Psychological Research (2016) 80:997–1019
DOI 10.1007/s00426-015-0706-5

ORIGINAL ARTICLE

Latent profiles of executive functioning in healthy young adults: evidence of individual differences in hemispheric asymmetry

Holly K. Rau[1] · Yana Suchy[1] · Jonathan E. Butner[1] · Paula G. Williams[1]

Received: 3 December 2014 / Accepted: 4 September 2015 / Published online: 26 September 2015
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Abstract Two competing theoretical models of individual differences in executive functioning (EF) were examined: the Prefrontal Convexity Model and the Hemispheric Asymmetry Model. Neurologically healthy individuals ($N = 315$; mean age 20.8) completed a modified switching task (MST) and the Attention Network Test (ANT) in a single testing session. Data analysis was conducted in two phases. In the first phase (model identification), latent profile analysis was applied to MST variables measuring the abilities to form, switch, and maintain mental sets under conditions designed to tax left or right hemisphere resources. In the second phase (model validation), participant clusters obtained from the first phase were compared on the ANT. The Model Identification phase yielded a 3-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 non-verbal conditions. Profile 3 ($N = 38$) demonstrated weaknesses in cognitive flexibility combined with poor executive performances under verbal conditions. The Model Validation phase confirmed group differences. Profile 1 demonstrated average EF performances. Profile 2 demonstrated distractibility and decreased alertness, consistent with a right hemisphere weakness. Profile 3 demonstrated cognitive rigidity in the absence of external cues, consistent with a left hemisphere weakness. Individual differences in EF appear to follow a Hemispheric Asymmetry Model of EF among neurologically healthy adults. Investigating the relationship between hemispherically mediated executive functions and other individual difference factors known to confer health risk or resilience could inform numerous disciplines within the field of psychology.

✉ Holly K. Rau
hollyrau@gmail.com

Yana Suchy
yana.suchy@psych.utah.edu

[1] Department of Psychology, University of Utah, 380 South 1530 East, Salt Lake City, UT 84112, USA

Introduction

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 (Suchy, 2009). Originally, EF was studied almost exclusively by clinical neuropsychologists working with brain-injured populations; however, in recent years there has been increasing recognition that individual differences in EF play a key role in daily functioning among non-brain-injured individuals. Consequently, researchers interested in examining EF in neurologically healthy populations have increasingly turned to clinical neuropsychology for guidance on how to best conceptualize EF and interpret theoretically and clinically meaningful profiles of EF strengths and weaknesses. In the absence of a firm empirical foundation, however, the developing field of individual differences has continued to rely on lesion studies and neuroimaging data to inform theories of "normal" brain functioning. The purpose of this study, therefore, was to identify behavioral profiles of EF in a healthy sample and to interpret these profiles with respect to current theoretical and neuroanatomical models of brain function.

Evidence from neurologically impaired populations supports the conceptualization of EF as a non-unitary 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 and subcortical regions richly connected to the PFC (Miller & Cohen, 2001), 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; Stuss et al., 2002). Importantly, some specificity of EF components within the PFC is also supported by functional imaging research conducted with healthy individuals (e.g., working memory operations generally supported by lateral regions: Owen et al., 1998; monitoring operations generally supported by medial regions: Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004), suggesting that unique EF profiles may also constitute individual differences.

Results of factor analytic examinations of EF have been equivocal, however, 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 model (Boone, Ponton, Gorsuch, Gonzalez, & Miller, 1998; Burgess, Alderman, Evans, Emslie, & Wilson, 1998; Busch, McBride, Curtiss, & Vanderploeg, 2005; Miyake et al., 2000; Nagahama et al., 2003; Stout, Ready, Grace, Malloy, & Paulsen, 2003; Vaughan & Giovanello, 2010; Willner et al., 2010). Importantly, only one of these studies (i.e., Miyake et al., 2000) examined neurologically healthy adults. Consequently, many questions remain unanswered about the structure of EF in the absence of neurological insult or degeneration.

In response to the growing need to understand individual differences in EF among non-neurologic populations, this study examined theoretical models of EF among healthy, neurologically intact individuals. Based on past research linking neuroanatomic regions to patterns of EF symptomatology in neurologic populations, at least two neuroanatomical models can be identified to guide this investigation of EF profiles: the prefrontal convexity model and the hemispheric asymmetry model.

The prefrontal convexity model: three profiles of executive weakness

Duffy and Campbell (1994) 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.

Dorsolateral convexity: dysexecutive/disorganized syndrome

The dorsolateral PFC (dlPFC) receives projections from the parietal cortex, as well as 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 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 (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).

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). When task or situational demands change, the ofPFC is involved with rapidly updating and switching mental set (Beer, John, Scabini, & Knight, 2006), thereby ensuring that behaviors are congruent with current contingencies. In the absence of such updating, inappropriate and inflexible behaviors are released, resulting in apparent impulsivity/disinhibition. Increased ofPFC activity is observed when individuals detect discrepancies in task-relevant behaviors (Berthoz, Armony, Blair, & Dolan, 2002) and accommodate changing task demands (Kim & Ragozzino, 2005). Not surprisingly, patients with ofPFC damage exhibit impaired behavioral monitoring (Beer et al., 2006; Mah, Arnold, & Grafman, 2004) and failure to integrate environmental feedback (Hornak et al., 2004).

Medial convexity: apathetic/hypokinetic syndrome

The medial PFC (mPFC), as well as associated areas including the cingulum and the supplementary motor area (SMA), collectively play a role in adequate levels of arousal and motivation required for maintaining mental set (Stelzel, Kraft, Brandt, & Schubert, 2008; Wilk, Ezekiel, & Morton, 2012). In neurologically intact individuals, mPFC activation corresponds to both subjective and physiological arousal (Phan et al., 2003) as well as efforts involved with motivating and directing attentional resources (Kouneiher, Charron, & Koechlin, 2009; Rushworth, Walton, Kennerley, & Bannerman, 2004). Consequently, patients with mPFC damage often exhibit impaired performances on tasks requiring speed, internally motivated behaviors, or internally maintained attentional set (Grinband et al., 2011; Picton, Stuss, Shallice, Alexander, & Gillingham, 2006).

The hemispheric asymmetry model: two profiles of executive weakness

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 indicates that the left cerebral hemisphere contributes to executive functions such as problem solving (Martin, 1999; Newman, Carpenter, Varma, & Just, 2003) by flexibly updating cognitive sets (Collette et al., 2005; Dreher & Grafman, 2003; Ocklenburg, Gunturkun, & Beste, 2012; Stuss et al., 2002; Sylvester et al., 2003). In other words, this model suggests that the ability to establish a new mental set is inherently linked with the ability to flexibly update and switch mental set, i.e., cognitive flexibility. Consistent with this notion, patients with left hemisphere lesions demonstrate a wide range of behavioral difficulties reflecting cognitive inflexibility, including impaired problem solving and poor conflict resolution (Keele & Rafal, 2000; Mecklinger, von Cramon, Springer, & Matthes-von Cramon, 1999; Rogers et al., 1998).

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; Sturm & Willmes, 2001) and attention (Asanowicz, Marzecova, Jaskowski, & Wolski, 2012; Langner & Eickhoff, 2013), 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 (Rueckert & Grafman, 1998; Vendrell et al., 1995) or slower performances (Pujol et al., 2001; Rueckert & Grafman, 1998) on tasks measuring attentional vigilance.

The current study

The purpose of the present study was to test which of the two neuroanatomical models described above is better at meaningfully capturing individual differences in EF behaviors among neurologically healthy individuals. To that end, we recruited 315 young healthy volunteers for a single assessment that consisted of two phases.

Model identification phase

The model identification phase was designed to test the two competing models of EF: the Prefrontal Convexity Model and the Hemispheric Asymmetry Model. We tested participants' abilities to form, switch, and maintain mental sets in the context of task stimuli that are preferentially processed by either the left or the right cerebral hemisphere (the modified switching task, MST; Suchy & Kosson, 2006). We then employed modern cluster-analytic techniques to determine whether the participants' performances would generate classes consistent with either of the two theoretical models.

