 2 (1) |
| 1-bit EF Task | 384 (58) | 2 (1) |
| 2-bit EF Task | 975 (301) | 3 (2) |

*Note:* RT means and *SDs* are based on correct responses and are given in milliseconds whereas error means and *SD* indicate incorrect responses and are given in numeric values.

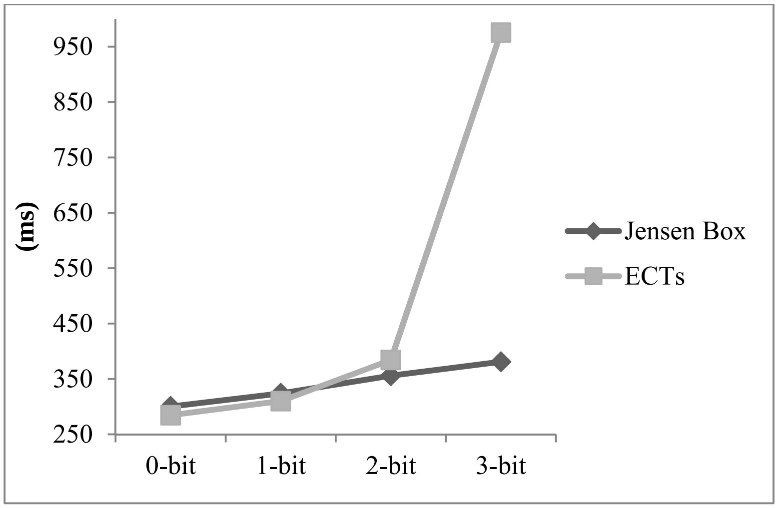


*Figure 1.* Comparison between subject's performance on the four ECTs and previous results from the literature (Jensen, 1987). The X axis shows results in bits using the Jensen Box, which correspond with the 0- and 1-bit non-EF tasks followed by the 1- and 2-bit EF tasks respectively.

*Curve Fitting.* A linear fit to the four ECTs' data was significant and accounted for 61% of the variance (RT = 166.82543 + 214.5846*Task, $F[1,108] = 145.73$, $p < .0001$). However, adding a quadratic component significantly improved the fit accounting for an additional 22% of variance, such that a total of 83% is explained by both linear and quadratic components ($RT = -10.02769 + 214.5846*Task + 141.4825*(Task)^2$, $F[1,108] = 259.73$, $p < .001$; see Figure 2). Additionally, a polynomial curve fitting procedure using just the 0-bit and 1-bit non-EF tasks as well as the 1-bit EF task was run to examine whether the 1-bit EF task added a nonlinear component to the curve. This analysis showed that a linear fit was significant explaining 37% of the variance, while a quadratic term was also significant explaining another 3% of variance (see Figure 3).

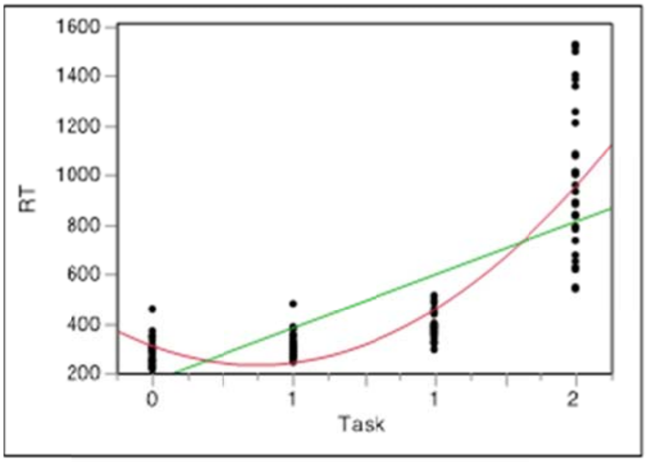


*Figure 2.* Curve fitting analysis including a linear fit to the four ECTs and a quadratic component showing statistically significant results for both linear and nonlinear fits.

