Children's Hospital of Philadelphia

What Are Executive Functions and How Are They Related to ADHD?

This supplemental handout provides an overview of executive functioning, what skills are considered executive functions, and how EFs are related to ADHD.

What are Executive Functions?

Executive functions are those uniquely human abilities that allow us to set and accomplish goals.

Most researchers and clinicians who study executive functions (EFs) would agree with this very general statement, but after well over 100 years of research, there is still no single definition (reviewed in Barkley, 2012). However, there is wide-spread recognition of the importance of EFs in the outcome of individuals with ADHD (Yang, et al., 2022). In order to make progress in intervention, parents and providers in education, pediatrics, psychiatry, and psychology need a common understanding of EFs and a common language for discussing them.

The concept of EFs came from observations of the role of the prefrontal cortex (PFC) in thinking and behavior. This was based on animal models and human examples of PFC injury (Welsh & Pennington, 1988). Individuals with PFC injury were noted to be hyperactive and easily distracted, to have irrelevant thoughts and reduced ability for intentional action, and to have lost the ability to accurately evaluate their own behavior (reviewed in Barkley, 2012). Pribram (1973) was the first to refer to the PFC as "the executive" brain. Over time, clinical and functional imaging studies have shown that a broader network of brain regions is required for the demonstration of EF, though the prefrontal system seems to play a central role (Stuss & Alexander, 2000).

There is general agreement on three core EFs (Miyake, et al., 2000; reviewed in Miyake & Friedman, 2012). These are:

- inhibition,
- set-shifting or cognitive flexibility, and
- updating (or incorporating new information into) working memory (working memory=holding information in mind while completing a task)

These three core EFs have also been identified in typically-developing children (Lehto, et al, 2003; Rose, et al, 2011). Barkley's model of EF in ADHD includes 4 components: working memory, self-regulation of affect, motivation, and arousal, internal speech, and behavior reconstitution (analysis and synthesis) (1997). Pennington and Ozonoff's model (1996) included planning and fluency in addition to the three core EFs.

As many as 33 different components have been considered EFs by different authors (Eslinger, 1996,) including:

- the complex act of purposefully maintaining attention to accomplish a task, while overcoming competing stimuli (also referred to as sustained attention or vigilance (Willcutt, et al., 2005), or executive attention (Anderson, 2008; Brown**,** 2008; Nigg, 2017)
- self-monitoring and utilization of feedback for strategy revision (Pennington & Ozonoff, 1996; Anderson, 2008),

- initiation (Anderson, 2008) or anticipatory set/ preparedness to act (Denkla, 1996; Fuster, 1989)
- interference control- the precursor to inhibition (Willcutt, et al., 2005)
- planning
  - Planning is typically present in some form in discussions of EF (a strategic plan of action sequences, strategy selection, sequencing of behavior), though some authors include it among higher cognitive functions along with organization, reasoning, problem-solving, and meta-cognition that may require combinations of EFs (Borkowski & Burke, 1996; Diamond, 2013).

The components described above are considered the more thinking-related or "cool" EFs. Some authors include another set of characteristics under the EF umbrella that involve emotion or feeling-related processes, known as "hot" EFs. In this framework, "hot" EFs include

- motivation,
- the ability to delay gratification (Borkowski & Burke, 1996; Sonuga-Barke, 2002, 2003, 2005; Welsh & Peterson, 2014), and
- making decisions that involve emotions (Salehinejad, et al., 2021)

There is general agreement that there is no central or primary EF- these are distinct, though related processes (reviewed in Anderson, 2002; Friedman, et al., 2008; Stuss & Alexander, 2000). "Cool" and "hot" EFs arise from different, but closely-related pathways in the brain, and individuals with ADHD may have different levels of dysfunction in these pathways (Sonuga-Barke, 2002). In all models, EF requires "top down" processing, that is, thoughts generated at higher levels of the nervous system that re transmitted "down" to the lower parts of the nervous system that direct the behavior response. This is in contrast to "bottom up" processing, which starts with information perceived at lower levels of the nervous system, e.g. the sensory system, that is transmitted "up" the nervous system to be interpreted and acted upon after thought at higher levels (Nigg, 2017).