If the Prefrontal Convexity Model best captured individual differences in EF in this population, then the data would yield four clusters characterized by: (a) average performance across all task variables (i.e., no EF weaknesses), (b) relative weakness in set formation regardless of the hemispheric demands of the stimuli, (c) relative weakness in set switching regardless of the hemispheric demands of the stimuli, and (d) relative weakness in set maintenance regardless of the hemispheric demands of the stimuli. Conversely, if the Hemispheric Asymmetry Model best captured individual differences in EF in this population, then we expected three clusters characterized by: (a) average performance across all task variables (i.e., no EF weaknesses), (b) relative weakness in set formation and set switching, especially on trials with greater demands for left hemisphere resources, or (c) relative weakness in set maintenance, especially on trials with greater demand for right hemisphere resources.

Model validation phase

The model validation phase was designed to test the validity of the identified models. To allow validation of the clusters yielded by the first phase, all participants completed a previously validated test (the attentional network task, ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) of three attentional processes: (a) the ability to maintain an alert state and rapidly respond to information (alerting), (b) the ability to flexibly shift attention in response to sensory cues so as to rapidly formulate and update mental set (orienting), and (c) the ability to select the correct response despite distracting or conflicting stimuli (executive attention). Each attention network is represented by a difference score calculated from six primary stimulus conditions (see "Model validation measures"), allowing for examination of both attention network scores and individual condition scores. The ANT afforded a single-task assessment of component processes, thereby reducing confounds related to method variance.

If the Prefrontal Convexity Model was supported, weaknesses on specific ANT stimulus trials associated with sustaining arousal (i.e., alerting no-cue condition) would be uniquely present in the cluster characterized by weaknesses in maintaining mental set; weaknesses on trials associated with conceptualizing task demands (i.e., orienting spatial-cue condition) would be uniquely present in the cluster characterized by weaknesses in forming mental set; and weaknesses on trials associated with changing task demands (i.e., orienting center-cue condition) would be uniquely present in the cluster characterized by weaknesses in switching mental set. Conversely, if the Hemispheric Asymmetry Model was supported, then weaknesses on the attention network measure associated with establishing or updating mental set (i.e., orienting score) would be present in the cluster characterized by weaknesses in set formation and set switching, and weaknesses on the attention network measures associated with sustaining arousal and inhibiting distractors (i.e., alerting and executive attention scores) would be present in the cluster characterized by weaknesses in set maintenance.

Methods

Participants

A total of 315 physically and neurologically healthy 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 to reduce the effect of age on processing speed (Schretlen et al., 2000). The racial/ethnic distribution of the sample was 88.6 % Caucasian, 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, blindness, etc.). Individuals who met these exclusion criteria were given the opportunity to complete alternative procedures as specified in the University's IRB-approved guidelines.

Model identification measures

We used a modified switching paradigm that we successfully used in the past to examine EF profiles in the context of differential hemispheric processing demands (Suchy & Kosson, 2006). All aspects of the paradigm were administered via computer. The stimuli for this paradigm consisted of lower- and upper-case letters, presented individually in various locations on the computer screen. Participants were required to classify the stimuli either according to the letter characteristics (i.e., the "verbal" task), or according to the stimulus locations (i.e., the "spatial" task), so as to differentially tax primarily the left vs. primarily the right hemisphere resources, respectively. Additionally, the task was designed to contain both (a) "executive" trials assessing the abilities to form, switch, and maintain mental sets, and (b) "comparison" trials examining relative strengths and weaknesses in left vs. right hemisphere processing. Additionally, comparison trials also served as a baseline of comparison for calculating costs associated with the extra demands of the executive trials, as is typically done in the switching task paradigm (Allport, Styles, & Hsieh, 1994; Jersild, 1927).

Verbal task

The verbal task (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; Wilkins & Stewart, 1974). The VT presented letters, one at a time. Participants were asked to classify stimuli according to one of the following classification principles: (a) Is this letter capitalized? or (b) Is this letter a vowel?. Cues about the correct classification principle were presented on the computer screen (i.e., "CAP?" or "vowel?") approximately every eight trials. 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 responded "yes" by pressing an index finger on the '1' key of a keyboard number pad or "no" by pressing a middle finger press on the '2' key of the number pad. Participants 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).

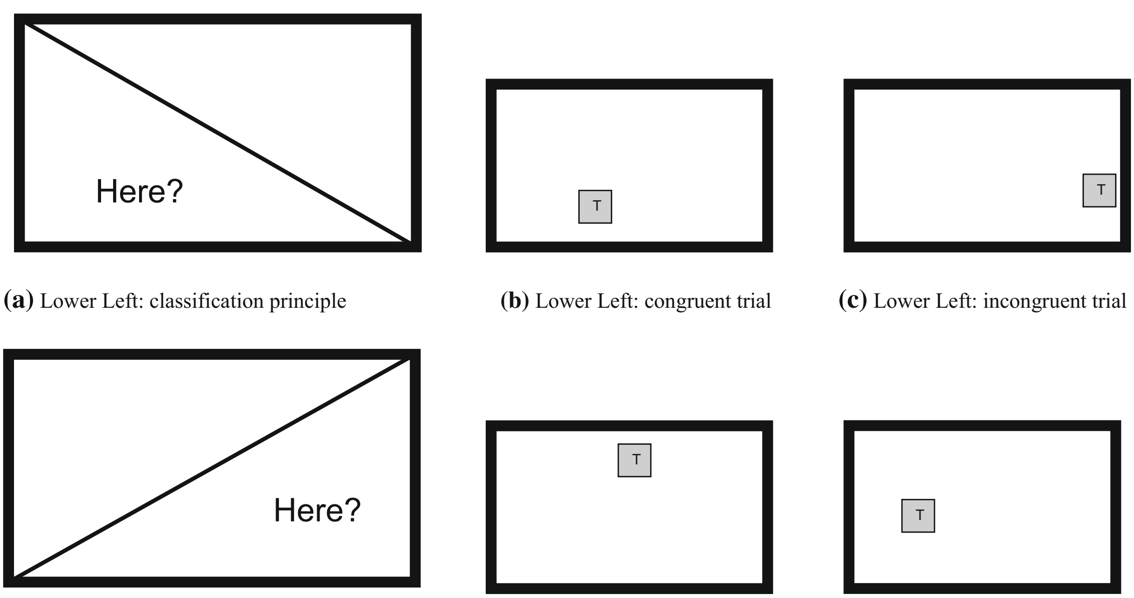
Spatial task

The spatial task (ST) 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 ST presented the same stimuli used for the VT. However, during the ST trials, participants were asked to classify the stimuli according to their spatial location on the computer screen. Specifically, participants were asked to respond regarding one of the following classifications: (a) Is the figure located in the lower left half of the screen? (see Fig. 1a), or (b) Is the figure located in the lower right half of the screen? (see Fig. 1b). As seen in Fig. 1a, b, screen "halves" were designated by a diagonal line, and 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). Consistent with the design of the VT, the ST stimuli could be either congruent or incongruent (see Fig. 1c–f). As was the case with the VT, participants respond either "yes" (an index finger press) or "no" (a middle finger press). As was the case in the VT, feedback regarding speed and accuracy was provided (see Fig. 1a–f).

Executive trials

Both the VT and the ST 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 et al., 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 vs. vowel, or left vs. 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." 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



(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

Fig. 1 Sample spatial locations and trial types for the non-verbal task no switching was required; these cues were referred to as "Form cues."

Trials immediately following Switch and Form cues are well 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; Kray, Li, & Lindenberger, 2002; Kray & Lindenberger, 2000). In this study, trials immediately following the Switch and Form cues were referred to as "Switch" and "Form" trials, respectively. All Switch and Form trials were incongruent, as were all trials immediately preceding Switch or Form cues (Fig. 2).

Second, to increase set maintenance demands, trial sequences were manipulated such that, some of the time, a series of approximately nine 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 lose set. 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) consist of a series of ten trials (i.e., nine congruent trials immediately followed by one incongruent trial; see Fig. 3 for a sample trial sequence). We have previously demonstrated that the single incongruent trial included within the Maintenance trials for this task is associated with an 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; Newman, Patterson, & Kosson, 1987; Newman, Schmitt, & Voss, 1997).

Comparison trials

The comparison trials (i.e., trials that placed fewer demands on executive systems) were comparable to executive trials in that they were incongruent (congruent trials were excluded from analyses), but they were not preceded by a cue and were not preceded by a series of congruent trials. See Fig. 1 for examples of Comparison trials.