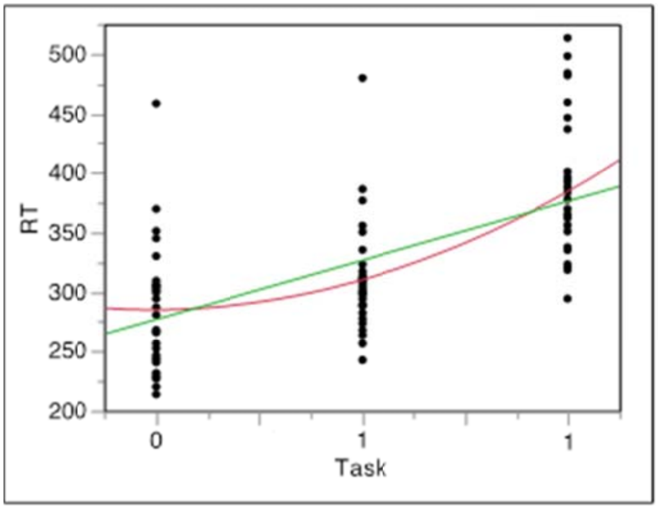
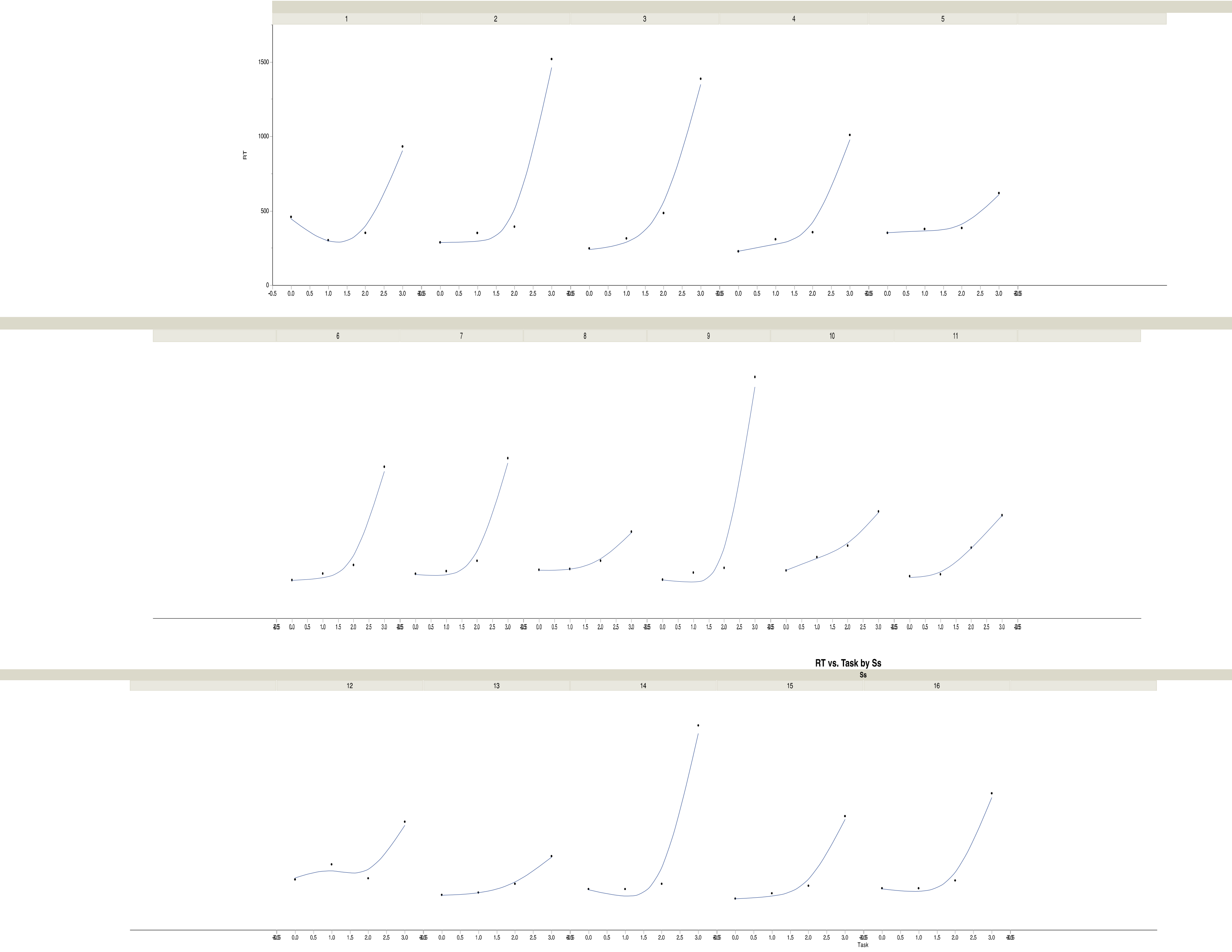


*Figure 3.* Curve fitting analysis including a linear fit to the 0- and 1-bit non-EF tasks as well as the 1-bit EF task and a quadratic component showing statistically significant results for both linear and nonlinear fits.

*Individual Subject-Level Analyses*. Individual subject data were analyzed to determine the penetrance of the nonlinear results (see Figure 4). Visual analysis of each of the 30 participants showed that the nonlinear relationship between the ECTs held strongly for every subject. Individual variation in the magnitude of the nonlinear relationship was evident with a few subjects showing extreme increases in RT from the 1-bit EF to the 2-bit EF tasks, while a few others showed much less, yet still nonlinear, increases (e.g., Subjects 5, 8, 10, 13).