Many authors agree that EFs overlap with other cognitive characteristics including:

- Meta-cognition-"thinking about thinking" (reviewed in Hayes, et al., 1996)
- Self-regulation-the ongoing, dynamic, and adaptive modulation of cognition, action and emotion (reviewed in Barkley, 2012; Denckla, 1996; Nigg, 2017)
- Emotional regulation (a subset of self-regulation)- the ability to modulate the intensity or duration of emotional states (reviewed in Bunford, et al., 2015; Christiansen, et al., 2019; Nigg, 2017)
- Cognitive control or effortful control- the ability to use "top down" thinking in to achieve self-regulation.
- Executive aspects of attention and working memory are important in these broader skills. Nigg, 2017; Tiego, et al., 2019)

In addition, other cognitive processes that are not typically considered EFs, are important in their measurement and performance. These include:

- praxis- the process required to put a thought into action; a medical term for motor planning (American Psychological Association).
    - There is a relationship between motor and EF function (reviewed in Remigereau, et al., 2018).
    - Denckla (1996) describes the following skills as related to both praxis and EF: anticipatory set, preparedness to act, freedom from interference, delay in responding, and the ability to construct a logical sequence of behavior.
- internal language- Self-directed, or "internal" language is widely considered to be an important mediator of EF.
    - It requires adequate verbal working memory and inhibition which allows delayed responding. This gives an individual time to consider all options (Denckla, 1996).
- automaticity (typically described as fluency, processing speed, and/ or reaction time)
    - Delayed reaction time is one component of slow processing speed. Reaction time is sometimes used as a measure of processing speed, however, there is a trade-off between speed and accuracy, so accuracy must be considered when measuring speed (Halperin, 1996).
    - Slow processing adds an additional burden to working memory.

Although there are multiple different descriptions, the components most commonly included in EF research include inhibition; working memory (verbal and visual); sustained attention; self-regulation; set-maintenance and set-shifting (cognitive flexibility); planning; organization; task analysis; the selection, monitoring and revising of behavioral strategies; and output efficiency (reviewed in Eslinger, 1996).

The Relationship Between ADHD and EF

As a group, individuals (children and adults) with ADHD consistently don't perform as well as those without ADHD on either

- EF rating scales (Barkley & Fischer, 2011; Barkley & Murphy 2010a, 2010b; Biederman, et al., 2008; Davidson, et al., 2016; Hummer, et al., 2010; Krieger & Amador-Campos, 2017; Mahone, et al., 2002a; Mahone & Hoffman, 2007; McCandless & O'Loughlin, 2007; Toplak, et al., 2009) or
- neuropsychological tests of EF (Davidson, et al., 2016; Krieger & Amador-Campos, 2017; Nigg, et al., 2005; Scheres, et al., 2004, Sergeant, et al., 2002; Willcutt, et al., 2005)

The variability within both ADHD and non-ADHD groups makes these EF measures alone insufficient for use as a diagnostic tool for ADHD. Not all individuals with ADHD have EF dysfunction and not all non-ADHD individuals are free of them, though levels of EF dysfunction tend to be lower in the non-ADHD group (Biederman, et al., 2008; Castellanos, et al., 2006; Nigg, et al., 2005; Vaidya, et al., 2020). Several, but not all studies have shown weaknesses in inhibitory control, working memory, and planning in subjects with ADHD (Kofman, et al., 2008; Martinussen, et al., 2005; Nigg, et al., 2002; Nigg, 2005; Sonuga-Barke, 2002).

Rating scales are generally better than neuropsychological tests at differentiating those with ADHD from those without ADHD (Davidson, et al., 2016; Dehili, et al., 2017; Krieger & Amador-Campos, 2017; McCandless & O'Loughlin, 2007) perhaps, in part, due to the influence of ADHD-related behavior symptoms on ratings of EF (Biederman, et al., 2008; Mahone, et al, 2002a). In children with ADHD followed into adulthood, EF ratings are also better predictors than EF tests of impairment in major life activities, including occupational functioning (Barkley & Fischer, 2011; Barkley & Murphy, 2010a, 2010b).