Task parameters

Each task consisted of 249 trials (136 congruent and 113 incongruent). Only incongruent trials were used in the

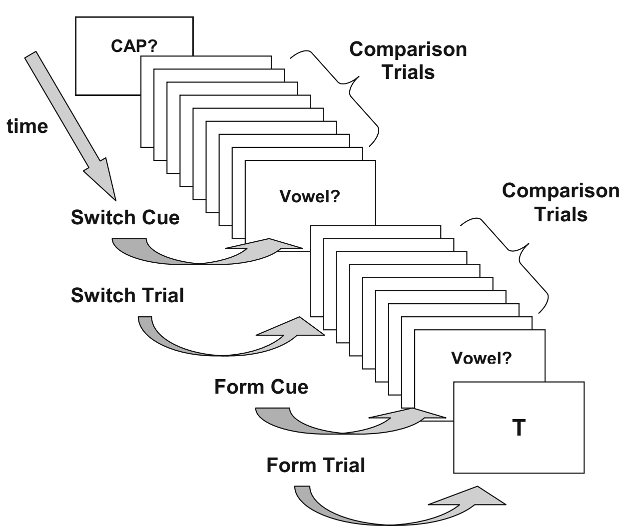


Fig. 2 Sample sequence of trials showing switch, form, and comparison trials

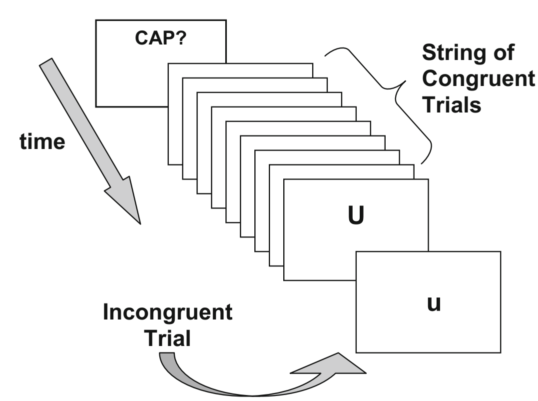


Fig. 3 Sample sequence of trials showing maintenance trials

analyses for Form, Switch, and Comparison trials; eight each of Form and Switch and 89 Comparison trials. Analyses for Maintain trials consisted of eight sets of ten consecutive trials: nine congruent trials followed immediately by one incongruent trial. The order of hemispheric manipulations (i.e., VT vs. ST) was randomized for each participant. Visual stimuli (i.e., letters) were black and were 1.75 in. tall. Letters were contained within squares that were 2.5 in. tall by 2.5 in. wide. Stimuli were presented on a neutral grey background. Each stimulus 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.

Model validation measures

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). A combination of a cued reaction time (Posner, Snyder, & Davidson, 1980) and flanker task (Eriksen & Eriksen, 1974), the ANT was designed to measure the efficiency of three attentional networks: alerting, orienting, and executive attention. Although the ANT was originally designed to examine the efficiency of attentional processes (i.e., via calculated difference scores using six primary stimulus conditions), researchers have increasingly relied on performance profiles across the six individual stimulus conditions to identify and characterize group differences (e.g., Adolfsdottir, Sorensen, & Lundervold, 2008; Gooding, Braun, & Studer, 2006; Johnson et al., 2008; Oberlin, Alford, & Marrocco, 2005). Both difference scores and individual condition scores were examined in this study.

Prior to calculating the attentional network scores, which are derived via difference scores, median reaction times (RTs) were calculated for each participant across six stimulus conditions on the basis of 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 stimulus conditions. Next, we generated arithmetical means of the median RT values so as to create the alerting, orienting, and executive attention scores, described below.

Alerting

The alerting 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). Consistent with published guidelines (Fan et al., 2002), alerting (i.e., the ability to distribute attention across two potential target locations) scores were calculated by subtracting the mean RT of the double-cue stimulus conditions from the mean RT of the no-cue stimulus conditions.

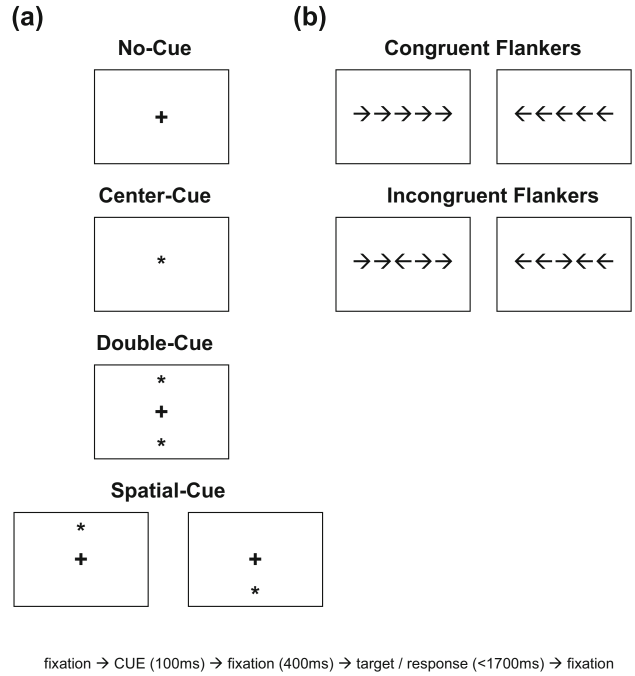


Fig. 4 Task conditions for the attention network task, showing: **a** the four cue conditions, **b** the three flanker/target conditions, and **c** the temporal sequence of a single trial

Orienting

The orienting 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). Consistent with published guidelines (Fan et al., 2002), orienting (i.e., how well attention is directed to task-relevant cues) scores were calculated by subtracting the mean RT of the spatial-cue stimulus conditions from the mean RT of the center-cue stimulus 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 medial 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; Stuss, Floden, Alexander, Levine, & Katz, 2001), 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. Consistent with published guidelines (Fan et al., 2002), executive attention (i.e., index of conflict monitoring) scores were calculated by subtracting the mean RT of all congruent flanker stimulus conditions from the mean of all incongruent flanker stimulus conditions.

ANT task parameters

The ANT consisted of 288 trials total, with the four cue conditions (i.e., no, center, double, spatial) consisting of 72 trials each 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 to 1600 ms. Figure 4 provides a visual schematic of task stimuli.

Procedure

Eligible participants underwent IRB-approved informed consent procedures. The verbal task (VT) and spatial task (ST) 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 was completed according to published guidelines (see Fan et al., 2002). All task stimuli were presented on a Gateway desktop computer with a 14 in. computer screen. Response latency and number of errors were recorded.

Data analysis

Modified switching task

Order effects Although task conditions were counterbalanced, an order effect was identified such that participants who began with the spatial task (ST) condition performed significantly more poorly on the ST trials relative to participants who began with the verbal task (VT) condition. To minimize this effect, we controlled for task order before calculating composite scores. This was done by performing a series of linear regressions, in which task order was used to predict the variable of interest (e.g., VT comparison trials) and unstandardized residuals were saved to reflect order-controlled values. We then used these order-controlled values when calculating the composite scores, described below.

Form, switch, and comparison scores We first computed the median response latency and the percentage of errors for each participant separately for VT and ST, and separately for Form, Switch, and Comparison trials. Next, we subtracted the Comparison trial values from the corresponding Form and Switch values (separately for percent errors and response latencies) to generate the Form and Switch cost variables for VT and ST. Last, because both speed and accuracy are indices of forming and switching mental set, composite scores were created by generating principal component scores from each corresponding set of latency and error values. In other words, separate scores were generated based on the tasks' hemispheric demands (i.e., VT vs. ST) and trial type (Comparison, Form cost, Switch cost). This resulted in a total of six final composite scores (i.e., VT-Comparison, VT-Form, VT-Switch, ST-Comparison, ST-Form, ST-Switch) that were used in the final analysis.

Set maintenance scores Maintenance scores were computed using only accuracy data, in line with our prior use of this task (Suchy & Kosson, 2006). First, we computed the percentage of errors for (a) the strings of nine consecutive congruent trials and (b) the immediately following incongruent trials, separately for VT and ST. Next, these percentage scores were entered into principal component analysis (PCA), producing two composite scores (i.e., VT-Maintain, ST-Maintain) that were used in the final analysis.