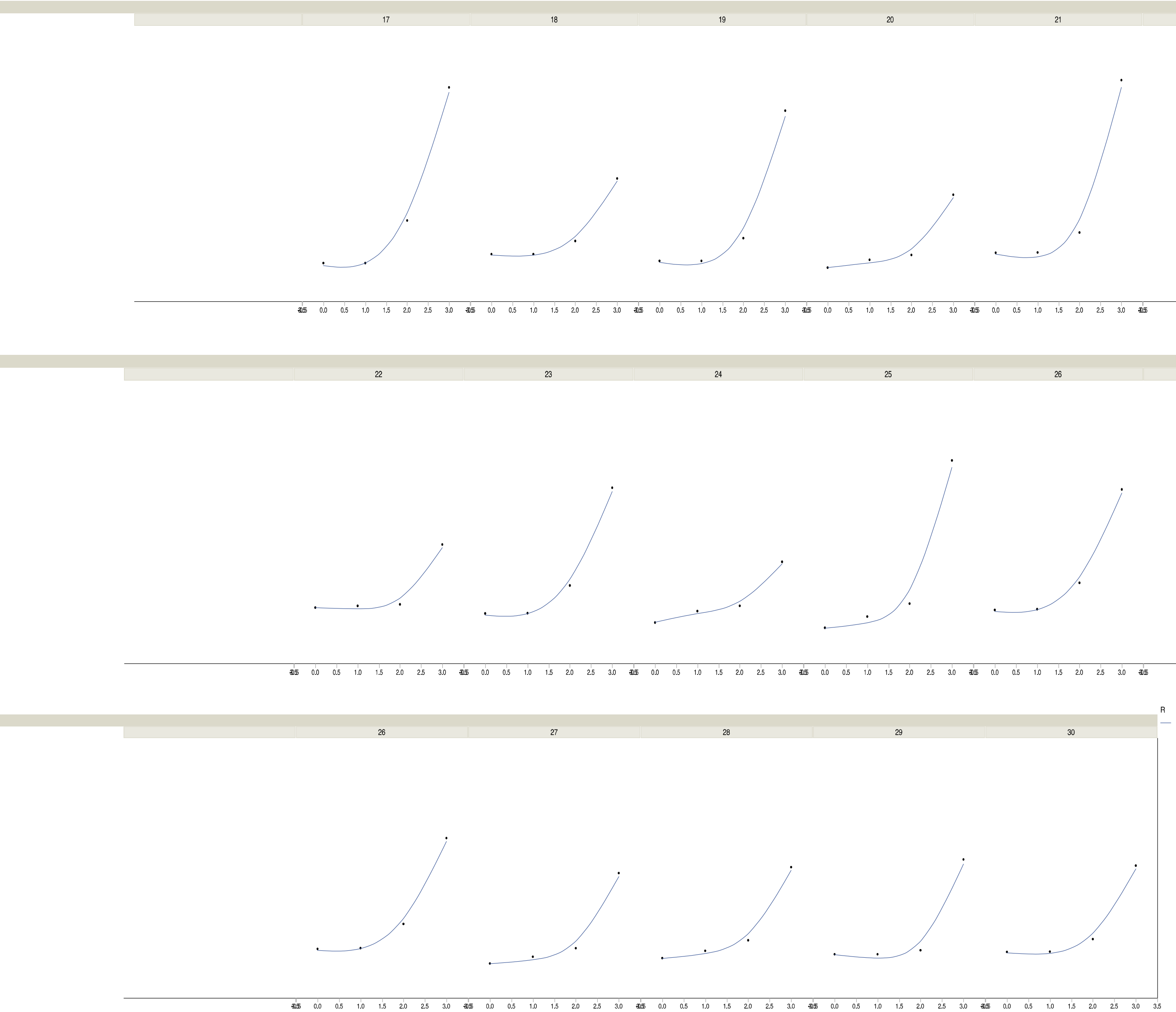


*Figure 4.* Individual subject-level analysis of performance across the four ECTs.

*Quartile Performance*. Given the wide range of variability on the 2-bit EF tasks, subjects were divided into quartiles to compare the better performers to the worse performers. Figure 5 shows the first three (0-, 1-bit non-EF and 1-bit EF) tasks compared to the fourth (2-bit EF) task broken into subjects by quartiles based upon RT. Evident was the continuing nonlinear nature of the curve even in the best performers on the 2-bit EF task. Specifically, there was no overlap between the distributions of the 1-bit EF and 2-bit EF tasks, indicating qualitatively different performance. Likewise, the linear curve fits the data with 86% of the variance explained (*F*[2,117] = 750, *p* <. 0001: RT = 169 + 171[task]), but the quadratic curve fits better explaining 96% of the variance (*F*[2,117] = 1516, *p* < .0001: RT = 168 + 119[task] + 32[task]$^2$).

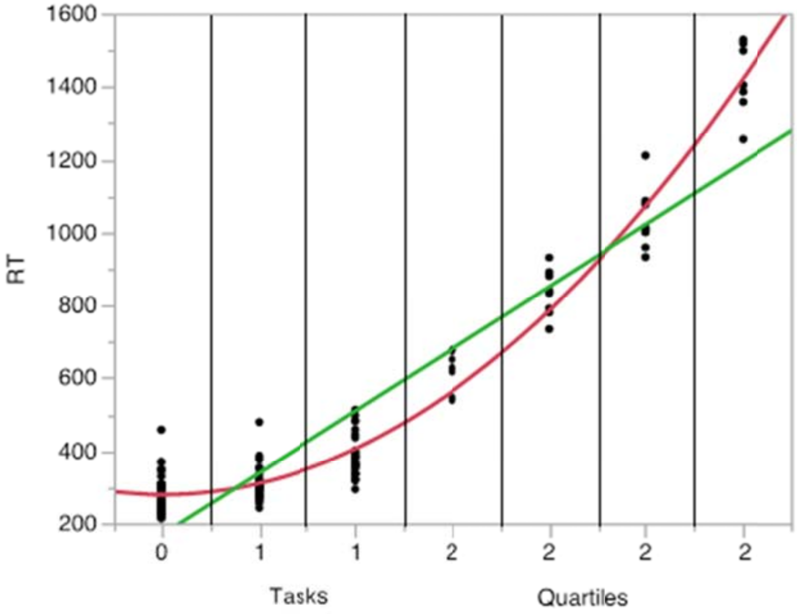


*Figure 5*. Linear and quadratic curve fitting the 0-, 1-bit non-EF and 1-bit EF compared to the 2-bit EF task broken into quartiles based upon RT.

*Recursive Nature of Executive Functions (EF)*. Given the large overlap between the 1-bit non-EF or Choice RT task and the 1-bit EF task, the linear and nonlinear curve fitting was applied to test the hypothesis that EF tasks have a recursive nature that adds accelerating processing time with each additional bit. Figure 6 shows the 1-bit non-EF task followed by the 1- and 2-bit EF tasks respectively compared for RT. Evident was the continuing nonlinear nature of the curve with no overlap between the distributions of the 1-bit EF and 2-bit EF tasks, indicating qualitatively different performance. The linear curve fit the data with 62% of the variance explained ($F[1,88] = 142$, $p < .0001$: RT = 109 + 33[task]), but the quadratic curve fit better, explaining 74% of the variance ($F[1,87] = 125$, $p <. 0001$: RT = -281 + 333[task] + 258[task]$^2$).

