LATENT PROFILES OF EXECUTIVE FUNCTIONING IN

NEUROLOGICALLY HEALTHY YOUNG ADULTS:

THE ROLE OF INDIVIDUAL DIFFERENCES IN

HEMISPHERIC ASYMMETRY

by

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ABSTRACT

In response to the growing need to understand individual differences in executive functioning (EF) among non-neurologic populations, this study examined two competing theoretical models of EF among healthy, neurologically-intact individuals: the prefrontal convexity model and the hemispheric asymmetry model. A total of 315 neurologically healthy individuals (M = 20.8 years; 50% female) completed two phases of the study. In the first phase (i.e., Model Identification), latent profile analysis was applied to variables measuring the abilities to form, switch, and maintain mental sets under conditions designed to tax the left or right hemisphere (i.e., a modified switching task). In the second phase (i.e., Model Validation), latent clusters from the first phase were compared on a separate EF task (i.e., Attention Network Test; ANT). The Model Identification phase yielded a three-profile solution consistent with the hemispheric asymmetry model. Profile 1 (N=203) was characterized by average EF performances. Profile 2 (N=43) revealed a set maintenance weakness under nonverbal conditions. Profile 3 (N=38) demonstrated a global weakness in cognitive flexibility and a specific weakness on tasks administered under verbal conditions. The Model Validation phase confirmed group/cluster differences (F(4,554) = 5.938, $p<.001$). Individual differences in EF follow a hemispheric asymmetry model of EF, with approximately 15% of neurologically healthy individuals exhibiting weaknesses in set maintenance and nonverbal processing, and 13% exhibiting weaknesses in set formation/switching and verbal processing.

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EXECUTIVE FUNCTIONING IN HEALTHY YOUNG ADULTS

Executive functioning (EF) is an umbrella term that refers to a set of cognitive and behavioral-control abilities that allow for goal-directed, purposeful behavior in everyday life (Cummings & Miller, 2007; Gazzaley, D'Esposito, Miller, & Cummings, 2007; Suchy, 2009). Although EF was originally almost exclusively studied by clinical neuropsychologists working with brain-injured populations, in recent years there is increasing recognition that individual differences in EF play a key role in daily functioning even among nonbrain-injured individuals. Specifically, discrete patterns of strengths and weaknesses in EF have been implicated in criminal offending (Brower & Price, 2001; Eastvold, Suchy, & Strassberg, 2011; Morgan & Lilienfeld, 2000; Suchy & Kosson, 2006; Suchy, Whittaker, Strassberg, & Eastvold, 2009), substance abuse (Ersche, Clark, London, Robbins, & Sahakian, 2006; Giancola & Moss, 1998; Giancola & Tarter, 1999), medical compliance (Hinkin et al., 2002; Stilley, Bender, Dunbar-Jacob, Sereika, & Ryan, 2010), and psychiatric disorders (Burdick, Robinson, Malhotra, & Szeszko, 2008; Palmer & Heaton, 2000; Reichenberg et al., 2009; Robinson et al., 2006). Additionally, individual differences in EF have been implicated in personality patterns (Nigg et al., 2002; Suchy, Williams, Kraybill, Franchow, & Butner, 2010; Williams, Suchy, & Kraybill, 2010; P. G. Williams, Y. Suchy, & H. K. Rau, 2009). Consequently, researchers from a variety of psychological disciplines are increasingly turning to clinical neuropsychology for guidance on how to best conceptualize EF, as well as which

components of EF are most likely to generate clinically and theoretically meaningful profiles of EF strengths and weaknesses.

Evidence from neurologically-impaired populations supports the conceptualization of EF as a nonunitary construct, as different profiles of executive dysfunction emerge among brain-injured individuals. These profiles of dysfunction are typically thought to be linked to general organization of the prefrontal cortex (PFC) and other cortical regions richly connected to the PFC (Miller & Cohen, 2001; Stuss & Alexander, 2007; Stuss et al., 2002), with the assumption that compromised functioning in specific aspects of EF is related to dysfunction in specific cortical-subcortical networks involving the frontal lobes (Duffy, Campbell, Salloway, & Malloy, 2001; Hanna-Pladdy, 2007; Stuss et al., 2002). Importantly, some specificity of EF components within the PFC is also supported by functional imaging research conducted with healthy individuals, suggesting that unique EF profiles may also present as normal individual differences.

However, some inconsistencies in research exist. Factor analytic examinations of EF have yielded equivocal results, with some studies reporting a two-factor model (Adrover-Roig, Sese, Barcelo, & Palmer, 2012; Bamdad, Ryan, & Warden, 2003; Doiseau & Isingrini, 2005; Goldman, Axelrod, Heaton, & Chelune, 1996; Hull, Martin, Beier, Lane, & Hamilton, 2008; Piguet et al., 2005; Savla et al., 2012; Willner, Bailey, Parry, & Dymond, 2010) and others supporting a three-factor solution (Boone, Ponton, Gorsuch, Gonzalez, & Miller, 1998; Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Busch, McBride, Curtiss, & Vanderploeg, 2005; Kucera-Thompson, 2003; Miyake et al., 2000; Nagahama et al., 2003; Ross, 1995; Stout, Ready, Grace, Malloy, & Paulsen, 2003; Vaughan & Giovanello, 2010; Willner et al., 2010). Importantly, most of these studies

examined either older or neurologically impaired adult populations, rather than

neurologically healthy adult individuals (e.g., Miyake et al., 2000; Ross, 1995), leaving

questions unanswered about the structure of EF in the absence of neurological insult.

Confusion also stems from the notion that EF abilities can be, at least in theory,

fractionated into progressively more discrete processes (Suchy, 2009), yet it is likely that

subsets of such processes are highly associated, either due to their neuroanatomic

proximity or due to their joint emergence during neural development (V. A. Anderson,

Anderson, Northam, Jacobs, & Catroppa, 2001; Stuss, 1992).

In response to the growing need to understand individual differences in EF among

nonneurologic populations, this study examines two competing theoretical models of EF

among healthy, neurologically-intact individuals. Based on past research linking

neuroanatomic regions to patterns of EF symptomatology, at least two models of EF

profiles can be identified to guide this investigation. These are: (1) the prefrontal

convexity model, which assumes three profiles of EF weakness, and (2) hemispheric

asymmetry model, which assumes two profiles of EF weakness.

The Prefrontal Convexity Model

Duffy and Campbell (1994) have organized constellations of executive dysfunction symptoms into three clinical syndromes: (a) dysexecutive/disorganized, (b) disinhibited/impulsive, and (c) apathetic/hypokinetic. These three syndromes are associated with damage to one of three main PFC convexities (Karnath & Kammer, 2003) subserving EF: (a) dorsolateral PFC, (b) orbitofrontal PFC, and (c) medial PFC, respectively. Empirical support for these syndromes is provided by imaging and lesion studies, described below.

Dorsolateral Convexity: Dysexecutive/Disorganized Syndrome

The dorsolateral PFC (dlPFC) receives projections from the visual, auditory, and somatosensory cortices, allowing for top-down coordination of task-relevant cognitions and behaviors (Shimamura, 2000). Therefore, the dlPFC appears to be particularly important for *establishing and executing mental set* (Mega & Cummings, 2001). Imaging studies with neurologically-intact individuals have shown that increased dlPFC activation is associated with conceptualizing task demands (Baker et al., 1996; Blumenfeld & Ranganath, 2006; Kroger et al., 2002) and generating responses that are consistent with identified task demands (Frith, Friston, Liddle, & Frackowiak, 1991; Garavan, Ross, Murphy, Roche, & Stein, 2002; Nathaniel-James & Frith, 2002; Pochon et al., 2001).

Similarly, patients with dlPFC damage tend to demonstrate impaired reasoning and problem-solving skills (Colvin, Dunbar, & Grafman, 2001; Eslinger, Biddle, Pennington, & Page, 1999; Lombardi et al., 1999; Milner, 1963) resulting in impaired performance on tasks such as the Wisconsin Card Sorting Test (Demakis, 2003; Milner, 1963; Stuss et al., 2000). Lastly, individuals with certain neuropsychiatric syndromes that are known to exhibit deficits in reasoning (e.g., cognitive slippage seen among schizophrenic patients; Gooding, Tallent, & Hegyi, 2001) also exhibit dlPFC dysfunction (Callicott et al., 2000; Manoach et al., 2000; Weinberger, Berman, & Zec, 1986).

Orbitofrontal Convexity: Disinhibited/Impulsive Syndrome

The orbitofrontal PFC's (ofPFC) rich connections to the paralimbic cortex implicate this brain region in monitoring and managing the release of limbic drives within changing contexts or contingencies (Kringelbach, 2005; Price, 1999). More specifically, the ofPFC quickly integrates environmental stimuli, refreshes awareness of behavioral consequences, and sustains behaviors consistent with top-down goals (Beer, Heerey, Keltner, Scabini, & Knight, 2003; Beer, John, Scabini, & Knight, 2006). In other words, when task or situational demands change, the ofPFC is involved with rapidly *updating and switching mental set*, thereby ensuring that behaviors are congruent with current contingencies. Imaging studies support this notion; increased ofPFC activity is observed when neurologically-healthy individuals evaluate the relevance of environmental stimuli (O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001), detect discrepancies between current and task-appropriate behaviors (Berthoz, Armony, Blair, & Dolan, 2002), and alter behavior to accommodate changing task demands (Kim & Ragozzino, 2005). Similarly, patients with damage to the ofPFC tend to disregard

relevant environmental or social cues and are instead driven by basic desires, exhibiting

impaired behavioral monitoring (Beer et al., 2006; Mah, Arnold, & Grafman, 2004) and

failures to integrate environmental feedback (Hornak et al., 2004). These deficits in turn

result in impulsive releases of inappropriate responses. Lastly, certain psychiatric

populations that are known to exhibit poor responsiveness to social and environmental

cues combined with excessive reliance on basic drives and desires (e.g., high reward

sensitivity and low punishment sensitivity seen among adults with psychopathy; Blair,

Morton, Leonard, & Blair, 2006) also exhibit weaknesses in ofPFC (N. E. Anderson &

Kiehl, 2012; Blair, Newman, et al., 2006; Gorenstein, 1982; Sequin, 2004).