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. Although confirmatory factor analysis (CFA) and LPA are both used to explain the relationship between dependent variables, only LPA can identify subpopulations of participants on the basis of those relationships. More specifically, LPA is a maximum likelihood procedure that uses a latent mixture model and 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. For the purpose of the model identification phase of this study, designed to identify groups of participants on the basis of similar EF performance patterns, LPA allows continuous variation across EF performances and classifies participants into clusters on the basis of emergent patterns in task performance. LPA has the additional advantage of being model dependent and has the ability to test alternative models (e.g., variances and covariances differing across the groups, vs. 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 (VLMR; 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 VLMR and the aVLMR each provide comparative indices of model fit, with the null hypothesis being that the addition of an extra class provides no gain in data discrimination.

The LPA was performed on the 8 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 3 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 3 selected LPs. These parameters represent each latent profile's prevalence, the specific mean profiles, and the 95 % confidence intervals considered in the LPA model. 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.

Model identification results

Profiles of executive functioning

Significantly different ($p < 0.05$) 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 (Smithson, 2003). Parameter estimates for the latent profiles are provided in Table 2; profile means and corresponding CIs for all indices of executive functioning are provided in Fig. 5. In addition, we were interested in specific performances that fell outside of the average, or "normal," range. In clinical psychology, cognitive performances within 0.7 standard deviation (SD) of the population mean are considered "average" (e.g., IQ scores between 90 and 110; Wechsler, 2008). Thus, mean estimates that fell beyond $\pm$ 0.7 SD of the sample mean were interpreted as meaningful group strengths or weaknesses.

In the three-profile solution, the first class (Latent Profile 1: LP1) included the majority of the sample (203 participants; 71.5 % of the sample) and thus, not surprisingly, was characterized by scores that fell in the average range

Table 1 Goodness-of-fit statistics, and class frequencies for LPA models from 1 to 5 latent classes

	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 (%)[a]					
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)

LPA latent profile analysis, *LC* latent class, *Log-L (Ho)* log-likelihood of hypothesized model (Ho); *BIC* Bayesian information criteria (=−2 × model log-likelihood + log(n) × number of model parameters); *ssBIC* sample size-adjusted BIC, *VLMR* Vuong–Lo–Mendell–Rubin likelihood ratio test for *N*–1 vs. *N* classes, *aVLMR* adjusted VLMR

[a] Class frequencies based on each participant's most likely latent class membership

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

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

(^) Statistically significant ($p < 0.05$) refers to means that are mutually exclusive across LP 95 % CI ranges. Significant differences between LP1/AVG vs. (LP2/RHW, LP3/LHW) are italicized, differences between LP2/RHW vs. (LP1/AVG, LP3/LHW) are underlined; differences between LP3/LHW vs. (LP1/AVG, LP2/RHW) are bold-faced

AVG average group, *CT* comparison trials, *LHW* left hemisphere weakness group, *LP* latent profile, *RHW* right hemisphere weakness group, *ST* spatial task, *VT* verbal task

* Significant difference between LP2/RHW and LP3/LHW

(i.e., within 0.7 SD of the mean; see Fig. 5). Because LP1 was characterized as having normal EF abilities, participants classified according to LP1 were collectively referred to as the average (AVG) group. Within-group comparisons revealed that AVG group participants performed significantly better on set formation trials under VT conditions relative to ST conditions. The opposite pattern was observed on set maintenance trials, with significantly better performances observed under ST conditions compared to VT conditions.

The other two classes were noticeably smaller and demonstrated weaknesses relative to the overall sample (i.e., based on SDs) and the AVG group (i.e., based on CIs). The second class (LP2) consisted of 43 participants (15.1 % of the sample). These participants exhibited a relative weakness during the ST, particularly on comparison and maintenance trials, which fell well beyond 0.7 SD of the sample mean. LP2 performances on these trials were significantly poorer compared to LP2 performances on other types of trials, as well as compared to performances of other study participants (i.e., LP1 and LP3). Performance on VT comparison trials fell just below the 0.7 SD demarcation point, and were considered significantly poorer relative to LP1 and LP3 on the basis of CIs. In

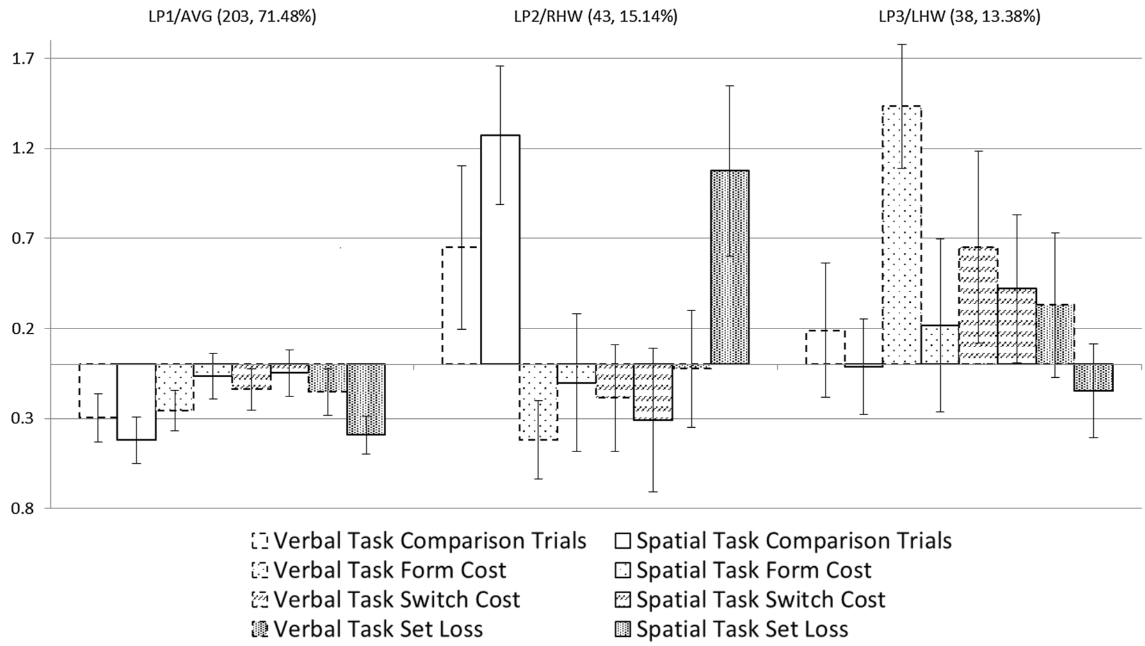


Fig. 5 Estimated means by cognitive marker for each latent class identified by the three profile solution. *Dotted outlines* represent performances under verbal task conditions, thought to tax left hemisphere resources. *Solid outlines* represent performances under spatial task conditions, thought to tax right hemisphere resources. *Error bars* indicate the 95 % CI around the mean. Two variables whose means fall outside of each other's confidence interval are interpreted as statistically significant at the 5 % probability level

contrast, participants in LP2 exhibited average (i.e., within 0.7 SD of the sample mean and statistically undifferentiated from LP1) performances across all forming and switching trials, regardless of VT or ST conditions. Consistent difficulties across comparison trials indicate that LP2 participants were both slower and less accurate on tasks involving low executive demand, suggesting a general weakness in attention and arousal. Difficulties with set maintenance under ST conditions only, combined with significant difficulties across comparison trials (especially those conducted under ST conditions), further suggests that maintaining cognitive set was difficult for LP2 participants, especially when the task also taxed right hemisphere resources. This combination of performances is consistent with weaknesses in the right cerebral hemisphere. Participants classified into LP2 were therefore collectively referred to as the right hemisphere weakness (RHW) group.