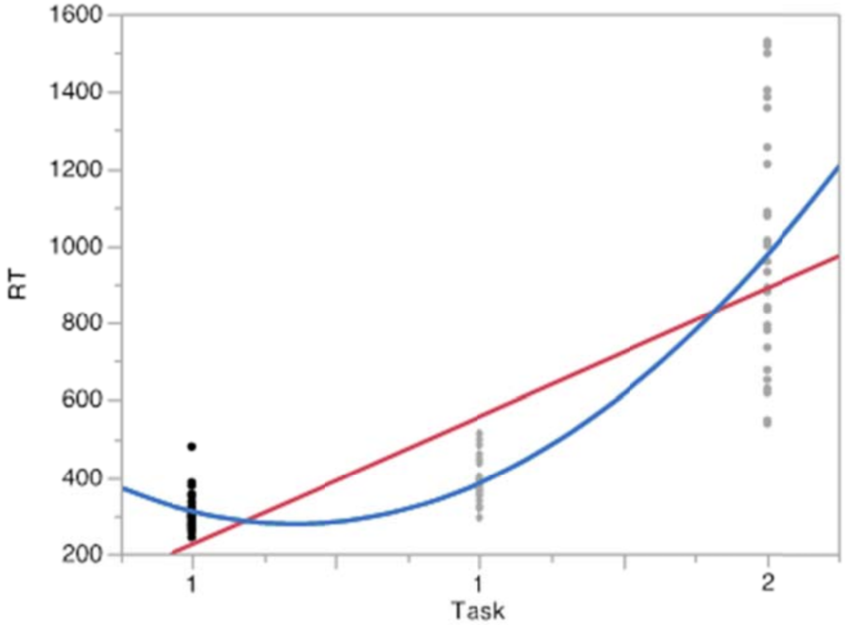


*Figure 6.* Linear and quadratic curve fitting the 1-bit non-EF task with the 1-and 2-bit EF tasks.

*Comparison between non-EF Elementary Cognitive Tasks (ECTs) and the Literature.* One-sample t-tests were conducted to compare the non-EF ECTs and results from the literature (Jensen, 1987). There were no significant differences in the 0-bit non-EF task ($M = 284.74$, $SD = 51.77$, $N = 30$) and the 0-bit Simple RT task using the Jensen Box ($M = 300.42$, $SD = 23.15$, $N = 912$), $t(42) = -1.38$, $p = 0.17$) two-tailed, as well as in the 1-bit non-EF task ($M = 310.12$, $SD = 45.81$, $N = 30$) and the 1-bit Choice RT task using the Jensen Box (M=324.09, SD=19.96, $N$ =912), $t(38) = -1.35$, $p = 0.18$) two-tailed.

## Discussion

The purpose of the present study was to evaluate whether typical Choice RT tasks, using a direct response format, would be qualitatively different from ECTs that required a response mediated by an internal rule. Past work has shown that simple and complex RT tasks that rely on automatic stimulus-response relationships (e.g., see a stimulus and respond as quickly as possible or see a lateralized stimulus and make a same-side lateralized response) follow a linear algorithm with each added bit of information, thus incrementing the response by a specific amount of time in a purely additive fashion (Hick, 1952). Specifically, using traditional RT tasks about a 27ms/bit increment has been seen in college students (Jensen, 1987) and has strongly predicted real-world RT behavior (e.g., .97 correlation reported by Jensen, 1987, 2006). EF, however, are generally considered to be qualitatively different from automatic, direct response cognitive behavior (Palmeri, 2002). Thus, it was thought that the linear increment in response time across tasks of increasing difficulty, as measured precisely by the IT construct of bits, may not hold for tasks requiring executive processes.

The different nature of EF might be manifest in a nonlinear relationship between RT and task complexity. That is, as task complexity increases according to the orderly operationalization of IT bits, more and more time would be required rather than a set amount of time (i.e., about 27ms/bit; Jensen, 1987). As predicted, results suggest that performance on the 0- and 1-bit non-EF tasks is similar to the performance on both Simple and Choice RT tasks using the Jensen box, following fairly closely the 27ms/bit increase found in prior literature using college students (Jensen, 1987). Specifically, the non-EF ECTs are no different from the traditional Simple and Choice RT tasks, which require a direct response and rely on perceptual processes. It was thought that when tasks become executive in nature, with internal rules driving task response, a recursive processing is necessitated in which time to process each successive bit is not additive but multiplicative. This was demonstrated in the increasing slopes associated with each complexity in the EF bit tasks. Therefore, an increasing slope was evident when progressing from the direct response 1-bit non-EF task to the internal rule 1-bit EF task (74ms/bit), and then even more so progressing from the simpler to the more complex EF-bit tasks (591ms/bit). This nonlinear increase from direct response to internal rule response was demonstrated by the increased variance explained by the quartic curve fit compared to a simple linear fit. The dramatic nature of this nonlinear relationship was even better demonstrated when increasing EF complexity (1- to 2-bit EF tasks). These results strongly support the thesis that the EF bit tasks, when defined according to an internal rule that reduces uncertainty by half as necessitated by IT, are qualitatively different from direct response tasks. Furthermore, this thesis puts EF assessment on a firm measurement basis that not only precisely defines the construct, but also measures it at the ratio level of quantification, which offers several advantages.

Advantages in the ratio level measurement of EF can be seen in three different ways. First, it allows better comparison across tasks because the tasks' level of difficulty can be operationalized precisely according to IT. Second, performance across different tasks of EF can be directly compared without fear that differing tasks of EF have differing basal and ceiling levels of performance. For example, if a test score on a visual perception task needs to be compared to an auditory perception score, then normative comparisons can equalize samples on *relative* level of performance if tests are co-normed. In contrast, there is no way with interval level measurement to insure that the *absolute* measurement of the two constructs is equilibrated. However, when using ratio level measurement with a true zero point, the basal level of performance is equivalent across both tasks, allowing direct comparison of the underlying constructs (Furr & Bacharach, 2008). A third advantage of ratio level measurement inherent in RT is the precision of the measurement. The millisecond level of precision across a wide range of timing is not only more objective but also more finely grained than the scoring of accuracy on most all psychometric instruments (e.g., Wechsler intelligence scales; Rao & Sinharay, 2007 ).

Clinical measurement necessitates a robust applicability of a construct. Measuring a cognitive construct in a manner that detects only group level differences is not sufficient for use in the clinic where individual differences must be detected (Bech, 2012). Thus, the penetrance of the ECT quantification of EF was assessed at the individual subject level of analysis. The nonlinear difference between direct response non-EF and internal rule EF tasks was obvious by visual inspection for every subject. Increased variability on the difficult 2-bit EF task was examined to insure that the nonlinear relationship was not due just to this wide variation in subject performance on this complex task. Group performance was divided into quartiles on the 2-bit EF task. This strategy showed that even the best performing subjects on this task did not overlap with the 1-bit EF task performance. Such a result corroborates the nonlinear nature of the EF measurement by ECTs. This result also showed the wide-ranging variability across subjects on a complex EF task that bodes well for the task's ability to differentiate subjects' ability level in EF; an important characteristic when trying to understand cognitive strengths and weaknesses in different individuals and different populations (Bech, 2012).