Medial Convexity: Apathetic/Hypokinetic Syndrome

The medial PFC (mPFC) is located between the cingulum, which controls

wakefulness and arousal (Parent, 1990), and the supplementary motor area (SMA), which

controls volition and motivation (Goldberg, 1985). Therefore, healthy functioning of the

mPFC network allows for adequate levels of arousal and motivation required for

maintaining mental set. In neurologically-intact individuals, mPFC activation

corresponds to both subjective and physiological arousal (Phan et al., 2003) as well as

mental computations involved with motivating and directing attentional resources

(Botvinick, Braver, Barch, Carter, & Cohen, 2001; Kouneiher, Charron, & Koechlin,

2009; Rushworth, Walton, Kennerley, & Bannerman, 2004). Disruption of the mPFC is

associated with decreased motivation and impaired motor planning (Cunnington et al.,

1996; Gerloff, Corwell, Chen, Hallett, & Cohen, 1997), with patterns of dysmotivation

ranging from apathy to akinetic mutism (Duffy & Campbell, 1994). Consequently,

performances on tasks requiring speed, internally-generated behaviors, or internally-

maintained attentional set are likely to be impaired (Grinband et al., 2011; Laplane, Talairach, Meininger, Bancaud, & Orgogozo, 1977; Picton, Stuss, Shallice, Alexander, & Gillingham, 2006; Stuss & Alexander, 2007; Stuss et al., 1998). Lastly, certain neurodevelopmental disorders that are marked by low arousal and the inability to sustain attention and maintain mental set (e.g., individuals with Inattentive Attention Deficit Hyperactivity Disorder; Brown & McMullen, 2006) exhibit dysfunctional processing within the mPFC (Bush et al., 1999; Ernst et al., 2003; Tamm, Menon, Ringel, & Reiss, 2004).

<center>The Hemispheric Asymmetry Model</center>

Although profiles of EF weaknesses have traditionally been conceptualized according to PFC convexities, additional evidence suggests that these profiles may also be hemispherically lateralized. In particular, attention and arousal systems appear to be right-hemisphere dominant, whereas problem-solving abilities tend to be left-hemisphere dominant. Empirical support for these 'hemispheric syndromes' is described below.

Left Hemisphere: Cognitive Inflexibility Syndrome

Evidence suggests that the left cerebral hemisphere contributes to executive functions such as problem-solving (Grossman et al., 1998; Gundel & Wilson, 1992; Martin, 1999; S. D. Newman, Carpenter, Varma, & Just, 2003) and updating cognitive or behavioral sets (Collette et al., 2005; Dreher & Grafman, 2003; Meyer et al., 1998; Moll, de Oliveira-Souza, Moll, Bramati, & Andreiuolo, 2002; Rezai et al., 1993; Stuss et al., 2002; Sylvester et al., 2003). In other words, this model suggests that the ability to flexibly update and switch mental set is inherently linked with the ability to establish a

new mental set. These particular cognitive abilities fall under the domain of *cognitive flexibility* and suggest that a weakness in cognitive flexibility may be associated with a left hemisphere weakness. Consistent with this notion, patients with left hemisphere lesions demonstrate a wide range of behavioral difficulties, including impaired problem solving, cognitive inflexibility, and poor conflict resolution (Grafman, Jonas, & Salazar, 1990; Keele & Rafal, 2000; Mecklinger, von Cramon, Springer, & Matthes-von Cramon, 1999; Rogers et al., 1998; Troyer, Moscovitch, Winocur, Alexander, & Stuss, 1998). Additionally, certain neuropsychiatric populations characterized by inflexibility (e.g., impaired abstraction and environmental adaptation seen in patients with schizophrenia (Rund & Borg, 1999) also exhibit pronounced left hemisphere abnormalities (Crow, 1997; Flor-Henry, 2003; Gur et al., 1985).

Right Hemisphere: Set-loss Syndrome

In neurologically healthy adults, the right cerebral hemisphere appears to be involved in sustaining adequate alertness/arousal (Fernandez-Duque & Posner, 2001; Pardo, Fox, & Raichle, 1991; Sturm et al., 1999; Sturm & Willmes, 2001) and attention (Beeman & Bowden, 2000; Collette et al., 2005; Deutsch, Papanicolaou, Bourbon, & Eisenberg, 1987; Pardo et al., 1991), that is, cognitive abilities that fall under the domain of *set maintenance*. Patients suffering from brain lesions or disorders primarily affecting the right hemisphere often demonstrate impaired set maintenance abilities, including greater set-loss errors (Devinsky, Morrell, & Vogt, 1995; Goldberg, 1985; Rueckert & Grafman, 1998; Stuss et al., 1983; Vendrell et al., 1995) or slower performances (Alexander, Stuss, Shallice, Picton, & Gillingham, 2005; Pujol et al., 2001; Rueckert & Grafman, 1998; A. J. Wilkins, Shallice, & McCarthy, 1987) on tasks measuring

attentional vigilance. In addition, certain neurodevelopmental disorders characterized by decreased arousal and failure to maintain set (e.g., individuals with Inattentive Attention Deficit Hyperactivity Disorder; Brown & McMullen, 2006) are associated with right hemisphere dysfunction/weakness (Stefanatos & Wasserstein, 2001).

CURRENT STUDY

The purpose of the present study was to test which of the two models described above is better at meaningfully capturing individual differences in EF among neurologically healthy individuals. To that end, we recruited 315 young healthy volunteers for a single assessment session that consisted of two phases: The first phase (i.e., Model Identification phase), designed to test the two competing models of EF, and the second phase (i.e., Model Validation phase), designed to test the validity of the identified models.

Model Identification Phase

To allow simultaneous testing of the two competing models of EF, we tested the participants' abilities to form, switch, and maintain mental sets in the context of task stimuli that are preferentially processed primarily by the left versus the right cerebral hemispheres (Suchy & Kosson, 2006). Because the primary interest of this study was to capture the distribution of individual differences (rather than capture principle components of EF), we employed modern cluster-analytic techniques to determine whether the participants' performance would generate classes that would be consistent with either of the two theoretical models. We tested two competing hypotheses:

(1) If the prefrontal convexity model best captured the individual differences in EF in this population, then we expected that the data would yield four clusters, one each

(2) characterized by: (a) average performance across all task variables (i.e., no EF weaknesses), (b) relative weakness in *set formation* (i.e., reflecting the dysexecutive/disorganized syndrome) regardless of the hemispheric demands of the stimuli, (c) relative weakness in *set switching* (i.e., reflecting the disinhibited/impulsive syndrome) regardless of the hemispheric demands of the stimuli, and (d) relative weakness in *set maintenance* (i.e., reflecting the apathetic/hypokinetic syndrome) regardless of the hemispheric demands of the stimuli.

(3) If the hemispheric asymmetry model best captured the individual differences in EF in this population, then we expected that the data would yield three clusters, one each characterized by: (a) average performance across all task variables (i.e., no EF weaknesses), (b) relative weakness in *set formation* and *set switching* (i.e., reflecting the cognitive inflexibility syndrome), especially on trials with greater demands for left hemisphere resources, or (c) relative weakness in *set maintenance* (i.e., reflecting the set-loss syndrome), especially on trials with greater demand for right hemisphere resources.

Model Validation Phase

To allow validation of the clusters yielded by the first phase of the study, all participants completed a previously validated test (the Attentional Network Test; ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) of three attentional processes: (a) the ability to maintain an alert state so as to rapidly take in information, facilitating rapid formulation of mental sets (referred to in the ANT literature as 'alerting'); (b) the ability to flexibly shift attention in response to sensory cues (referred to in the ANT literature as 'orienting'); and (c) the ability to maintain a mental set despite distracting or conflicting stimuli (referred to in the ANT literature as 'executive attention'). We hypothesized that:

(1) if the prefrontal convexity model was supported, weaknesses in alerting, orienting, and executive attention would be uniquely present in clusters characterized by weaknesses in forming, switching, and maintaining mental sets, respectively, or (2) if the hemispheric asymmetry model was supported, then weaknesses in orienting (which has been shown to be predominantly a left-hemisphere process) would be present in the cluster characterized by weaknesses in set formation and set switching; and weaknesses in executive attention (which has been shown to be predominantly a right-hemisphere process) would be present in the cluster characterized by weaknesses in set maintenance. We did not expect differences in alerting, as this process has been shown to be bilaterally distributed).

METHODS

Participants

A total of 315 college students (50.5% female) received course credit for their participation. Mean age was 20.8, $SD = 2.7$, and mean education was 13.2, $SD = 1.1$. Because EF performances were partially indexed via response latencies, individuals older than 30 were excluded in order to reduce the effect of age on processing speed (Schretlen et al., 2000). The racial/ethnic distribution of the sample was 88.6% White, 4.4% Asian, 0.7% African American, 0.3% Pacific Islander, and 5.4% other; of these individuals, 7.3% identified their ethnicity as Latino/Latina. Exclusion criteria included the following characteristics assessed by self-report: (a) English as a second language, (b) left-handedness, (c) age less than 18 or more than 30 years, and (d) physical or sensory impairment that would preclude test performance (e.g., paralysis in the dominant hand). Individuals who met these exclusion criteria were given the opportunity to complete alternative procedures as specified according to the University's Internal Review Board (IRB).