The third class (LP3) was the smallest (38 participants; 13.4 % of the sample) and demonstrated a near-inverted profile compared to LP2 (RHW group). Compared to the overall sample, LP3 participants exhibited a relative weakness during the VT, particularly on forming and switching trials. Under VT conditions, set formation fell well beyond the 0.7 SD demarcation for average performance, and switching performance fell on the cusp of this demarcation point. Examination of CIs, however, revealed a weakness on all switching trials regardless of VT or ST conditions (i.e., compared to LP1 and LP2), combined with a weakness across all executive tasks (forming, switching, maintaining) administered under VT conditions (i.e., when compared to LP1). Thus, Profile 3 was characterized by a global weakness on tasks requiring cognitive flexibility (i.e., switching) and a specific weakness on executive tasks that also challenged left hemisphere resources. This pattern of performances overlaps with the cognitive inflexibility syndrome characterizing a left cerebral hemisphere weakness. Participants classified according to LP3 were therefore referred to as the left hemisphere weakness (LHW) group.

Model identification: summary of results

Results from the model identification phase indicated that that a 3-class model provided the best fit, resulting in one large class characterized by generally average EF performances (LP1) and two smaller classes characterized by distinct patterns of EF weaknesses (LP2, LP3). Participants in LP2 exhibited a global weakness in attention and arousal combined with a set maintenance weakness, especially on trials with greater demand for right hemisphere resources (i.e., RHW group). Participants in LP3 exhibited a global weakness on tasks requiring cognitive flexibility and a specific weakness on executive trials posing greater demand on left hemisphere resources (i.e., LHW group). In other words, a relative weakness in right hemisphere processing was associated with a relative weakness in set maintenance, whereas a relative weakness in left hemisphere processing was associated with a relative weakness in cognitive flexibility. Taken together, individual differences in EF among healthy adults in this study supported the Hemispheric Asymmetry Model and argued against the Prefrontal Convexity Model.

Model validation results

To validate that the three latent profiles represent groups of individuals who meaningfully differ in their cognitive performance, we conducted a mixed model repeated measures analysis of variance using the ANT attentional network scores (i.e., alerting, orienting, and executive attention) as the dependent variables, ANT profile across the three ANT scores as a within-subjects factor, and latent profile classification (i.e., AVG, RHW, LHW) as the between-subjects factor. Each latent profile group yielded a different pattern of ANT performances, indicated by a significant interaction between latent profile classification and ANT performance ($F(4,554) = 5.938$, $p < 0.001$). As depicted by the interaction graph in Fig. 6, the AVG group was associated with balanced performances across the three attentional networks, whereas classification into either the RHW or LHW group resulted in distinct patterns of relative EF weaknesses. Consistent with hypotheses, participants classified into the RHW group demonstrated a relative weakness on the executive attention measure and participants classified into the LHW group demonstrated a relative weakness on the orienting measure. Contrary to predicted results, the LHW group was also characterized by relatively poorer alerting scores, whereas the RHW group demonstrated preserved alerting scores.

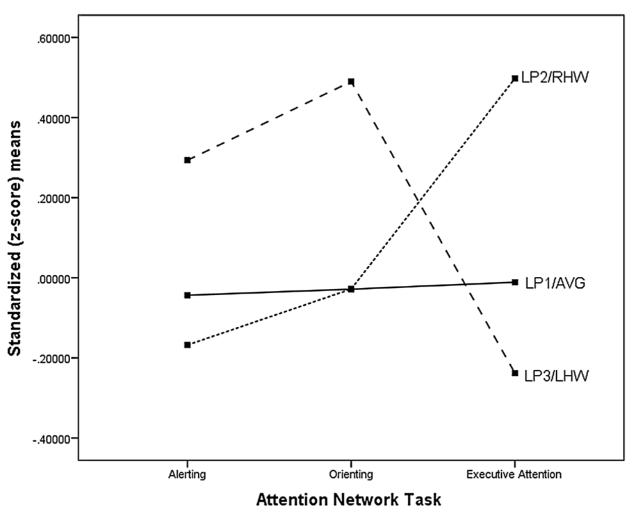
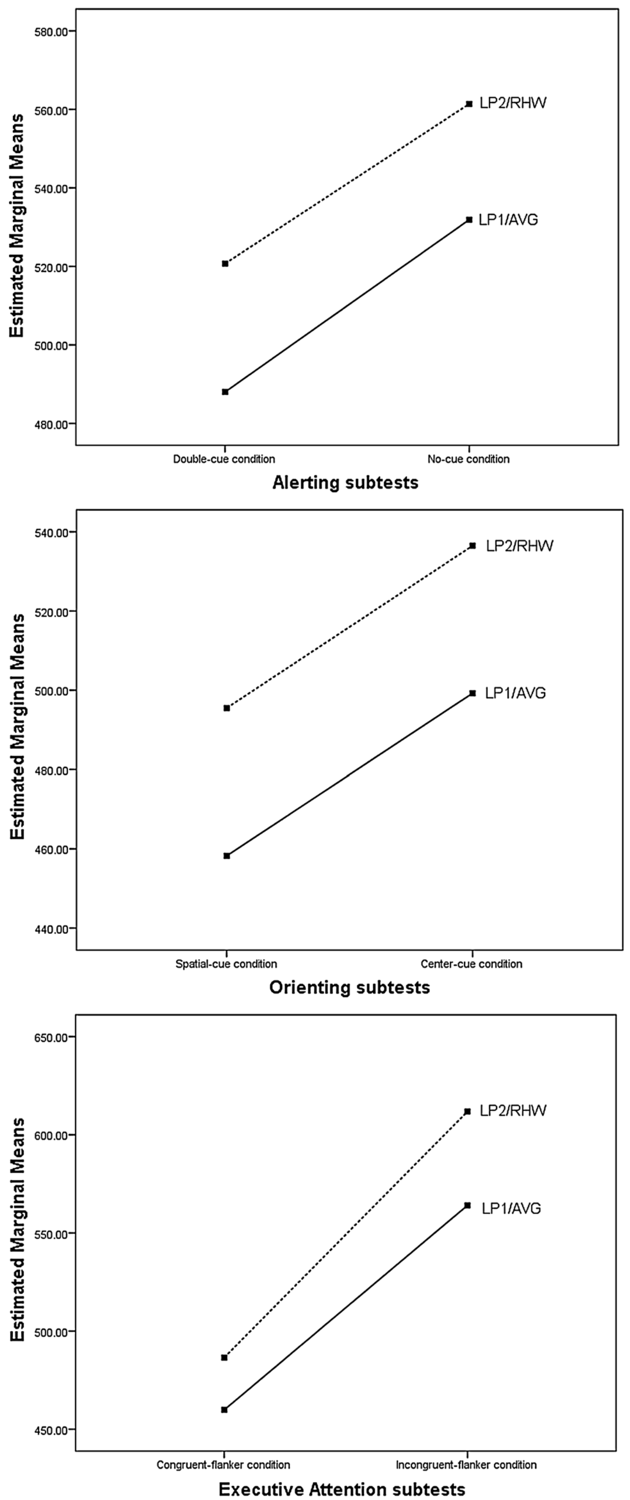


Fig. 6 Attention network task performance and latent profile (*LP*) classification. LP classification had different effects on ANT performances such that LP1/AVG classification was associated with balanced performances across the three attentional networks, LP2/RHW classification was associated with a weakness on executive attention, and LP3/LHW was associated with a weakness on alerting and orienting

To further elucidate these findings, we next examined performances across the six primary ANT stimulus conditions used to calculate attentional network scores. As a reminder, each attentional network score reflects a difference score between two stimulus conditions (i.e., alerting: no cue, double cue; orienting: center cue, spatial cue; executive attention: incongruent flanker, congruent flanker). For each pair of ANT stimulus conditions corresponding to the three attentional networks, we conducted a mixed model repeated measures analysis of variance using ANT stimulus condition pairs as the dependent variables, performance profile across the paired ANT stimulus conditions as the within-subjects factor, and latent profile classification (i.e., AVG, RHW, LHW) as the between-subjects factor. Results indicated that latent profile groups (i.e., AVG, RHW, LHW) demonstrated significantly different patterns of performance speeds across stimulus condition pairs for each attentional network [alerting stimulus conditions, $F(2,277) = 6.728$, $p = 0.001$; orienting stimulus conditions, $F(2,277) = 8.663$, $p < 0.001$; executive attention stimulus conditions, $F(2,277) = 7.835$, $p < 0.001$].