Future directions are suggested by the present results. While such results demonstrate a firm basis for making a substantial distinction between non-EF and EF tasks, administration order effect and reliability, and concurrent validity remain to be established for these ECTs. Also, various studies are important in showing the use of this EF definition. For example, populations with known EF difficulty (e.g., ADHD) need to be examined. Additionally, different instantiations of the ECT format will be important in establishing the applicability of this format to different EF constructs. As an example, verbal and nonverbal stimuli may be useful to examine for lateralized frontal dysfunction. Finally, further research is needed to demonstrate whether the executive processes in the EF ECTs represent a single construct or multiple constructs. Construct validity studies might be helpful to determine whether various ECTs represent different EF constructs.

### *Limitations*

Limitations of the present study include sample generalization and problems with RT measurements of behavior. Since the sample included only college students in a relatively narrow age range, the external validity of the present results is limited. Also, RT tasks have several limitations for measuring cognitive processes. Specifically, RT tasks can measure cognitive power, as demonstrated by the 2-bit EF task in this study; however, that measurement is intimately confounded with speed issues that cannot be completely disentangled (Colom, 2009). Therefore, RT tasks are not suitable for all populations (e.g., hemiparetic patients and populations like multiple sclerosis; Flehmig et al, 2007). Additionally, RT tasks typically have positively skewed distributions (Luce, 1986), although this limitation can often be moderated by using outlier trimming procedures (Jensen, 2006). RT tasks also can suffer from reduced test-retest reliability problems (Luce, 1986). Finally, RT tasks necessitate computer administration, which limits the practicality of such tasks for clinical use.

## Summary and Conclusions

In summary, the purpose of the present study was to evaluate whether typical Choice RT tasks, using a direct response format, would be qualitatively different from ECTs that required a response mediated by an internal rule. Therefore, four ECTs, two putative non-executive direct response tasks (0- and 1-bit non-EF tasks) and two putative executive internal rule tasks (1- and 2-bit EF tasks), were developed. In contrast to the currently available EF tests, these ECTs exhibit several advantages such as a clear differentiation between non-executive and executive functioning abilities, a ratio level of measurement based on a RT paradigm, task complexity defined according to bits of information, and a flexible platform that can be adapted to both verbal and nonverbal modalities. These tasks were given to 30 intact undergraduate students. It was hypothesized that the non-EF tasks would show a linear increase in RT as task complexity increases that follows the Hick's law. Additionally, it was hypothesized that the EF tasks would show an exponential increase in RT as task complexity increases.

Results supported the hypothesis showing a linear increase in RT on the 0- and 1-bit non-EF, consistent with past literature, and increasing slopes associated with each complexity in the EF bit tasks; the dramatic nature of this nonlinear relationship was even better demonstrated when increasing EF complexity (1- to 2-bit EF tasks). This nonlinear increase from direct response to internal rule response was demonstrated by the increased variance explained by the quartic curve fit compared to a simple linear fit. These results strongly support the thesis that the EF bit tasks, when defined according to an internal rule that reduces uncertainty by half as necessitated by IT, are qualitatively different from direct response tasks. Furthermore, this thesis puts EF assessment on a firm measurement basis that not only precisely defines the construct, but also measures it at the ratio level of quantification.

Future directions are suggested by the present results such as administration order effect, reliability, and construct validity remain to be established for these ECTs. Also, various studies with populations with known EF difficulty (e.g., ADHD) need to be examined, as well as establishing the ECTs' relationship to different EF constructs (e.g., verbal and nonverbal stimuli to examine for lateralized frontal dysfunction) and conducting concurrent validity studies. Limitations include sample generalization, problems with RT measurements of behavior, and the need for computer administration.

# References

Anderson, S. W., Damasio, H., Jones, R. D., & Tranel, D. (1991). Wisconsin Card Sorting Test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology, 13,* 6, 909-22.

Anderson, V., Northam, E., Hendy, J., & Wrenall, J. (2001). *Developmental neuropsychology: A clinical approach*. New York: Psychology Press.

Ardila, A., & Surloff, C. (2004). Dysexecutive syndromes. *Medlink Neurology.* San Diego: Arbor Publishing Co.

Baddeley, A. (2002). Fractionating the central executive. In D. T. Stuss, & R. T. Knight (Eds.) *Principles of frontal lobe function* (pp. 246–260). New York, NY: Oxford University Press.

Baddeley, A., & Hitch, G. (1974). Working memory. In G. H. Bower (Ed.), *Recent advances in learning and motivation* (Vol. 8). New York: Academic.

Baldo, J. & Shimamura, A. (1998). Verbal and category fluency in patients with frontal lobe lesions. *Neuropsychology*, *12*, 259–267.

Baldo, J. V., Shimamura, A. P., Delis, D. C., Kramer, J., & Kaplan, E. (2001). Verbal and design fluency in patients with frontal lobe lesions. *Journal of the International Neuropsychological Society*, *7*(05), 586-596.

Banich, M. T. (2004). *Cognitive neuroscience and neuropsychology*. Boston: Houghton Mifflin Co.

Bauer, R. M. (2012, February) *Neuropsychology in the era of translational neuroscience.* Presentation at the 40th Annual Meeting of the International Neuropsychological Society (INS), Montreal, Canada.

Bech, P. (2012). *Clinical psychometrics*. Chichester, West Sussex: Wiley-Blackwell.

Benton, A. L., Hamsher, d., & Sivan, A. B. (1994). *Multilingual Aphasia Examination, Third Edition.* Iowa City: Marchman Psychology.