Model Identification Measures

We used a modified switching task that we successfully used in the past to examine EF profiles in the context of differential hemispheric processing demands (Suchy & Kosson, 2006). The task was administered via computer. Within this task, two classification procedures were administered: a verbal task (VT), containing stimuli

designed to rely primarily on left-hemisphere processing, and a nonverbal task (NVT), containing stimuli designed to rely primarily on right-hemisphere processing. Tasks were designed to contain: (a) high executive-demand (HED) trials designed to assess the abilities to form, switch, and maintain mental sets, and (b) comparison trials (CTs) designed to examine relative strengths and weaknesses on trials reflecting left versus right hemispheric processing demands (i.e., VT, NVT) under low executive-demand conditions. CTs also served as a baseline of comparison for calculating costs (i.e., speed, accuracy) associated with HED trials. All instructions, cues, stimuli, and feedback were presented via computer screen.

Verbal Task (VT)

The VT trials were designed to tax left-hemisphere resources, based on empirical support for left hemisphere involvement in letter recognition and discrimination tasks (Cohen, 1972; Farah, Gazzaniga, Holtzman, & Kosslyn, 1985; Gootjes, Raij, Salmelin, & Hari, 1999; A. Wilkins & Stewart, 1974). The VT presented letters, one at a time. On each trial, participants were asked to respond 'yes' (an *index* finger press on the '1' key of a keyboard number pad) or 'no' (a *middle* finger press on the '2' key of the number pad) regarding one of the following classifications: (a) Is this letter capitalized? or (b) Is this letter a vowel?). Some letters belonged to *both* categories (e.g., 'U'), or neither category (e.g., 't'), and as such were designated as 'congruent;' other letters belonged to only *one* category (e.g., 'T' or 'u') and as such were designated as 'incongruent.' Participants classified letters according to cues presented on the computer screen (i.e., 'CAP?' or 'vowel?'), and received feedback regarding the speed and accuracy of their performance. Specifically, responses slower than 1200 ms were followed by the words

'Too slow,' and incorrect responses were followed by error feedback (the word 'Wrong,'

accompanied by a cue regarding the currently correct classification principle).

Nonverbal Task (NVT)

The NVT trials were designed to tax the right cerebral hemisphere, based on

studies indicating increased right hemisphere activation during tasks involving judgments

of spatial coordinates (Jager & Postma, 2003; Kosslyn et al., 1989). The NVT presented

the same stimuli used for the VT. However, during the NVT trials, participants were

asked to classify the stimuli according to their spatial location on the computer screen.

On each trial, participants were asked to respond either 'yes' (an *index* finger press) or

'no' (a *middle* finger press) regarding one of the following classifications: (a) Is the

figure located in the lower left half of the screen? (see Figure 1a), or (b) Is the figure

located in the lower right half of the screen? (see Figure 1d). Once again, stimuli could

be either congruent or incongruent (see Figure 1). Participants were instructed to classify

the stimuli according to the location that was indicated to them via both visual and verbal

cues ('Here?' presented in either the lower left or the lower right portion of the screen).

As was the case in the VT, feedback regarding speed and accuracy was provided.

High Executive-demand (HED) Trials

Both the VT and the NVT were designed to instantiate three types of executive

demands: forming, switching, and maintaining mental set. Increases in executive

demands were accomplished by: (a) presenting cues indicating the classification principle

to be used in the subsequent block of trials, based on the classic switching task paradigm

(Allport, Styles, & Hsieh, 1994; Jersild, 1927), and (b) arranging the sequence in which

the trials occurred, based loosely on the Wisconsin Card Sorting Test (Heaton, Chelune, Talley, Kay, & Curtiss, 1993) and on principles employed in various continuous performance tasks (e.g., Connors, 2000).

First, to manipulate set switching and set forming demands, approximately every eight trials a cue was presented signaling which classification principle (e.g., cap/vowel vs. left/right location) should be observed next. This principle was valid until the next cue appeared. Each new cue could be either different from the previous cue, indicating a change in classification principle, or the same as the previous cue, indicating that the classification principle should remain unchanged. When a cue indicated a change, participants needed to switch to the new principle on the immediately following trial; these cues were referred to as 'switch cues,' in which the participant is required to modify their objective. When a cue did *not* indicate a change, participants simply needed to 'reconsider' (Gopher, Armony, & Greenshpan, 2000) their current response set, ascertaining that their set and the cue matched and that no switching was required; these cues were referred to as 'form cues,' in which the participant is required only to reconsider their objective.

Trials immediately following switch and form cues are known to be associated with increased processing demands, reflected in longer response latencies (Allport et al., 1994; Gopher et al., 2000; Jersild, 1927). Because of the top-down requirements of responding to cues under these conditions, the additional processing demand is believed to represent an index of executive control (Mecklinger et al., 1999; Rogers et al., 1998). This notion is corroborated by experimental studies conducted with normal participants (Gopher et al., 2000; Lorist et al., 2000; Monsell, Yeung, & Azuma, 2000) and with

individuals known to demonstrate weaknesses in executive abilities (Cepeda, Kramer, & Gonzalez de Sather, 2001; Kramer, Hahn, & Gopher, 1999; Kray, Li, & Lindenberger, 2002; Kray & Lindenberger, 2000; Salthouse, Fristoe, McGuthry, & Hambrick, 1998). In this study, trials immediately following switch and form cues were referred to as 'switch trials' and 'form trials,' respectively. All switch and form trials were incongruent, as were all trials immediately preceding switch or form cues. See Figure 2 for a sample trial sequence.

Second, to increase set-maintenance demands, trial sequences were manipulated such that, some of the time, a set of approximately eight *congruent* trials was followed by an *incongruent* trial. As a reminder, each *incongruent* trial has *two* different potentially correct responses (one for each classification principle), whereas each *congruent* trial has only *one* potentially correct response (regardless of the current classification principle). This difference in the number of possible responses has important implications for set maintenance demands. In particular, when performing a series of *incongruent* trials, the need to select from among two potential responses forces the participant to constantly refresh the classification principle in working memory, thereby maintaining arousal and vigilance. In contrast, when performing a series of only *congruent* trials, nothing about the stimuli reminds participants to refresh their mental set regarding the classification principle (because the response is the same regardless), which increases the potential for participants to become inattentive and forget which classification principle they are supposed to be responding to. Thus, to perform the task correctly, participants need to *self-cue* to maintain mental set and to avoid allowing the congruent nature of these trials to lull them into attentiveness.

In this paradigm, the trials of interest (referred to as 'Maintenance trials') are the *first incongruent trials* immediately following a series of congruent trials (see Figure 3 for a sample trial sequence). We have previously demonstrated that the Maintenance trials in this task are associated with increased number of errors among participants with mixed features of inattentiveness and impulsivity (Suchy, Gold, Biechler, & Osmon, 2003), as well as among psychopathic offenders (Suchy & Kosson, 2006), who are known to have difficulties with self-monitoring and self-cueing (Brazil et al., 2009; J. P. Newman, Patterson, & Kosson, 1987; J. P. Newman, Schmitt, & Voss, 1997).

Comparison Trials (CTs)

The CTs (i.e., trials that placed fewer demands on executive systems) were identical to switch, form, and maintain trials in every regard except the need to switch, form, or maintain mental set. They consisted of incongruent trials that occurred between cues, excluding switch, form, and maintenance trials. CTs were similar to maintenance trials in that they were incongruent and were *not* preceded by a cue, but they also were *not* preceded by a series of congruent trials, and as such did not require the same demands for self-cued set-maintenance. See Figure 1 for examples of CTs.

Task Parameters

Each task consisted of 302 trials (141 congruent and 161 incongruent) and only the incongruent trials were used in the analyses. There were eight each of form, switch, and maintenance, and 137 comparison trials. The order of manipulations (i.e., VT vs. NVT) was randomized for each participant. Visual stimuli boxes were 2.5 inches tall by 2.5 inches wide and contained verbal stimuli (1.75 inches tall) overlying a neutral

background (i.e., mixture of grey shades and hues). Each stimulus box remained on the screen until a participant responded. Response-stimulus interval was 20 ms. Cues and feedback were presented on the screen for 750 ms, followed by a 20 ms interval.

<div align="center">Model Validation Measures</div>

In order to determine whether performance patterns generalized beyond a single measure, participants were administered The Attention Network Task (ANT; Fan et al., 2002; Fan, Wu, Fossella, & Posner, 2001). The ANT, a combination of a cued reaction time (Posner, Snyder, & Davidson, 1980) and flanker task (Eriksen & Eriksen, 1974) was designed to measure the efficiency of three attentional networks: alerting, orienting, and executive attention. Prior to calculating the efficiency variables, median reaction times (RTs) were calculated for each participant across eight variables calculated from two types of trial-based stimuli: cue type (no cue vs. center cue vs. double cue vs. spatial cue) and flanker type (congruent vs. incongruent). Figure 4 provides a visual schematic of various task conditions. Next, we generated arithmetical means of the median reaction time (RT) values so as to create the alerting, orienting, and executive attention scores, described below.