To further explicate these findings, follow-up analyses were conducted by comparing the RHW and LHW groups, in turn, to the AVG group across stimulus conditions pairs via two-factor analysis of variance. These analyses showed that, compared to the AVG group, the RHW group was consistently slower across stimulus conditions used to calculate both alerting scores (i.e., no cue, double cue), $F(1,241) = 13.742$, $p < 0.001$, and orienting scores (i.e., center cue, spatial cue), $F(1,241) = 18.358$, $p < 0.001$. In contrast, the RHW group did not differ from the AVG group with respect to the overall pattern of performances across stimulus conditions (i.e., relative difference between pairs of stimulus conditions) as indicated by non-significant interactions between latent profile group and stimulus condition: alerting, $F(1,241) = 0.665$, $p = 0.416$; orienting, $F(1,241) = 0.000$, $p = 0.998$. Thus, similar scores on alerting and orienting networks (i.e., obtained via stimulus condition difference scores) captured similar performance patterns but failed to detect significantly slower performances exhibited by the RHW group (Fig. 7a, b). On executive attention stimulus conditions (i.e., congruent vs. incongruent flankers), the RHW group was again substantially slower compared to the AVG group across stimulus conditions, $F(1,241) = 16.571$, $p < 0.001$. Slowed performances were especially noticeable on trials involving distractors (i.e., incongruent flanker) as indicated by a stimulus condition by latent profile group interaction,



◀**Fig. 7** Comparison of AVG and RHW group performances across attention network task stimulus conditions. **a** On alerting stimulus conditions, the RHW group performed significantly slower than the AVG group; both groups benefitted from temporal cues. **b** On orienting stimulus conditions, the RHW group performed significantly slower than the AVG group; both groups benefitted from spatial cues. **c** On executive attention stimulus conditions, the RHW group performed significantly slower than the AVG group, especially on trials involving the presence of distractors

$F(1,241) = 11.535$, $p = 0.001$ (Fig. 7c). Collectively, these findings indicate that the RHW group was consistently slower than the AVG group across ANT stimulus conditions, especially when faced with distracting stimuli. This pattern of performances suggests that the RHW group experienced difficulties with alertness, arousal, and maintaining mental set, consistent with a right hemisphere weakness.

Next, comparisons of LHW and AVG groups on alerting and orienting stimulus conditions indicated that LHW participants performed slower than AVG participants but only in the absence of task-relevant cues (Fig. 8a, b). As a reminder, alerting network scores are typically used to examine the effect of temporal cues (i.e., double-cue vs. no-cue conditions), whereas orienting network scores are typically used to examine the effect of spatial cues (i.e., spatial-cue vs. center-cue conditions). Although the LHW group did not differ from the AVG group with respect to overall performance speed [alerting, $F(1,235) = 1.755$, $p = 0.186$; orienting, $F(1,235) = 1.134$, $p = 0.288$], the LHW group performed more slowly on trials without assistive cues [stimulus condition × latent profile group interaction: alerting, $F(1,235) = 4.017$, $p = 0.046$; orienting, $F(1,235) = 9.657$, $p = 0.002$]. On executive attention stimulus conditions (i.e., congruent vs. incongruent flankers), LHW and AVG groups did not differ on the basis of overall performance speed, $F(1,235) = 0.920$, $p = 0.339$, or on the basis of particular stimulus conditions, $F(1,235) = 1.879$, $p = 0.172$ (Fig. 8c). Together these findings indicate that LHW participants became substantially slowed in the absence of assistive cues, suggesting difficulties with intrinsic cognitive flexibility, consistent with a left hemisphere weakness.

Model validation: summary of results

Results from the model validation phase are generally consistent with predictions. Participants belonging to the AVG group exhibited balanced performance across the three attentional network scores, RHW participants exhibited a relative weakness on the executive attention measure, and LHW participants exhibited a relative weakness on the orienting measure. Contrary to predictions, a relative weakness on the alerting measure was associated with the LHW group rather than the RHW group. However, closer examination of ANT stimulus conditions revealed that the RHW group was slower across all stimulus conditions, and the LHW group was slower on trials requiring intrinsic cognitive flexibility.

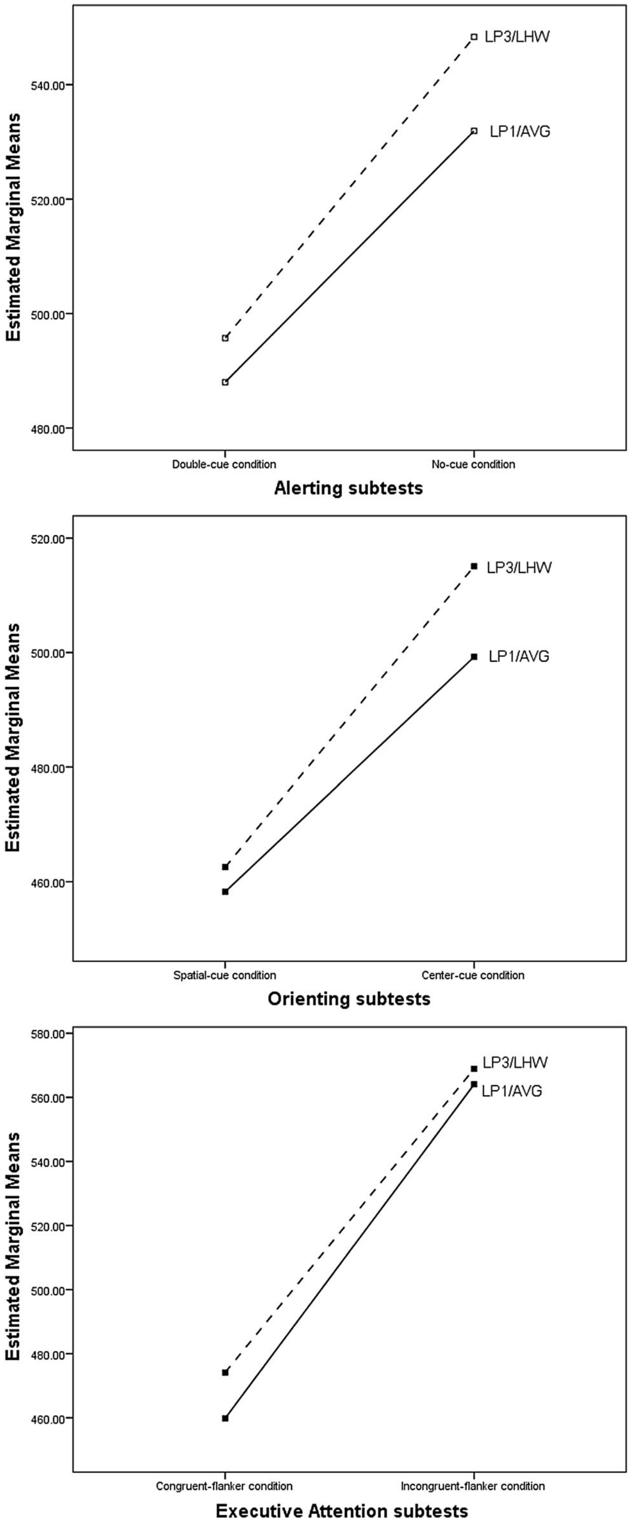


Fig. 8 Comparison of AVG and LHW group performances across attention network task stimulus conditions. **a** On alerting stimulus conditions, the LHW group performed slower than the AVG group in the absence of temporal cues. **b** On orienting stimulus conditions, the LHW group performed slower than the AVG group in the absence of spatial cues. **c** On executive attention stimulus conditions, the LHW and AVG groups performed similarly across trials

General discussion

The present study examined eight markers of neurocognitive function to identify profiles of executive functioning (EF) among healthy young adults. Study design involved administering an experimental cognitive task that assesses switching, forming, and maintaining mental set under conditions designed to tax the left and right cerebral hemispheres. Latent profile analysis was used to identify specific patterns of executive functioning. Three profiles emerged, suggesting that most individuals exhibit patterns of average EF, with slightly better ability to conceptualize task demands under left hemisphere conditions, and slightly better ability to sustain task-focused cognitions under right hemisphere conditions. Those with an EF weakness exhibited contrasting profiles suggesting difficulties with either cognitive organization and flexibility or self-monitoring, arousal, and attentional control, consistent with either a left or a right hemisphere weakness, respectively.