Borkowsky, J. G., & Burke, J. E. (1996). Theories, models and measurements of executive functioning: An information processing perspective. In G. R. Lyon. & N. A. Krasnegor (Eds.), *Attention, memory and executive function*. Baltimore: Paul H. Brookes.

Burgess, P. W., Veitch, E., de Lacy Costello, A., & Shallice, T. (2000). The cognitive and neuroanatomical correlates of multitasking. *Neuropsychologia, 38*(6), 848-863.

Carroll, J. B. (1993). *Human cognitive abilities : a survey of factor-analytic studies*. Cambridge; New York: Cambridge University Press.

Chan, R. C., Shum, D., Toulopoulou, T., & Chen, E. Y. (2008). Assessment of executive functions: Review of instruments and identification of critical issues.*Archives of Clinical Neuropsychology*, *23*(2), 201-216.

Colom, R. (2009). Neuroticism, intelligence, and intra-individual variability in elementary cognitive tasks: Testing the mental noise hypothesis. *Psicothema*, *21*(3), 403-408.

Coltheart, M. (1989). *From Neuropsychology to Mental Structure.* Cambridge University Press, New York.

Cronbach, L. J., & Meehl, P. E. (1955). Construct validity in psychological tests. *Psychological bulletin*, *52*(4), 281.

Damasio, A. R. (1995). Toward a Neurobiology of Emotion and Feeling: Operational Concepts and Hypotheses. *The Neuroscientist, 1*(1), 19-25.

Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *Delis-Kaplan executive function system (D-KEFS).* San Antonio, Tex: Psychological Corp.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (January 01, 1996). Intelligence and the frontal lobe: the organization of goal-directed behavior. *Cognitive Psychology, 30,* 3, 257-303.

Duncan, J., & Owen, A. M. (January 01, 2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences, 23,* 10, 475-83.

Elfgren, C. I., & Risberg, J. (1998). Lateralized frontal blood flow increases during fluency tasks: influence of cognitive strategy. *Neuropsychologia*, *36*(6), 505-512.

Elliott, R. (2003). Executive functions and their disorders. *British Medical Bulletin, 65*(1), 49-59.

Flehmig, H. C., Steinborn, M., Langner, R., Scholz, A., & Westhoff, K. (2007). Assessing intraindividual variability in sustained attention: reliability, relation to speed and accuracy, and practice effects. *Psychology Science, 49*(2), 132-149.

Floyd, R. G., Bergeron, R., Hamilton, G., & Parra, G. R. (2010). How do executive functions fit with the Cattell–Horn–Carroll model? Some evidence from a joint factor analysis of the Delis–Kaplan executive function system and the Woodcock–Johnson III tests of cognitive abilities. *Psychology in the Schools*,*47*(7), 721-738.

Fuster, J. (2002). Physiology of executive functions: The perception– action cycle. In D. T. Stuss, & R. T. Knight (Eds.) *Principles of the frontal lobe.* New York: Oxford University Press.

Golden, C. J. (1978). *Stroop color and word test.* Chicago: Stoelting.

Grafman, J., & Litvan, I. (1999). Importance of deficits in executive functions. *Lancet, 354*(9194), 1921-1923.

Grant, D. A., Berg, E. A., & Heaton, R. K. (1993). *Wisconsin card sorting test*. Odessa, Fla: Psychological Assessment Resources.

Furr, R. M., & Bacharach, V. R. (2008). *Psychometrics: An introduction*. Los Angeles: Sage Publications.

Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology, 4*(1), 11-26.

Hobson, P., & Leeds, L. (2001). Executive functioning in older people. *Reviews in Clinical Gerontology, 11*(04), 361-372.

Horn, J.L., & Cattell, R.B. (1966). Refinement and test of the theory of fluid and crystallized ability intelligence. *Journal of Education Psychology 57,* 253-270.

Janowsky, J., Shimamura, A., Kritchevsky, M., & Squire, L. (1989). Cognitive impairment following frontal lobe damage and its relevance to human amnesia. *Behavioral Neuroscience*, *103*, 548–560.

Jarvis, B. G. (2008). DirectRT (Version 2008.2.1) [Computer Software]. New York, NY: Empirisoft Corporation.

Jensen, A. R. (1987). Individual differences in the Hick paradigm. In P. A. V. e. al. (Ed.), *Speed of information-processing and intelligence* (pp. 101-175). Norwood, NJ, USA: Ablex Publishing Corp.

Jensen, A. R. (1998). *The g factor: the science of mental ability*. Westport, Conn.: Praeger.

Jensen, A. R. (2006). *Clocking the mind: mental chronometry and individual differences*. Amsterdam; Boston; London: Elsevier.

Jensen, A. R., & Munro, E. (1979). Reaction time, movement time, and intelligence. *Intelligence, 3*(2), 121-126.

Jones-Gotman, M., & Milner, B. (1977). Design fluency: the invention of nonsense drawings after focal cortical lesions. *Neuropsychologia*, *15*(4), 653-674.

Jurado, M. B., & Rosselli, M. (2007). The elusive nature of executive functions: a review of our current understanding. *Neuropsychology review*, *17*(3), 213-233.

Keith, T. Z. (1997). Using confirmatory factor analysis to aid in understanding the constructs measured by intelligence tests. In D. P. Flanagan, J. L. Genshaft & P. L. Harrison (Eds.), *Contemporary intellectual assessment: Theories, tests, and issues* (pp. 373-402). New York, NY, US: Guilford Press.

*Academy of Science of the United States of America, 97,* 7651–7656.

Lafleche, G., & Albert, M. S. (1995). Executive function deficits in mild Alzheimer's disease. *Neuropsychology, 9*(3), 313-320.

Lezak, M. D. (1995). *Neuropsychological assessment* (3rd ed.). New York: Oxford University Press.

Lezak, M. D. (2012). *Neuropsychological assessment* (5th ed.). Oxford ; New York: Oxford University Press.