Alerting

This network refers to *attentional readiness,* or the ability to sustain an alert state for the purpose of preparing a reaction if necessary. The alerting network is thought to be associated with activation of the right frontal and parietal brain regions based on the cortical distribution of the brain's norepinephrine system (Coull, Frith, Frackowiak, & Grasby, 1996), which affects alertness and arousal (Beane & Marrocco, 2004). In

addition, certain clinical populations characterized by a right hemisphere weakness (i.e.,

ADHD; Stefanatos & Wasserstein, 2001) have been found to perform more poorly on the

alerting trials compared to healthy controls (Johnson et al., 2008). The alerting variable

(i.e., the ability to distribute attention across two potential target locations) was calculated

by subtracting the mean RT of the double-cue conditions from the mean RT of the no-cue

conditions.

Orienting

This network refers to *environmental attention,* or the ability to rapidly and

flexibly shift the focus of attention in response to changing task demands. The orienting

network is thought to reflect underlying attentional processes involved with switching

mental set, as the ability to respond to unexpected targets is essential for both

conceptualizing task demands and modifying cognitive and behavioral set as indicated.

Whereas broad distribution of attention (i.e., alerting network) appears to rely on the right

hemisphere, results from neuroimaging studies suggest that the ability to respond to

rapidly changing events or cues is left lateralized (Coull, Frith, Buchel, & Nobre, 2000;

Fan, McCandliss, Fossella, Flombaum, & Posner, 2005). The orienting variable (i.e.,

how well attention is directed to task-relevant cues) was calculated by subtracting the

mean RT of the spatial-cue conditions from the mean RT of the center-cue conditions.

Executive Attention

The executive attention network refers to higher-order EF abilities involved with

response selection, or the ability to quickly and accurately select the correct response

among competing, incongruent stimuli. Executive attention is thought to rely on

prefrontal areas, based on research examining other cognitive tasks involving response selection, such as the Stroop task (Bush, Luu, & Posner, 2000; MacDonald, Cohen, Stenger, & Carter, 2000), and evidence suggests predominantly right hemisphere involvement (see Vendrell et al., 1995 for a review). Individuals with more effective response selection abilities exhibit less interference in performance; therefore, better executive attention performances are indicated by a relatively smaller increase in response latencies on incongruent flanker trials. The executive attention variable was calculated by subtracting the mean RT of all *congruent* flanking conditions from the mean of all *incongruent* flanking conditions (i.e., index of conflict monitoring).

ANT Task Parameters

Each task consisted of 288 trials, with the four cue conditions (i.e., no, center, double, spatial) consisting of 72 trials each and presented at random. Cues were presented on the screen for 100 ms, followed by a brief 400 ms delay interval. Each target arrow was displayed until the participant responded or 1700 ms had elapsed. Response-stimulus interval varied randomly from 400-1600 ms.

Procedure

Eligible participants underwent IRB-approved informed consent procedures. The VT and NVT were counterbalanced and were preceded by 12 practice trials. Participants were given the option to repeat practice trials if they felt they did not fully understand how to perform the task. Participants responded by pressing designated keys on a computer keyboard number pad using their index and middle fingers. The ANT task was completed according to published guidelines (see Fan et al., 2000). All task stimuli were

presented on a Gateway desktop computer with a 14 inch computer screen. Response

latency and number of errors were recorded.

(a) Lower Left: classification principle

(b) Lower Left: congruent trial

(c) Lower Left: incongruent trial

(d) Lower Right: classification principle

(e) Lower Right: congruent trial

(f) Lower Right: incongruent trial
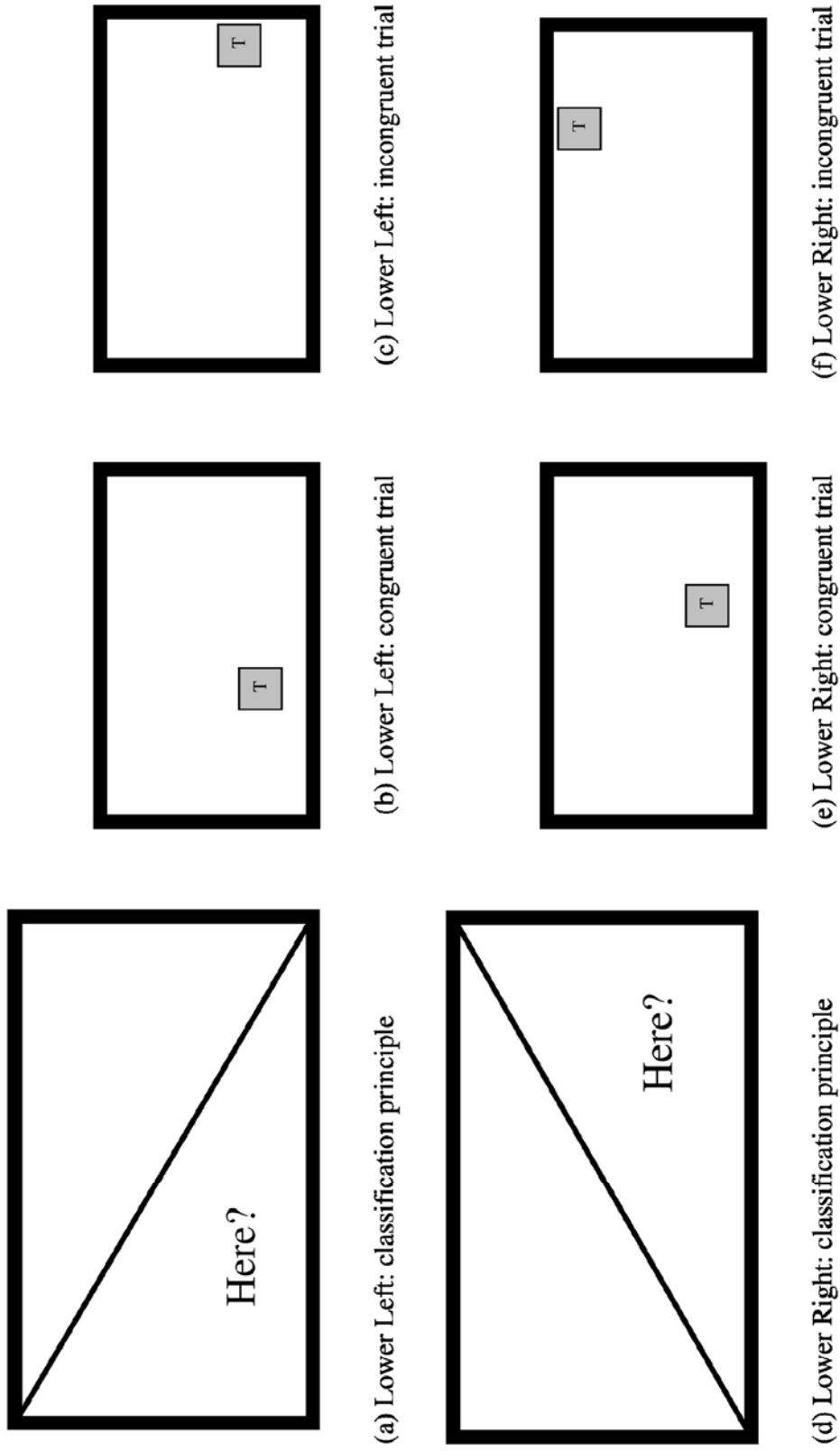
Figure 1. Sample spatial locations and trial types for the nonverbal task.
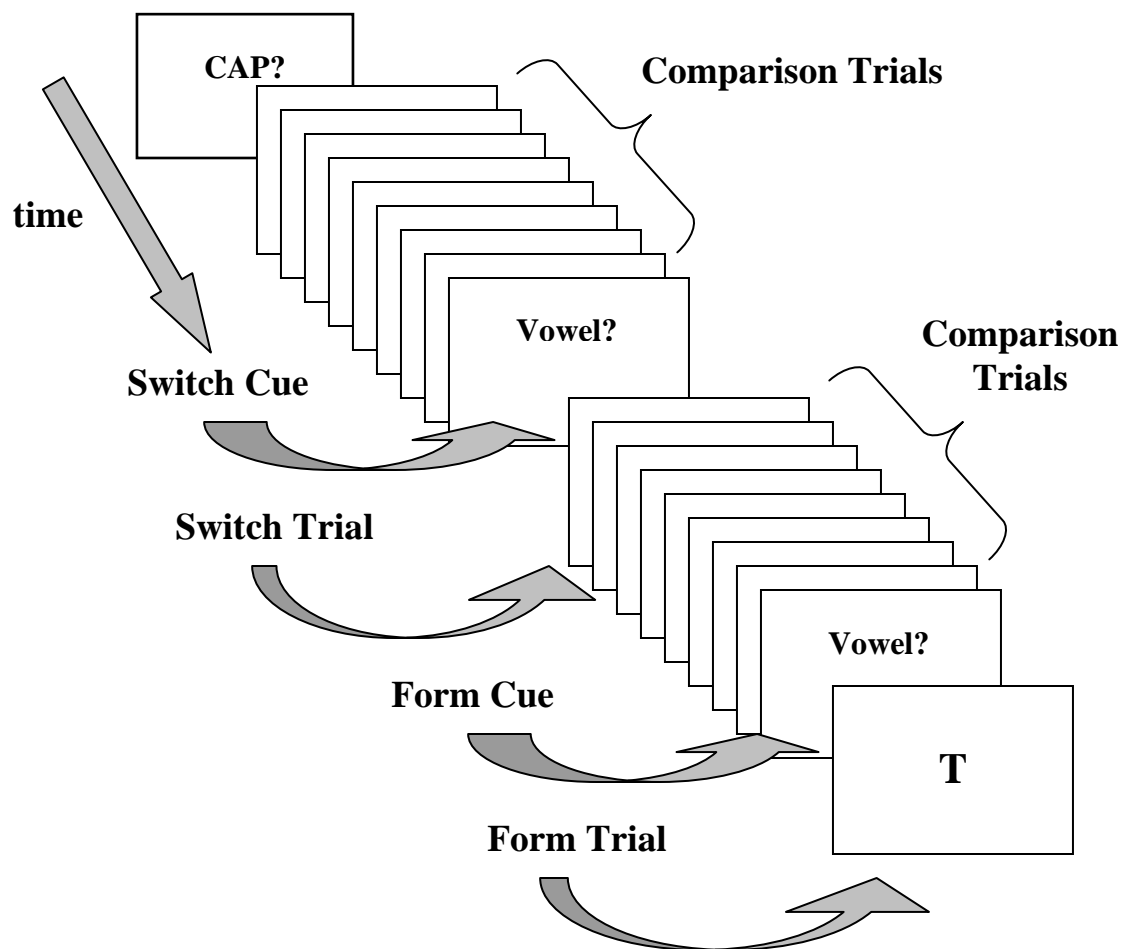
Figure 2. Sample sequence of trials showing switch, form, and comparison trials.
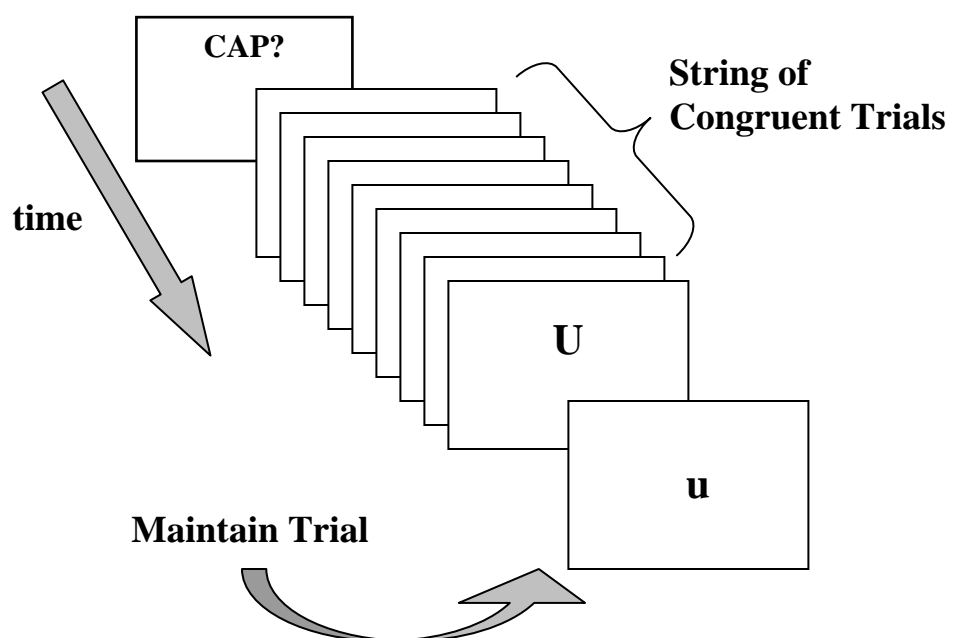
Figure 3. Sample sequence of trials showing maintain trials.