No executive weakness

Of the three profiles, only participants classified according to latent profile 1 (LP1) demonstrated good performances (i.e., no detected weaknesses) across tasks and hemispheric conditions (Fig. 5). Because LP1 was characterized as having normal EF abilities, LP1 participants were collectively referred to as the average (AVG) group. Interestingly, AVG participants appeared better able to form mental set when performing a verbal task and maintain mental set when performing a spatial task. This finding alone holds interest for several reasons.

First, the finding that performance was relatively better under conditions thought to preferentially activate separate cerebral hemispheres provides support for models emphasizing EF laterality. This interpretation rests on the notion of hemispheric arousal effects, in which selective hemispheric activation facilitates cognitive processes associated with that hemisphere (Almerigi, Carbary, & Harris, 2002). Numerous studies have demonstrated a left hemisphere specialization for processing fine-grained (i.e., closely related concepts) and verbal (i.e., letters, linguistic properties) information and a right hemisphere specialization for processing coarse (i.e., diffusely related concepts) and visual (i.e., objects, spatial location) information (Bedson & Turnbull, 2002; Keita & Bedoin, 2011; Keita, Bedoin, Burack, & Lepore, 2014; Loring, Meador, & Lee, 1989; Marsh, Pilgrim, & Sorqvist, 2013), further indicating that stimulus type is an important covariate in hemispheric asymmetries. Higher-order cognitive processes also appear to be lateralized, with greater left hemisphere involvement required for reasoning tasks (e.g., Goel, Gold, Kapur, & Houle, 1998; Langdon & Warrington, 2000) and greater right hemisphere involvement required for set maintenance tasks (e.g., D'Espositio et al., 1998; Prabhakaran, Narayanan, Zhao, & Gabrieli, 2000). From the standpoint of hemispheric arousal effects, better ability to form mental set under verbal conditions suggests that cognitive flexibility and reasoning abilities are governed primarily by the left hemisphere. Likewise, better ability to maintain mental set under spatial conditions suggests that attention and self-monitoring abilities are governed primarily by the right hemisphere.

The pattern of behavioral performances observed in this sample is particularly noteworthy given that localization of function is often inferred via neuroimaging studies. Asymmetries observed during set maintenance tasks are often interpreted as domain specific (Nagel, Herting, Maxwell, Bruno, & Far 2013; Smith & Jonides, 1997; Thomason et al., 2009; Smith et al., 1995), suggesting that behavioral performances on verbal and spatial set maintenance tasks should be roughly equivalent to each other. However, behavioral data from these neuroimaging studies and the current study suggest otherwise: individuals are both faster (Nagel et al., 2013; Thomason et al., 2009; Smith et al., 1995) and more accurate (Smith & Jonides, 1997; Smith et al., 1995) on set maintenance tasks performed under spatial compared to verbal task conditions. The lack of equivalent behavioral performances across task modalities argues against separate set maintenance subsystems and suggests that asymmetric activation reflects secondary processes within a broader, domain-general function.

The current study findings suggest that normal cognitive functioning involves a left hemisphere strength in reasoning and a right hemisphere strength in monitoring. Although adequate cognitive performance clearly requires the functional contribution of each hemisphere, cooperation between the two hemispheres is likely to be equally important for optimal cognitive functioning (Grimshaw, 1998; Kinsbourne, 1982; Osmon, 1996). As described below, performances observed with the remaining latent profile groups illustrate a distinct pattern in which a weakness in one domain is accompanied by relatively preserved abilities in the other domain, consistent with hemispherically lateralized EF weaknesses.

Right hemisphere weakness

Participants classified into latent profile 2 (LP2) demonstrated a significant global weakness across low executive demand tasks (i.e., comparison trials) with substantially worse performance on non-verbal compared to verbal comparison trials. On more cognitively demanding tasks, LP2 demonstrated significant set maintenance difficulties, again under non-verbal conditions (Fig. 5). In other words, difficulties with alertness and arousal were observed across low and high cognitive demand tasks but became particularly problematic during conditions that preferentially taxed right hemisphere resources, consistent with a right hemisphere weakness (RHW).

In the model validation phase, RHW participants experienced difficulty maintaining mental set in the presence of distractors (i.e., ANT executive attention measure; Fig. 6), but exhibited comparable alerting and orienting performances compared to the AVG group. Conversely, the AVG and RHW groups benefitted similarly (i.e., enhanced speed) from temporal and spatial cues, resulting in comparable alerting and orienting scores. As a reminder, the alerting and orienting measures reflect relative improvements in speed following either a temporal cue or a spatial cue, respectively. When the individual stimulus conditions were examined, however, the RHW group exhibited globally suppressed performance speeds across stimulus conditions (Fig. 7a, b). In other words, examination of ANT difference scores alone masked global difficulties with arousal and attentional vigilance exhibited by RHW participants. Performance speeds across executive attention stimulus conditions were also significantly slower relative to the AVG group, especially on trials that involved the presence of distractors (Fig. 7c). These findings are consistent with results hypothesized for the Hemispheric Asymmetry Model and provide additional support for a right hemisphere weakness.

The observed pattern of performances on the ANT is similar to those observed in a sample of recently acquired mild traumatic brain-injured (mTBI) patients (Halterman et al., 2006). Similar to the RHW group, mTBI patients were less able to disregard irrelevant distractors (i.e., executive attention) but equally able to benefit from temporal cues (i.e., alerting) compared to healthy controls. These findings are particularly relevant given that both mTBI and right hemisphere lesion patients exhibit prominent deficits in attention and processing speed despite differences in pathophysiology and severity (Mathia, Beall, & Bigler, 2004; Pare, Rabin, Fogel, & Pepin, 2009). Halterman et al. (2006) concluded that "…the mTBI investigated in the current study is not sufficient to produce substantial alterations in the participants' ability to maintain vigilance and/or arousal" (p. 752). Although this interpretation may be accurate, results from the current study indicate that difference scores alone may not adequately detect more subtle difficulties with maintaining vigilance and arousal across stimulus conditions.

Indeed, a handful of studies have begun to examine aspects of ANT performance beyond the traditional network scores. In one study, adults diagnosed with attention-deficit hyperactivity disorder (ADHD) combined type (i.e., inattentiveness combined with hyperactivity) were no different than healthy controls on the alerting network despite significantly slower performances across alerting stimulus conditions (Oberlin et al., 2005). Given that ADHD has been conceptualized as a right hemisphere deficit (Stefanatos & Wasserstein, 2001), the similarity of these performances to those observed with the RHW group further supports a right hemisphere weakness. These findings also underscore the importance of examining the primary stimulus conditions when investigating attentional processes with the ANT.

Left hemisphere weakness

Latent profile 3 (LP3) was characterized by a relative weakness across all executive tasks administered under verbal conditions. Examination of individual executive tasks revealed that the LHW group demonstrated significant difficulties on tasks requiring cognitive flexibility (i.e., forming, switching) (Fig. 5). Similarly, in the model validation phase, a relative weakness on the ANT orienting measure indicated that LHW participants experienced difficulty with cognitive flexibility, or the ability to quickly adapt to changing conditions (Fig. 6). Contrary to predicted results, however, LHW participants also exhibited a relative weakness on the ANT alerting measure.

Investigation of performance profiles on ANT alerting stimulus conditions revealed that the LHW group performed more slowly than the AVG group, but only on trials that did not provide timing information (i.e., double-cue conditions) (Fig. 7a). The LHW group also performed more slowly than the AVG group on orienting stimulus conditions that did not provide locating information (i.e., orienting network center-cue conditions) (Fig. 7b). Thus, relatively poorer orienting and alerting network scores for the LHW group appear to be driven by difficulty forming or switching mental set in the absence of spatial or temporal cues. We therefore interpreted poor performances on orienting and alerting measures as collectively reflecting cognitive inflexibility (i.e., intrinsic difficulty shifting attention).