Luce, R. D. (1986). *Response Times: Their Role in Inferring Elementary Mental Organization.* Oxford University Press

Luria, A. R. (1973). *The Working brain: An introduction to neuropsychology.* New York: Basic.

Miceli, G., Caltagirone, C., Gainotti, G., Masullo, C., & Silveri, M. (1981). Neuropsychological correlates of localized cerebral lesions in non-aphasic brain-damaged patients. *Journal of Clinical Neuropsychology*, *3*, 53– 63.

Microsoft. (2010). Microsoft Excel (Version 14.0.4734.1000) [computer software]. Redmond, Washington: Microsoft.

Miller, E. (1984). Verbal fluency as a function of a measure of verbal intelligence and in relation to different types of cerebral pathology. *British Journal of Clinical Psychology*, *23*, 53–57.

Miller, B. L., & Cummings, J. L. (2007). *The Human frontal lobes: Functions and disorders*. New York: The Guilford Press.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive psychology*, *41*(1), 49-100.

Norman, D. A., & Shallice, T. (1986). Attention to action: Willed and automatic control of behavior. In e. a. R. J. Davidson (Ed.), *Consciousness and self-regulation* (Vol. 4). New York: Plenum.

Osmon, D. C. (1999). Complexities in the evaluation of executive functions. *Forensic neuropsychology: Fundamentals and practice*, 185-226.

Palmeri, T. J. (2002). Automaticity. In L. Nadel (Ed.), *Encyclopedia of Cognitive Science* (pp. 390-401). London: Nature Publishing Group.

Perret, E. (1974). The left frontal lobe of man and the suppression of habitual responses in verbal categorical behaviour. *Neuropsychologia*, *12*, 323–330.

Peters, G. J., David, C. N., Marcus, M. D., & Smith, D. M. (2013). The medial prefrontal cortex is critical for memory retrieval and resolving interference. *Learning & Memory*, *20*(4), 201-209.

Piguet, O., Grayson, D. A., Broe, G. A., Tate, R. L., Bennett, H. P., Lye, T. C., Creasey, H. & Ridley, L. (2002). Normal aging and executive functions in "old-old" community dwellers: poor performance is not an inevitable outcome. *International Psychogeriatrics, 14,* 2, 139-159.

Rao, C. R., & Sinharay, S. (2007). *Psychometrics*. Amsterdam: Elsevier North-Holland.

Reitan, R. M. (1992). *Trail making test*. Tucson, AZ: Reitan Neuropsychology Laboratory.

Royall, D. R., Lauterbach, E. C., Cummings, J. L., Reeve, A., Rummans, T. A., Kaufer, D. I., . . . Coffey, C. E. (2002). Executive control function: a review of its promise and challenges for clinical research. A report from the Committee on Research of the American Neuropsychiatric Association. *Journal of Neuropsychiatry & Clinical Neurosciences, 14*(4), 377-405.

Ruff, R. M., Allen, C. C., Farrow, C. E., Niemann, H., & Wylie, T. (1994). Figural fluency: Differential impairment in patients with left versus right frontal lobe lesions. *Archives of Clinical Neuropsychology*, *9*(1), 41-55.

SAS Institute, Inc. (2013) JMP (Version Pro 11.0) [Computer Software]. New York, NY: Empirisoft Corporation.

Schoenberg, M. R., & Scott, J. G. (2011). *The little black book of neuropsychology: A syndrome-based approach*. New York: Springer.

Sergeant, J. A., Geurts, H., & Oosterlaan, J. (2002). How specific is a deficit of executive functioning for attention-deficit/hyperactivity disorder? *Behavioural Brain Research, 130*(1-2), 3-28.

Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. Urbana: University of Illinois Press.

Shepard, S., & Metzler, D. (1988). Mental rotation: effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(1), 3-11.

Sheppard, L. D., & Vernon, P. A. (2008). Intelligence and speed of information-processing: A review of 50 years of research. *Personality and Individual Differences, 44*(3), 535-551.

Smith, E. E., & Jonides, J. (1997). Working memory: A view from neuroimaging. *Cognitive psychology*, *33*(1), 5-42.

Stern, R. A., White, T., & Psychological Assessment Resources, Inc. (2003). *NAB, neuropsychological assessment battery: Administration, scoring, and interpretation manual*. Lutz, FL: Psychological Assessment Resources.

Sternberg, S. (1969). Memory-scanning: Mental processes revealed by reaction-time experiments. *American scientist*, *57*(4), 421-457.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643-662.

Stuss, D. T. (2011). Functions of the frontal lobes: relation to executive functions. *Journal of the International Neuropsychological Society, 17*(5), 759-765.

Stuss, D. T., & Benson, D. F. (1984). Neuropsychological studies of the frontal lobes. *Psychological Bulletin, 95*(1), 3-28.

Stuss, D. T., Alexander, M. P., Floden, D., Binns, M. A., Levine, B., & McIntosh, A. R., et al. (2002). Fractionation and localization of distinct frontal lobe processes: Evidence from focal lesions in humans. In D. T. Stuss, & R. T. Knight (Eds.) *Principles of frontal lobe function* (pp. 392–407). New York, NY: Oxford University Press.

Suchy, Y. (2009). Executive functioning: Overview, assessment, and research issues for non-neuropsychologists. *Annals of Behavioral Medicine*, *37*(2), 106-116.

Szatkowska, I., Szymańska, O., Bojarski, P., & Grabowska, A. (2007). Cognitive inhibition in patients with medial orbitofrontal damage. Experimental Brain Research, 181(1), 109-115.

Wilson, B. A., & Thames Valley Test Company. (1996). *BADS: Behavioural assessment of the dysexecutive syndrome*. Bury St Edmunds: Thames Valley Test Company.

Woodcock, R. W., Mather, N., McGrew, K. S., Schrank, F. A., Johnson, M. B., Wendling, B. J., Woodcock, R. W., ... Riverside Publishing Company. (2001). *Woodcock-Johnson III complete*. Itasca, IL: Riverside Pub. Co.