(a)   **(b)**

No-Cue

Center-Cue

Double-Cue

Spatial-Cue

Congruent Flankers

Incongruent Flankers

Neutral Flankers
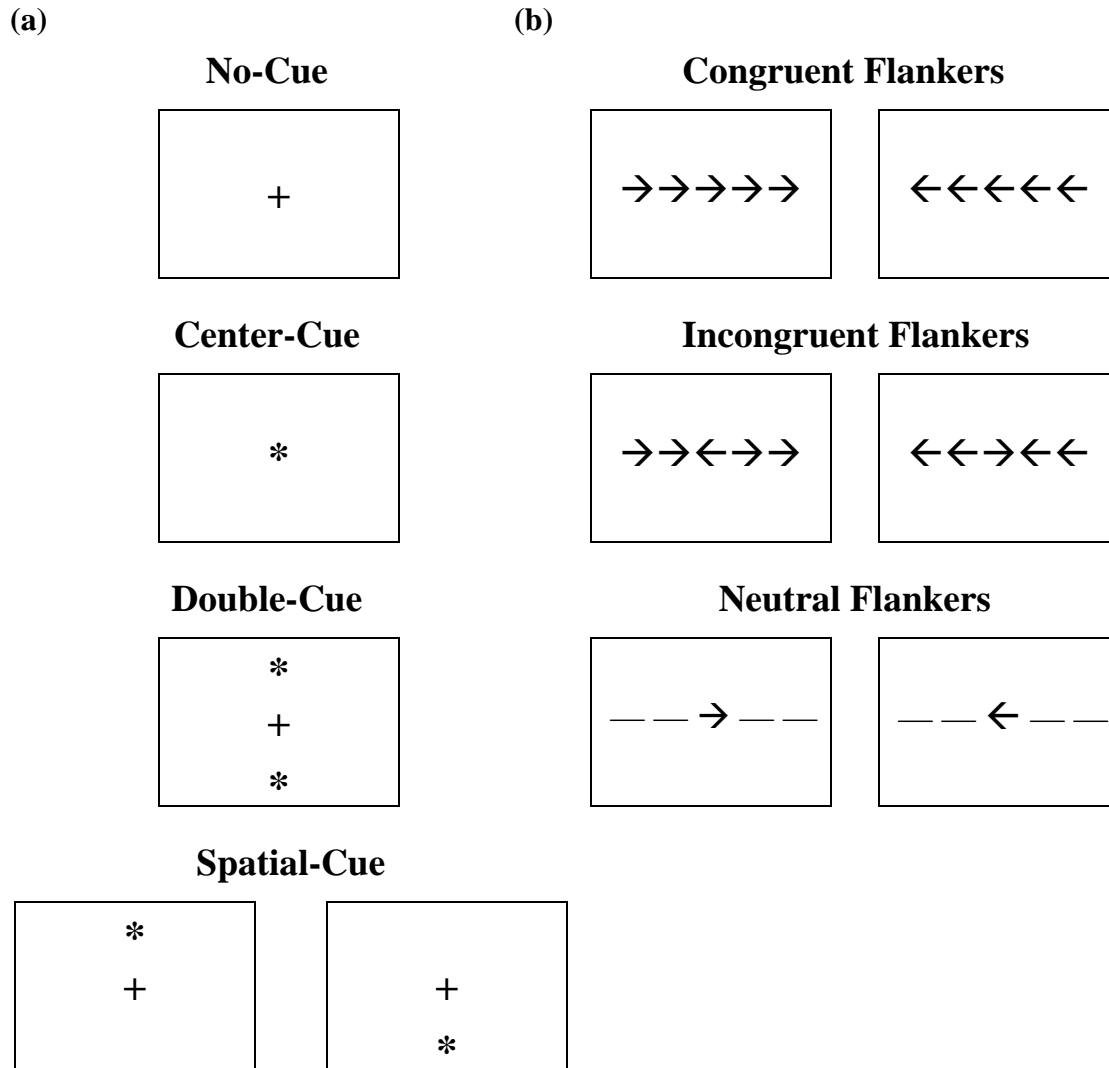
(b)   fixation → cue (100ms) → fixation (400ms) → target / response (<1700ms)

Figure 4. Task conditions for the Attention Network Task, showing: (a) the four cue conditions, (b) the three flanker/target conditions, and (c) the temporal sequence of a single trial.

DATA ANALYSIS

Modified Switching Task

Form, Switch, and Comparison Scores

We first computed the median response latency and total errors for each

participant separately for form, switch, and comparison trials. Next, we generated

arithmetical median response latencies and total error values so as to create the following

scores: (1) verbal task, high executive demand (VT-HED), consisting of the VT form and

switch scores, (2) nonverbal task, high executive demand (NVT-HED), consisting of the

NVT form and switch scores, (3) verbal task, low executive demand (VT-CT), consisting

of all the VT comparison trial scores, and (4) nonverbal task, low executive demand

(NVT-CT), consisting of all the NVT comparison trial scores.

In order to calculate the form and switch cost variables, we subtracted the mean of

the CT score from the mean of each of the HED scores for VT and NVT.   Thus, the

experimental design produced eight 'cost' variables resulting from three types of

conditions and measurement: trial type (switch vs. form), task type (verbal vs.

nonverbal), and outcome type (response latency vs. errors). In addition, four CT

variables were created from two types of conditions and measurement: task type (verbal

vs. nonverbal) and outcome type (response latency vs. errors). Although task conditions

were counterbalanced, an order effect was identified such that participants who began

with the NVT condition performed significantly more poorly on the NVT trials relative to

participants who began with the VT condition. To minimize this effect, task order was controlled for in all analyses.

Finally, because both speed and accuracy are indices of forming and switching mental set, composite scores were created by extracting a principal component from an analysis into which response latencies and errors were entered. A total of six final composite scores were used in the final analysis, based on two types of conditions: trial type (comparison, form, switch) and task type (verbal vs. nonverbal).

Set Maintenance Scores

Set maintenance scores were computed using *only* accuracy data, in line with our prior use of this task (Suchy & Kosson, 2006). Total number of errors made on the *pre*-set-loss trials (i.e., string of eight consecutive congruent trials preceding the single set-loss trial) were divided by the total number of *pre*set-loss trials (i.e., 36 per condition), producing a *percentage* of preset-loss errors. The same approach was taken for set-loss trials (i.e., the first incongruent trial following the string of congruent trials, for a total of eight per condition). This resulted in four variables derived from two within subjects factors: trial type (*pre*set-loss trial vs. set-loss trial) and task type (Verbal vs. Nonverbal). As with the comparison, form, and switch variables, task sequence was controlled to minimize order effects. Lastly, the trial type variables (*pre*set-loss trial vs. set-loss trial) were collapsed into composite scores via principal components analysis, producing two final *set maintenance* variables based on task type (Verbal vs. Nonverbal).