Given the increased frequency of EF dysfunction in individuals with ADHD, whether by test or rating scale, it is reasonable to question whether ADHD is primarily the "external" manifestation of underlying executive dysfunction. A great deal of research has focused on the overlap of executive skills and ADHD symptoms. There is substantial, but not 100% overlap (Castellanos, et al., 2006; Linder, et al, 2010; Willcut et al., 2005), depending on how each is measured, as well as how intellectual ability (Mahone et al, 2002) and non-EF cognitive processing characteristics (Castellanos et al, 2006) are accounted for on test performance. A substantial body of research suggests that EF dysfunction is a major underlying feature of ADHD, but not the only one (Boonstra, et al., 2005; Duff & Sulla, 2015; Willcut, et al., 2005).

EF Deficits in ADHD

In the 1990s, Barkley described the intersection of ADHD and EF as stemming from the core feature of inhibition and limitations in the ability to delay responding (reviewed in Barkley, 1997). He theorized that working memory, self-regulation (of affect, motivation and arousal), internalization of speech, and the analysis and synthesis of behavior all required inhibitory ability.

Studies often use go-no go tests (particularly the Stop task) in which children have to inhibit responding to a particular stimulus when they have been primed to respond to similar ones, to study problems with inhibition in ADHD. Results show longer reaction times to the Stop signal in ADHD, however, they also show slower reaction times to the Go signal, and more reaction time variability to both Go and Stop signals (Alderson, et al., 2008; Lijffijt, et al., 2005; reviewed in Castellanos et al, 2006). These findings are likely due to more than just deficient inhibition, and may include problems with stimulus anticipation, response preparation, speed of stimulus processing, and holding instructions in mind.

Inhibition may be the most commonly studied EF in ADHD, but the largest differences between those with ADHD and controls are on tests of spatial working memory. In a meta-analysis of working memory studies in children with ADHD, Martinussen, et al. (2005), identified weaknesses in both verbal and spatial working memory, and in both simple storage and manipulation of information, regardless of language and general intellectual ability.

In the early 2000s, motivational processes and resultant delay aversion were proposed to play a primary role in at least some individuals with ADHD (reviewed in Sonuga-Barke, 2005). The dual pathway model of ADHD, based on the concept of the "hot"(inhibition, motivation, and delay aversion) and "cool"(executive attention, working memory, planning) EFs is now widely accepted, given the important role of motivation deficits in many individuals with ADHD.

- Cool EF dysfunction is typically related to inattention while hot EF dysfunction is related to hyperactivity and impulsivity (Denkla, 1996, p 264; Sonuga-Barke, 2002, 2003; Zelazo & Carlson, 2012).

- The hot and cool EFs are similarly responsible for functional impairments in ADHD (Castellanos, et al., 2006; Sagvolden, et al., 2005; Sonuga-Barke, et al., 2002, 2003;, Toplak, et al., 2005; Zelazo & Carlson, 2012, Zelazo & Muller, 2002).
- Behavioral inhibition is more consistently characteristic of the combined, rather than inattentive presentation of ADHD (Riccio, et al., 2006).
- Otherwise, EF characteristics do not appear to separate by ADHD presentation (Geurts, et al., 2005) or gender (Seidman,et al., 2005).

Non-EF Processing Characteristics in ADHD

Slow processing speed, delayed reaction time, reaction time variability, problems with the estimation of time, and arousal dysregulation are common findings in individuals with ADHD. Deficits in response speed are commonly present in ADHD, most notably in the inattentive presentation (Solanto, et al, et al., 2007).