Zelazo, P. D., Carter, A., Reznick, J., & Frye, D. (1997). Early development of executive functions: A problem-solving framework. *Review of General Psychology,* 1, 198–226.

Appendix A

## UNIVERSITY OF WISCONSIN – MILWAUKEE
## CONSENT TO PARTICIPATE IN RESEARCH

**General Information** ID #: __________

**Study title:** Using information theory and elementary cognitive tasks to define executive functions.

**Person in Charge of Study (Principal Investigator):** Dave C. Osmon, Ph.D., ABPP-CN, Dept. of Psychology, University of Wisconsin – Milwaukee (UWM)

**Study Description**

The purpose of this study is to investigate the pattern of responses to stimuli associated with direct response versus internal rule type of tasks. Individual's performance will be assessed through their reaction time to stimuli on four tasks; two direct response, non-executive tasks and two executive, internal rule two executive function tasks.

It should take approximately 30 minutes to complete all of the study activities. In total, we expect to recruit 120 participants from the University of Wisconsin-Milwaukee (UWM) student body. All the study activities will be completed in the rooms located within Garland Hall Suite 338.

**Study Procedures**

(1) To be eligible to participate in this study you must be 18 years old or older. You are ineligible to participate in the study if you have a past history of a psychiatric or neurological condition, learning disabilities or ADHD, and/or cannot see the stimuli on the computer.

If you agree to participate you will be asked to fill out some demographic information and complete some stimuli-response tasks on a computer. No audio/video/photographic recordings will be taken during the study. Completing the study should take approximately 30minutes. All the study activities will be completed in the rooms located within Garland Hall Suite 338.

**Risks and Minimizing**

The risk associated with the study is minimal and is not anticipated to be greater than the risk associated with performance of routine psychological testing.

**Benefits**

The only benefit to participating in this study is that you may receive extra credit in your psychology course. Whether you will receive extra credit is determined by your instructor and cannot be guaranteed by the Principal Investigator of the study.

**Study Costs**

You will not be responsible for any of the costs from taking part in this research study.

**Confidentiality**

All information collected about you during the course of this study will be kept confidential to the extent permitted by law. We may decide to present what we find to others, or publish our results in scientific journals or at scientific conferences. Information that identifies you personally will not be released without your written permission. Only the Principle Investigator and a small number of research assistants under his supervision will have access to your information. However, the Institutional Review Board at UW-Milwaukee or appropriate federal agencies like the Office for Human Research Protections may review your records. Any data collected associated to you will not be identified with your name, but with a unique subject identification number. To insure that you receive extra credit for your participation, your name will be recorded on a spreadsheet that is in no way associated with the study data. All data collect will be stored in locked area that can only be accessed by the PI and RAs. Data will only be entered into password protected computers. The data will be stored in Garland Hall Suite 338 for up to ten years.

**Alternatives**

Your course Instructor will provide an alternative extra credit option (other than this research study). There are also other research studies in which you could participate.

**Voluntary Participation and Withdrawal**

Your participation in this study is entirely voluntary. You may choose not to take part in this study. If you decide to take part, you can change your mind later and withdraw from the study. You are free to not answer any questions or withdraw at any time. If you choose to withdraw we will destroy all information we collect about you. Your decision will not change any present or future relationships with the University of Wisconsin-Milwaukee. Not taking part in the study or withdrawing will not affect your grade or class standing.

**Questions?**

**Who do I contact for questions about this study?**

For more information about the study or the study procedures or treatments, or to withdraw from the study, contact:

Dave C. Osmon, Ph.D., ABPP-CN
Department of Psychology
PO Box 413
Milwaukee, WI 53201
414-229-6751

**Who do I contact for questions about my rights or complaints towards my treatment as a research subject?**
The Institutional Review Board may ask your name, but all complaints are kept in confidence.

Institutional Review Board
Human Research Protection Program
Department of University Safety and Assurances
University of Wisconsin – Milwaukee
P.O. Box 413
Milwaukee, WI 53201
(414) 229-3173

**Research Subject's Consent to Participate in Research:**
*To voluntarily agree to take part in this study, you must sign on the line below. If you choose to take part in this study, you may withdraw at any time. You are not giving up any of your legal rights by signing this form. Your signature below indicates that you have read or had read to you this entire consent form, including the risks and benefits, and have had all of your questions answered, and that you are 18 years of age or older.*

_____________________________________________ ID # : __________
Printed Name of Subject/ Legally Authorized Representative

_____________________________________________ _____________________
Signature of Subject/Legally Authorized Representative Date

**Principal Investigator or Designee or RA**
*I have given this research subject information on the study that is accurate and sufficient for the subject to fully understand the nature, risks and benefits of the study.*

_____________________________________________ _____________________
Printed Name of Person Obtaining Consent Study Role

_____________________________________________ _____________________
Signature of Person Obtaining Consent Date

## Appendix B

ID #: ________

**Demographic Information**:

Age: _________

DOB: ____________________

Sex: Male Female

Handedness: Right Left Ambidextrous

Highest Level of Education or Year in School: ____________________

Primary Language: ____________________

How many people are in your nuclear family (including self): _________

Of these, how many are left-handed: _______

What ethnicity do you associate most strongly with?

African American Caucasian Hispanic Asian and Pacific Islander

Native American Middle Eastern Other:________________________

**History**:

Any history of psychiatric disorders (i.e., depression, anxiety) in you or your immediate family? Yes No

If YES, what and in whom?

Any history of learning disorders (e.g. dyslexia) in you or your family members? Yes No

If YES, what in whom?

Any history of ADHD in your immediate family? Yes No

If YES, in whom?

Any history of neurological disorders (i.e., epilepsy, dementia) in you or your immediate family? Yes No

If YES, what and in whom?

Any current medications prescribed: Yes No

If yes, what are they, dosage, frequency and how long: _______________________

Vision related problems (w/o glasses or contacts): Yes No