Latent Profile Analysis

The first aim of the study was to identify profiles of executive functioning.

Therefore, latent profile analysis (LPA) in Mplus (Version 5; Muthen & Muthen, 2009)

was used as a classification procedure to group participants on the basis of patterns in

their neurocognitive markers. LPA is a maximum likelihood procedure that uses a latent

mixture model and that identifies probable groupings within the data (Lanza, Flaherty, &

Collins, 2003). Similar to other clustering techniques, LPA is a classification procedure

designed to identify various groupings within a larger data set. LPA has the advantage of

being model dependent and has the ability to test alternative models (e.g., variances and

covariances differing across the groups, versus forcing variances and covariances to be

equal) that would otherwise be model assumptions according to other clustering methods.

LPA has become an increasingly promising method in the typology literature (for

an in depth discussion of latent class analysis, see Lanza et al., 2003) as it can provide

statistical indicators that assist in identifying the proper number of profile solutions. One

such indicator is the Bayesian information criterion (BIC) that, when minimized,

indicates the best fit compared to other possible solutions (Nagin, 1999). For small

samples ($n < 500$), the BIC has been shown to be superior for determining model fit

compared to other indicators (Nylund, Asparouhov, & Muthen, 2007) although

adjustments for sample size (ssBIC) may also be appropriate (Sclove, 1987). Because

studies have shown improved class selection with both the unadjusted BIC (Bauer, 2007;

Nylund et al., 2007) and the sample size adjusted BIC (Lubke & Neale, 2006; Tofighi &

Enders, 2007), both fit statistics were examined when determining optimal model fit.

Although the BIC and ssBIC both provide a statistical criterion regarding the ideal

number of solutions, the derived profiles are still considered probabilistic and do not reflect absolute group membership.

Model identification can also be informed by various likelihood ratio tests (LRT), which are used to test relative model fit by testing the null hypothesis that competing models demonstrate comparable fit (Vuong, 1989). Within latent variable models, the Vuong-Lo-Mendell-Rubin test (Lo, Mendell, & Rubin, 2001) is an accepted methodology for testing the equivalence of two associated probability density functions (Henson, Reise, & Kim, 2007). Simulation studies have indicated that the VLMR test favors selection of more components when used with small samples, resulting in increased Type I error rates; this suggests the need for an adjusted test (aVLMR) with samples less than 300 (Lo et al., 2001). Because both LRT approaches involve relative strengths, including increased power with VLMR and decreased Type I error rates with aVLMR, both statistics were used when determining optimal model fit.

The LPA was performed on the eight EF variables included in the study. Only the means for each variable were allowed to vary across clusters. Missing data (i.e., due to technical problems; n=31) were handled during the analysis with full information maximum likelihood, in which it is assumed that the data were missing at random. Because no extreme values were detected, no outliers were removed in order to maintain representativeness of normal profiles of EF in healthy adults. Therefore, the total sample size consisted of data from 284 participants.

The fit statistics suggested that the model with three LPs had the best fit, producing minimum BIC and ssBIC values, and having the best relative model fit as determined by VLMR and aVLMR statistics (see Table 1). Table 2 shows the parameter

estimates for the three selected LPs. These parameters represent each latent profile's

prevalence, the specific mean profiles, and the 95% confidence intervals considered in

the LPA model. Significantly different ($p<.05$) performances between and within classes

were determined via confidence intervals (CIs); performance means that were mutually

exclusive across any two 95% CIs were considered statistically different. These profiles

are described in detail below, identifying one large class characterized by generally

average performance and two smaller classes characterized by distinct EF weaknesses.

Table 1.
Goodness of fit statistics and class frequencies for latent profile models.

	LC(1)	LC(2)	LC(3)	LC(4)	LC(5)
Log-L (H0)	-2906.017	-2818.300	-2773.835	-2750.285	-2714.469
n parameters	16	25	34	43	52
BIC	5902.417	5777.825	5739.735	5743.476	5722.685
ssBIC	5851.681	5698.549	5631.920	5607.122	5557.791
VLMR p-value	n/a	0.0562	0.0330	0.2587	0.0593
aVLMR p-value	n/a	0.0590	0.0348	0.2637	0.0607
Class frequencies (%)*					
n1	284 (100.00)	237 (83.45)	203 (71.48)	197 (69.37)	197 (69.37)
n2		47 (16.55)	43 (15.14)	48 (16.90)	38 (13.38)
n3			38 (13.38)	33 (11.62)	24 (8.45)
n4				6 (2.11)	17 (5.98)
n5					8 (2.82)

*class frequencies based on each participant's most likely latent class membership. LPA: Latent Profile Analysis; LC: Latent Class; Log-L (Ho): Log-likelihood of hypothesized model (Ho); BIC: Bayesian Information Criteria (= -2 x model log-likelihood + log(n) x number of model parameters); ssBIC: sample-size adjusted BIC; VLMR: Vuong-Lo-Mendell-Rubin Likelihood Ratio Test for N-1 versus N classes; aVLMR: adjusted VLMR.

Table 2.
Maximum likelihood estimates (MLE) and 95% confidence intervals (CI) of mean profiles.

	Latent profile means (^)					
Variable	**LP1** (n=203)	**95% CI**	**LP2** (n=43)	**95% CI**	**LP3** (n=38)	**95% CI**
V-CT	*-0.29*	-0.43, -0.16	0.65	0.19, 1.10	0.19	-0.18, 0.56
NV-CT	*-0.42*	-0.54, -0.29	1.27*	0.88, 1.65	-0.01*	-0.27, 0.25
V-Form	-0.25	-0.36, -0.14	-0.41	-0.63, -0.20	**1.43**	1.08, 1.77
NV-Form	-0.06	-0.19, 0.06	-0.10	-0.48, 0.28	0.21	-0.26, 0.69
V-Switch	-0.13	-0.25, -0.02	-0.18*	-0.48, 0.10	**0.65***	0.12, 1.18
NV-Switch	-0.04	-0.17, 0.07	-0.30*	-0.70, 0.09	**0.42***	0.01, 0.82
V-Maintain	-0.15	-0.28, -0.02	-0.02*	-0.34, 0.30	**0.32***	-0.07, 0.72
NV-Maintain	-0.39	-0.49, -0.28	<u>1.07*</u>	0.60, 1.54	-0.14*	-0.40, 0.11

(^) Statistically significant (*p*<.05) refers to means that are mutually exclusive across LP 95% CI ranges. *Denotes significant difference between LP2 and LP3. Significant differences between differences between LP1 vs. (LP2, LP3) are italicized, differences between LP2 vs. (LP1, LP3) are underlined; differences between LP3 vs. (LP1, LP2) are bold-faced.

MODEL IDENTIFICATION RESULTS

Profiles of Executive Functioning

In the three-profile solution, the first class was the more favorable profile (Latent Profile 1: LP1) and included the majority of the participants in the sample (203 participants; 71.5% of the sample). See Figure 5 for means of profiles for all markers of executive functioning. Participants belonging to LP1 were generally positive in their profile of EF abilities and were characterized by consistent performances across CT and switching markers. Within LP1, participants performed significantly better on set-formation trials under VT conditions relative to NVT conditions. The opposite pattern was observed on set-maintenance trials, with significantly better performances observed under NVT conditions compared to VT conditions. Because these differences are to be expected and do not reflect any EF weaknesses per se, participants belonging to LP1 were classified as having *normal* EF abilities.

The other two classes were noticeably smaller and demonstrated weaknesses relative to LP1. The second class (LP2) consisted of 43 participants (15.1% of the sample). Participants in Profile 2 exhibited balanced performance across forming and switching trials (i.e., no significant difference between VT and NVT trials). Relative to these preserved performances, however, participants in LP2 exhibited a relative weakness across all comparison trials, with significantly poorer performances on NVT comparison trials compared to VT comparison trials. LP2 participants also performed

poorly on set-maintenance trials, but only under NVT conditions. Poor performance

across comparison trials indicated that LP2 participants were both slower and less

accurate on tasks involving low-executive demand, suggesting weaknesses in attention

and arousal. In addition, difficulties with set-maintenance under NVT conditions only,

combined with significant difficulties across comparison trials (especially under NVT

conditions), suggests that maintaining cognitive set was particularly difficult for LP2

participants when the task *also* required right hemisphere activation. Because this

combination of performances is consistent with weaknesses in mPFC and right

hemisphere, LP2 was classified as having a *right/superomedial* EF weakness.

The third class (LP3) was the smallest (38 participants; 13.4% of the sample) and

demonstrated a near-inverted profile compared to LP2. Compared to LP1, participants in

LP3 exhibited a relative weakness across all CT and switching trials (i.e., regardless of

VT versus NVT conditions). When required to form or maintain mental set, LP3

participants performed poorly but *only* under VT conditions (i.e., performances were

preserved under NVT conditions). Stated another way, Profile 3 was characterized by a

global weakness (i.e., regardless of VT/NVT conditions) on tasks requiring cognitive

flexibility (i.e., switching) and organized behavior (i.e., CT), combined with a *specific*

weakness on tasks administered under VT conditions alone. Because this pattern of

performances overlaps strongly with both the dysexecutive/disorganized syndrome

characterizing dlPFC weakness as well as the cognitive inflexibility syndrome

characterizing left hemisphere weakness, LP3 was classified as having a *left/dorsolateral*

EF weakness.