Lesion and neuroimaging studies have demonstrated the importance of the left cerebral hemisphere for adequate performance on tasks requiring fluid cognitive functioning (Goel, Gold, Kapur, & Houle, 1997; Keele & Rafal, 2000; Ocklenburg et al., 2012; Rogers et al., 1998; Willis et al., 1979). What is less clear is whether cognitive flexibility better reflects a linguistic process or a more general executive control ability (Mecklinger et al., 1999), especially given the presence of large-scale language processing networks embedded within the LH (Vigneau et al., 2006). Evidence supporting a linguistic contribution has been provided by studies examining inner speech, a form of internally generated self-talk recruited during complex cognitive tasks and mediated by the LH (Morin & Michaud, 2007; McGuire et al., 1996). In neurologically healthy adults, increased switch costs are observed following articulatory suppression (Baddeley, Chincotta, & Adlam, 2001; Emerson & Miyake, 2003; Miyake, Emerson, Padilla, & Ahn, 2004), suggesting that inner speech is used to retrieve, activate, and manipulate task-relevant information. Clinical populations characterized by a LH weakness (e.g., autism) exhibit impaired inner speech which, in turn, is associated with poorer performance on problem solving and set switching tasks (Lidstone, Fernyhough, Meins, & Whitehouse, 2009; Wallace, Silvers, Martin, & Kenworthy, 2009). Because inner speech is often used to internalize task instructions and guide mental planning (Sokolov, 1972), novel tasks—especially those with a language component—may increase reliance on inner speech until a more procedural representation is established through practice (Monsell, 2003).

Research examining task cues also supports a link between linguistic processes and cognitive flexibility. LH lesion patients perform better when provided with external cues, but become "helpless" (Luria & Tsvetkova, 1967) and unable to spontaneously self-cue (Fasotti, Bremer, & Eling, 1992) in the absence of external cues. Neuroimaging studies with neurologically healthy individuals show increased LH activation in response to a task cue, a pattern that is also associated with improved behavioral responding (Brass & von Cramon, 2002). Evidence that external cues recruit LH resources, activate task schema, and facilitate task-relevant behavior is consistent with the performance profile exhibited by the LHW group (i.e., normal performance under cued conditions only).

Limitations

The three-profile solution obtained in the model identification phase must be interpreted with caution. Although fit statistics informed stopping at a three-profile solution, these findings should be replicated in different samples. Whereas generalizability of the current findings to older populations is limited, the age of the sample used in this study is less concerning considering that these results provide some indication of EF in "normal" adults and that most experimental cognitive research is conducted with individuals of similar age and demographic features (i.e., undergraduate college students).

It is unclear whether additional confounding factors may be contributing to the profiles of EF weakness characterizing two smaller classes. For example, it is possible that not all participants reached complete cortical brain maturation by the time of this study, based on evidence of late phase brain development as late as early adulthood (Paus et al., 2001). Thus, despite evidence of EF stability beginning in early adulthood (Miyake & Friedman, 2012), what we are interpreting as innate weaknesses in EF could reflect maturational differences that may become less noticeable with time. It is also possible that the profiles of EF weaknesses observed in this study reflect underlying differences in general intelligence (Barbey et al., 2012). The ability to control for general intelligence could illustrate the extent to which these profiles reflect functionally specialized executive processes vs. more broadly distributed cognitive operations.

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 hemispheres, respectively, are thought to play a dominant role in certain cognitive functions, both hemispheres are likely to be jointly involved to some degree with discrete EFs. Some evidence suggests that hemispheric dominances influence initial responding, but that bilateral networks are recruited as needed for successful task completion (Ocklenburg, Guentuerkuen, & Beste, 2011).

Interhemispheric compensation and cooperation may help to explain conflicting empirical reports. For example, our results indicated that participants with a left hemisphere weakness performed more poorly than average participants on orienting and executive attention measures, suggesting a LH bias on these tasks. In contrast, Asanowicz et al. (2012) found a left visual field (LVF) advantage for orienting and executive attention, suggesting a RH bias on these tasks. Note, however, that mechanisms involved with both attention (i.e., right hemisphere) and cognitive flexibility (i.e., left hemisphere) are recruited during orienting and executive attention trials. Therefore, it is possible that a left hemisphere weakness interferes with initial sensory processing (i.e., those involved with flexibly orienting attention or resolving conflict) required to trigger and recruit right hemisphere attentional processes. Thus, it should not be concluded that set maintenance is governed solely by the right hemisphere and set switching is governed solely by the left hemisphere. Instead, considering the relative contribution of each hemisphere on a given task is important for accurate interpretation of results.

Further, although we attempted to control for the effects of handedness by including only right-hand-dominant participants, reliance on the dominant hand for task completion limits interpretation of the hemispheric asymmetry model to some degree. Functional evidence indicates that handedness can index functional brain asymmetries, including language lateralization and facilitation/inhibition of sensorimotor processes, and may be implicated in frontal lobe asymmetries. There is also evidence that hand location can account for hemispheric asymmetries in response monitoring processes for spatial information (Stock, Wascher, & Beste, 2013; Stock & Beste, 2014). Without administering these cognitive tasks under non-dominant and crossed hand conditions, the effect of handedness (i.e., dominance, spatial location) cannot be entirely controlled. In addition, it is possible that not all participants in this study were LH dominant for language. Although all participants were healthy right handers based on self-report (i.e., “Which hand is your dominant, or writing, hand?”), research suggests RH language dominance exists in 4–15 % of right-handed individuals (Knecht et al., 2000a) depending on the strength of handedness (Knecht et al., 2000b). Consequently, what we are interpreting as a lateralized EF weakness could instead reflect differences in typical vs. atypical language dominance.

Last, specific neuropsychiatric conditions including undiagnosed clinical depression or attention-deficit hyperactivity disorder could be responsible for the small number of individuals characterized as having either left or right cerebral hemisphere weakness. Regardless of these potential confounds, it is also possible that a small percentage of the population experiences similar profiles of weaknesses.

Future directions

Future research examining profiles of EF should continue to examine the validity, reliability, and clinical implications of current findings. For example, administering the present research paradigm to patients with either left or right hemisphere lesions could prove valuable for informing existing research. Alternatively, replicating the current study with tasks modified to more closely examine hemispheric contributions could validate current findings and further characterize the nature and frequency of hemispheric weaknesses. Task paradigms such as the Lateralized Attention Network Task (Greene et al., 2008) and tachistoscopically administered switching tasks (e.g., Ocklenburg et al., 2012) illustrate possible methods for assessing laterality in healthy populations. Future research should also include a more thorough assessment of handedness; excluding participants who exhibit a low laterality quotient on the Edinburgh Handedness Inventory (Oldfield, 1971), for example, would reduce language dominance as a potential confound. Conditions involving the non-dominant hand, as well as crossed hand paradigms, could further rule out potential confounds and clarify laterality.

Investigating similar markers in a more demographically diverse population of neurologically healthy adults could also substantiate these findings and provide evidence of reliability and generalizability. 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, including links to early temperament and personality development. 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.

Conclusion

The results obtained in this study provide support for the Hemispheric Asymmetry Model and suggest that hemispherically mediated patterns of executive dysfunction observed in clinical populations may also exist within neurologically healthy populations. Based on neurodevelopmental processes, hemispherically mediated patterns of cognitive weakness are to be expected. Diffuse cortical activity observed during childhood becomes more localized with age and experience, reflecting increased functional specialization and efficiency over the course of normal human development (Durston et al., 2006; Scherf, Sweeney, & Luna, 2006; Stiles, Moses, Passarotti, Dick, & Buxton, 2003). Early signs of hemispheric asymmetry begin to emerge during adolescence (Nagel et al., 2013), and variations in hemispheric strengths or weaknesses may manifest as specific profiles of executive strengths and weakness (Gur, 1980). In turn, top-down executive processes can override or modify bottom-up hemispheric asymmetries (Takio, Koivisto, & Hamalainen, 2014), a curvilinear process that changes as a function of age (Takio et al., 2009). Given the bidirectional link between neurobiological processes and individual differences factors (i.e., temperament, personality), this suggests that hemispheric strengths or weaknesses could also impact psychobiological health outcomes. For example, a recent review suggests that individual differences in executive functioning have important implications for stress regulation (Williams, Suchy, & Rau, 2009). In addition, several studies have reported links between hemispheric asymmetries and differences in emotional style, personality, and self-regulation (Davidson 1992; Hagemann et al., 1999; Hardman et al., 1997; Sackeim, 1978; Tomarken & Keener, 1998; Tucker & Williamson, 1984). Investigating the relationship between hemispherically mediated executive functions and other individual difference factors known to confer health risk or resilience could inform numerous disciplines within the field of psychology.

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