- Slow processing speed negatively impacts the degree of response to behavioral intervention in children with ADHD-I, even when baseline severity of symptoms is taken into account (Adalio, et al., 2018).
- Rose, et al. (2011) found that while the EFs updating working memory, inhibition, and shifting are important in math and reading achievement in formerly premature infants at the age of 11 years, processing speed was an important factor for academic achievement.
- Children, adolescents, and adults have slower and more variable reaction times than non-ADHD controls. Children, but not adolescents or adults with ADHD are only slightly more variable than clinical control groups, so this characteristic is not unique to ADHD. Reaction time variability largely accounted for findings of slow processing speed (slow mean reaction time) (Kofler, et al., 2013). It has also been suggested that slower and more variable reaction time helps to explain the behavioral inhibition deficits of children with ADHD on the classic neuropsychological measure of deficient inhibition, the stop signal task (Alderson, et al., 2008; Senderecka, et al., 2012).
- On a go/no go task, reaction time could be lowered and rendered less variable with incentives in the ADHD, but not control group, suggesting that motivation could uniquely affect this characteristic in the context of ADHD (Uebel, et al., 2010).

Temporal processing deficits are additional non-EF cognitive characteristics that are common in ADHD.

- Aspects of time processing that have been studied include the ability to discriminate different durations of time, to determine whether or not two stimuli are separated by time, to estimate the duration of a stimulus, to predict the onset of a stimulus, and to tap (fingers) at a specified rate.
- Temporal processing requires attention and memory, is associated with attention and EFD, particularly sustained attention, working memory, and inhibition (reviewed in Toplak, et al., 2006).

Sergeant (2005) describes a cognitive-energetic model of ADHD that included an "energy factor" consisting of effort, arousal, and activation to provide the substrate for the cognitive and executive processes.

- This model suggests that ADHD could result not only from the failure of cognitive or executive processes, but also failure of the energy systems designed to support them.
- Cognitive-energetic dysregulation refers to the potential for imbalance in either direction (under- or over-arousal) between the top-down (cortical) cognitive/ executive control systems and the bottom up (subcortical) arousal/activation ("energetic") systems (Mahone & Denkla, 2017).

Sluggish cognitive tempo (SCT) was historically considered by some authors to be a subtype of the inattentive presentation of ADHD, however, more recent research indicates that it is psychometrically distinct, though often associated (reviewed in Becker, et al., 2016). It is currently also called cognitive disengagement syndrome (Fredrick & Becker, 2023a&b).

- It may be a clinical example of the under-arousal hypothesis.
- It is characterized by excessive daydreaming, mental fogginess, hypoactivity, lethargy, mental confusion, and apathy or low motivation.
- SCT has been associated with deficits in both processing speed and arousal (reviewed in Becker & Willcutt, 2019).
- Several studies indicate that it is also associated with elevated rates of symptoms of anxiety and depression, social dysfunction/social withdrawl, and academic and executive impairments (Fredrick & Becker, 2023a&b; reviewed in Mueller, et al., 2014).
- In college students, SCT is associated with poorer study skills and daily life EFs, even when controlling for overall level of symptoms of ADHD, anxiety and depression (Flannery, et al., 2017).

Many authors emphasize the role of language ability, internal language, verbal self-regulation, and or verbal working memory in maintaining rule-governed behavior by functioning as an intermediary between stimulus and response (Denkla, 1996; Hayes, et al., 1996) or by serving as an aid to the retrieval of task-relevant information (Miyake, et al., 2004).

Finally, children with ADHD have greater praxis deficits than controls, even when controlling for impulsivity Romero-Ayuso, et al., 2020).

In summary, EF dysfunction is important, but as currently defined, only one of several categories of cognitive characteristics that impact functioning in individuals with ADHD. What is clear is that the DSM core features of ADHD (inattention, distractibility, impulsivity, overactivity) do not alone account for the broader features that cause impairment for children with ADHD. Executive dysfunction clearly warrants our attention, but so does the "larger circle" of cognitive characteristics that may or may not be included under the rubric of EF. Additional cognitive features such as motivation / gratification delay, self-regulation, contribute to the cognitive underpinnings of ADHD. Additional cognitive characteristics related to signal detection, processing speed, response time variability, sense of time, and praxis clearly exist in ADHD, although we may know less about their impact on daily function. And finally, children vary with respect to the degree of each of these characteristics they exhibit, which is also true for TD children. EF, as well as these additional characteristics cannot be ignored if we are to understand and ameliorate the barriers to success for children with ADHD.

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