Model Identification Discussion

Results from the Model Identification Study indicated that that a 3-class model provided the best fit, resulting in one large class characterized by generally average executive functioning (EF) performances (LP1) and two smaller classes characterized by distinct EF weaknesses (LP2, LP3). Participants in LP2 exhibited a global weakness in attention and arousal combined with a relative set-maintenance weakness, especially on trials with greater demand for right hemisphere resources. Based on this combination of performances, LP2 participants were classified as having a *right/superomedial* EF weakness. Participants in LP3 exhibited a global weakness on tasks requiring cognitive flexibility and organized behavior, combined with a specific weakness on trials posing a greater demand on left hemisphere resources. Therefore, LP3 participants were classified as having a *left/dorsolateral* EF weakness. Together, these results provide support for the hemispheric asymmetry model, suggesting that set-maintenance abilities may be right hemisphere lateralized, whereas cognitive-flexibility abilities may be left hemisphere lateralized.
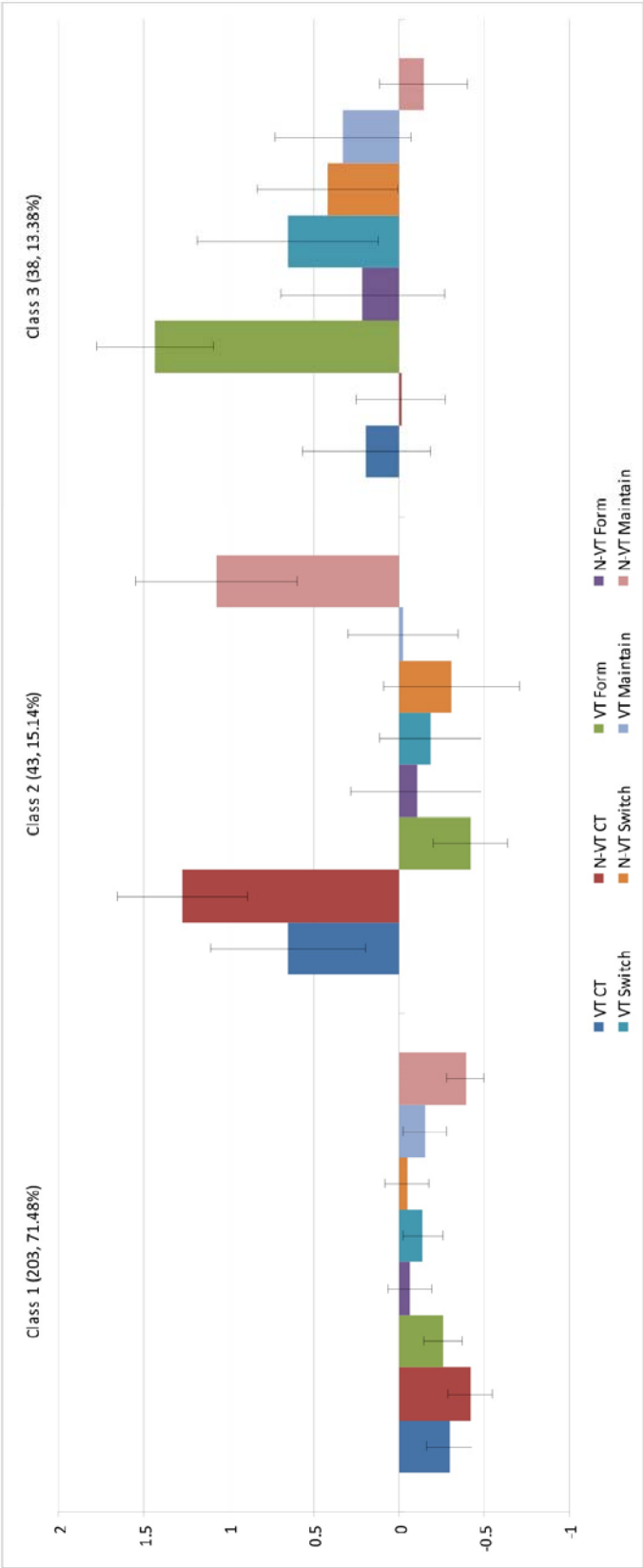
Figure 5. Means by cognitive marker for the three-profile solution. Error bars indicate the 95% confidence interval around the mean. VT = verbal trials; CT = comparison trials; NVT = nonverbal trials.

MODEL VALIDATION RESULTS

Repeated-measures analysis of variance was conducted to detect significant within-subjects effects between latent profiles (LPs) on alerting, orienting, and executive attention performances on the ANT. There was a significant interaction effect between ANT performance and LP classification ($F(4,554) = 5.938$, $p<.001$), indicating that LP classification had different effects on ANT performances. Looking at the interaction graph in Figure 6, these effects reflect that classification into LP1 was associated with balanced performances across the three attentional networks, whereas classification into LP2 or LP3 resulted in distinct patterns of relative EF weaknesses. Consistent with hypotheses, LP2 participants demonstrated a relative weakness on orienting trials and LP3 participants demonstrated a relative weakness on executive attention trials. Contrary to predicted results, LP2 was also characterized by relatively poorer performances on alerting trials.

Model Validation Discussion

Results from the Model Validation Study are generally consistent with the predicted results. Specifically, LP1 participants exhibited balanced performances across the three ANT measures, consistent with the lack of apparent EF weaknesses characterizing LP1 in the Model Identification Study. Participants classified into the remaining LPs demonstrated contrasting performance patterns, consistent with

hemispherically lateralized EF weaknesses. In particular, LP2 participants exhibited a relative weakness on executive attention, consistent with a right/superomedial weakness, whereas LP3 participants exhibited a relative weakness on orienting, consistent with a left/dorsolateral weakness. Interestingly, the pattern predicted for alerting was not supported and indicated that a weakness on this attentional network was associated with LP3 (i.e., left/dorsolateral weakness) rather than LP2 (i.e., right/superomedial weakness). This discrepancy is interpreted in greater detail in the General Discussion section.
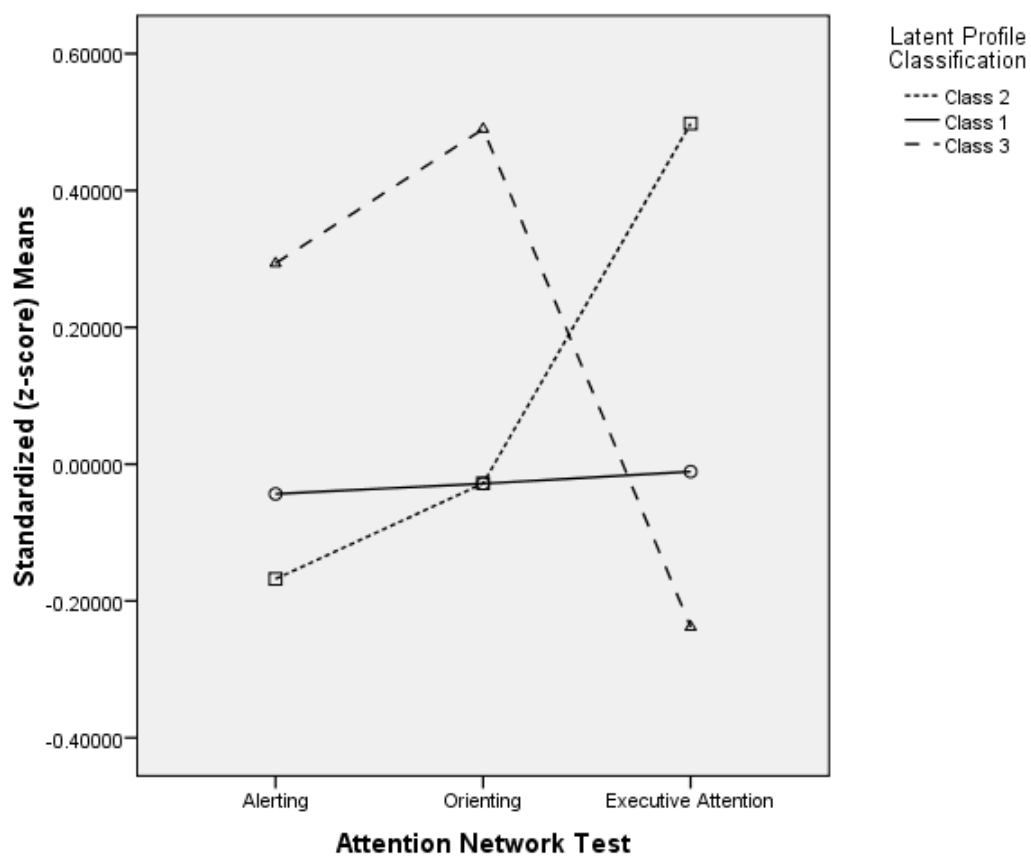
Figure 6. Interaction graph for the Attention Network Test. Latent profile classification is represented by three lines: Class 1 (solid line, circles), Class 2 (dotted line, squares), and Class 3 (dashed line, triangles).

GENERAL DISCUSSION

Profiles of executive strengths and weaknesses can be used to describe and predict certain patterns of behaviors (P. Williams, Y. Suchy, & H. Rau, 2009). The present study examined eight markers of neurocognitive function in order to identify profiles of executive functioning (EF) and provide support for neuroanatomical models of EF. Study design involved administering an experimental cognitive task that allowed assessment of switching, forming, and maintaining mental set under conditions believed to activate the left and right cerebral hemispheres. Within a sample of neurologically intact adults, three profiles of executive functioning emerged. These profiles suggest that most individuals exhibit patterns of average EF, with slightly better ability to conceptualize task demands (i.e., form mental set) under left-hemisphere-conditions and slightly better ability to sustain task-focused cognitions (i.e., maintain mental set) under right hemisphere conditions. Those with an EF weakness appeared to have contrasting profiles suggesting difficulties with *either* cognitive organization and flexibility *or* self-monitoring, arousal, and attentional control.

Profiles of Executive Functioning

This study approached EF from a multidimensional perspective, using latent profiles to characterize specific patterns of cognitive imbalances that may contribute to maladaptive executive functioning. In essence, Profile 1 depicts what we would expect

to see with hemispherically-balanced executive functioning, whereas Profiles 2 and 3 appear to depict manifestations of right or left hemispheric weaknesses as described below.

No EF Weaknesses

Of the three profiles, only participants belonging to LP1 demonstrated good performances (i.e., no detected weaknesses) across tasks and hemispheric conditions. Interestingly, LP1 participants also performed significantly *better* on tasks thought to be hemispherically-mediated, especially when those tasks were administered under hemispherically-activating conditions; that is, set-forming performances were better under VT conditions and set-maintaining performances were better under NVT conditions. This finding alone holds interest for three reasons. First, relatively better performances under conditions thought to preferentially activate separate cerebral hemispheres provides support for models emphasizing EF laterality, with reasoning and switching abilities being relegated to the left hemisphere and attention and self-monitoring abilities being relegated to the right hemisphere. Second, the left hemisphere-form and right hemisphere-maintain pattern suggests that balanced performance on other tasks (i.e., both low-executive/CT and high-executive/switching) requires a left-lateralized strength in reasoning and a right-lateralized strength in monitoring. Third, the notion that reasoning and monitoring may be asymmetrically lateralized provides support for opponent processor models of executive functioning (Osmon, 1996) and suggests that different EFs may function dynamically in the effort of balanced performance across various tasks. For example, LP1 participants performed equally well across the three

attentional network measures included in the Model Validation Study, suggesting balanced executive functioning abilities.

As described below, the performance patterns observed in LP2 and LP3 support many of the notions suggested by LP1.

Right/Superomedial Weakness

Results from the Model Identification Study indicated that participants classified according to LP2 demonstrated significant set-maintenance difficulties, but only under *nonverbal* conditions. On CT trials, LP2 demonstrated a global weakness, consistent with research linking a right hemisphere weakness to difficulty maintaining an active attentional state. In addition, this group of participants performed significantly more poorly on *verbal* CT trials compared to *nonverbal* CT trials, suggesting that difficulties with alertness and arousal may become exacerbated under conditions thought to preferentially tax the right hemisphere. Because this particular pattern of performances is consistent with those characterizing the set-loss syndrome (i.e., hemispheric asymmetry model) and the apathetic/hypokinetic syndrome (i.e., prefrontal convexity model), this class was referred to as having a *right/superomedial weakness.*

With respect to the Model Validation Study, a relative weakness on executive attention trials demonstrated by LP2 participants was consistent with a right/superomedial weakness. However, the *lack* of a predicted relative weakness on the ANT alerting variable was unexpected and can be interpreted in several ways. Keeping in mind that that alerting reflects a within-subject difference-score, comparable performances across double-cue and no-cue trials could reflect: (a) adequate ability to maintain attentional readiness, regardless of whether a cue preceded the flanker trial (i.e.,

no alerting weakness); (b) globally-suppressed ability to maintain attentional readiness, regardless of whether a cue preceded the flanker trial (i.e., pervasive alerting weakness); or (c) poor innate arousal combined with an inability to benefit from visuospatial cues (i.e., arousal-visuospatial weakness).

As a reminder, in the Model Identification Study LP2 was characterized by poor performance across low-executive demand conditions (i.e., comparison trials), consistent with the pervasive alerting weakness and arousal-visuospatial weakness interpretations described above. Importantly, however, on trials requiring consistent behavioral responses (i.e., comparison trials) or internally sustained mental representations (i.e., maintain trials), LP2 participants performed substantially more poorly under conditions thought to preferentially involve the right hemisphere (i.e., visuospatial classification). This distinct pattern of performances lends additional support to the arousal-visuospatial weakness interpretation. In sum, the results of the Model Validation Study appear to support those obtained in the Model Identification Study and further suggest that individuals characterized as having a *right/superomedial weakness* exhibit difficulty with alertness and arousal, especially under conditions that increase right hemisphere demands.

<u>Left/Dorsolateral Weakness</u>

The Model Identification Study revealed that LP3 produced a near-opposite profile relative to LP2; that is, a distinct weakness for *all* tasks performed under left-hemisphere-conditions (i.e., regardless of difficulty) combined with a specific weakness for CT and switching trials. Consistent with research implicating the left hemisphere in cognitive and behavioral set shifting, this finding suggests that a pervasive left

hemisphere weakness (i.e., such as that characterizing LP3) may contribute to poor performance on tasks that require cognitive flexibility. Because this particular pattern of performances is consistent with those characterizing the cognitive inflexibility syndrome (i.e., hemispheric asymmetry model) and the dysexecutive/disorganized syndrome (i.e., prefrontal convexity model), this class was referred to as having a *left/dorsolateral weakness.*

In the Model Validation Study, LP3 participants exhibited a relative weakness on orienting, consistent with a left/dorsolateral weakness. Contrary to predicted results, however, LP3 participants also exhibited an alerting weakness; based on research linking alerting performances to increased right-hemisphere activation, poorer performances by LP3 participants (i.e., conceptualized as having a *left*-hemisphere weakness) was unexpected. However, considering that the alerting variable reflects a difference-score between no-cue and double-cue trials, one possibility is that relatively slower performances on no-cue trials could reflect cognitive inflexibility (i.e., difficulty shifting attention) rather than low levels of innate arousal, whereas relatively faster performances on double-cue trials could merely reflect compensation by the right-hemisphere (i.e., in response to a visuospatial cue). Alternatively, based on studies demonstrating increased left hemisphere activation in response to both auditory and visual temporal cues (see Coull 1998), one possibility is that the double-cue trials may have facilitated performance by providing information about timing. That is, increased left-hemisphere stimulation prior to trial exposure may have helped to initiate the process of shifting attention toward the upcoming target. Although this theory would need to be tested, this implies that certain conditions may help compensate for underlying weakness in cognitive flexibility.

Overall, the results of the Model Validation Study appear to support those obtained in the Model Identification Study and further suggest that individuals characterized as having a *left/dorsolateral weakness* exhibit difficulty with cognitive flexibility, especially under conditions that increase left hemisphere demands.

Interpretation

The results obtained in both the Model Identification and Model Verification studies provide support for the hemispheric asymmetry model. This indicates that hemispherically-mediated patterns of executive dysfunction observed in clinical populations may also exist within neurologically healthy populations. More broadly, the profiles of EF identified in this study demonstrate the utility of approaching EF from a multidimensional perspective. Rather than considering EF to be a dimensional construct ranging from good to poor or adaptive to maladaptive, this approach allowed for variability to occur across dimensions. Our results revealed that although most young adults demonstrate average EF abilities balanced across hemispheric domains, the unevenness characterizing individuals with EF-weaknesses may be partly attributable to hemispheric weaknesses.

Limitations

The three-profile solution obtained in the Model Identification Study must be interpreted with caution for several reasons. First, the fit statistics led us to stop at the three-profile solution, indicating that the vast majority of individuals in this sample of healthy adults exhibited average and consistent performances across EF markers. This larger profile likely reflects our particular sample, i.e., young college students who may

have better than average abilities to think abstractly, shift attention, and perform at a faster pace. Therefore, what we have interpreted as normal may in fact be above normal for the average adult, and the results of this study may not be generalizable to adults over the age of 30, those without a college background, or those with physical or mental health problems. Second, it is unclear what additional factors may be contributing to the profiles of EF-weakness characterizing the two smaller classes. A history of neuropsychiatric impairment could, for example, be responsible for the small number of individuals characterized as having either left or right hemisphere weakness. However, it is also possible that a small percentage of the population experiences similar profiles of weaknesses. Third, despite evidence linking switching/maintenance and verbal/spatial abilities to opposite hemispheres, the extent to which the two hemispheres interact during task performance is unclear. Although the left and right hemisphere likely play a dominant role in certain cognitive functions, both hemispheres are likely to involved to some degree with discrete EFs, thus making it difficult to conclude that set maintenance is governed primarily by the right hemisphere and set switching is governed primarily by the left hemisphere.

<div align="center">Future Directions</div>

Future research examining profiles of EF should investigate similar markers in a more demographically diverse population. In addition, the implications of profiles of EF-weaknesses identified in this study should be examined with respect to the neurobiological underpinnings associated with psychological and neuropsychiatric impairment. Certain clinical populations are known to have executive deficits in either switching or maintaining mental set, and it is possible that these difficulties are associated

with gross hemispheric weaknesses. For example, behaviors characteristic of depression
(e.g., impaired cognitive flexibility, poor initiation and motivation, ruminative thought
patterns) may reflect hemispheric weaknesses associated with neuropsychological
impairments, such as difficulty inhibiting prior mental set (Davis & Nolen-Hoeksema,
2000; Whitmer & Banich, 2007). Establishing these associations in clinical populations
could potentially improve our understanding of the cognitive underpinnings of certain
disorders and inform ways to improve clinical assessments, interventions, and treatments.

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