HANDBOOK OF CLINICAL NEUROLOGY

Series Editors

MICHAEL J. AMINOFF, FRANÇOIS BOLLER, AND DICK F. SWAAB

VOLUME 173

ELSEVIER

Handbook of Clinical Neurology, Vol. 173 (3rd series)
Neurocognitive Development: Normative Development
A. Gallagher, C. Bulteau, D. Cohen and J.L. Michaud, Editors
https://doi.org/10.1016/B978-0-444-64150-2.00020-4

Chapter 19

Executive functions

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Abstract

First, executive functions are defined. Then the development of executive functions in children, from infancy to 10–11 years of age, is briefly described. The relation between the speed of processing and the development of executive functions is addressed. Finally, tools and pointers for evaluating executive functioning in younger and older children are discussed. A cautionary note is sounded, in that almost no executive function measure requires only one executive function. A child might fail a working memory task because of problems with inhibitory control (not working memory), fail an inhibitory control task because of working memory problems, or fail a cognitive flexibility, planning, or reasoning task because of problems with inhibitory control or working memory.

DEFINITION OF EXECUTIVE FUNCTIONS

Executive functions (EFs) are a family of top-down mental processes that make it possible for us to pay attention and stay focused; reason and problem solve; exercise choice, discipline, and the self-control to avoid being impulsive, rash, or reacting without thinking; see things from different perspectives; mentally consider alternatives, see how different ideas or facts relate to one another, and reflect on the past or consider an imagined future; and flexibly adjust to change or new information (Jacques and Marcovitch, 2010; Diamond, 2013; Zelazo et al., 2016). EFs are recruited when it would be ill-advised, insufficient, or impossible to go on autopilot or rely on instinct or intuition, such as when presented with novel, unanticipated challenges.

Using EFs is effortful. It is not easy to manipulate numbers, facts, or ideas in your head. It is easier to give into temptations than to resist them. It is easier to continue doing what you have been doing than to change or to put thought into what to do next. It only makes sense, therefore, to reduce the demands on one's EFs as much as possible. It makes sense to write down notes rather than try to hold everything in your head. It makes sense to avoid situations where you will be strongly tempted rather than taxing your willpower.

There are three core EFs—working memory (WM), inhibitory control, and cognitive flexibility—and each is composed of two subparts. *WM* involves actively holding information in mind and mentally working with that information, i.e., mentally working with information that is not perceptually present (Baddeley and Hitch, 1994; Smith and Jonides, 1999; Kent, 2016). WM is critical, e.g., for making sense of anything you read or hear spoken that is longer than a word or two—for you have to hold in mind what you read or heard earlier and relate that to what you are reading or hearing now. WM is critical for doing any mental calculations or mentally playing with ideas or possibilities. Those "aha" moments when you suddenly see how one thing relates to another happen are made possible by your working memory ability. The subparts of WM refer to content area. Thus, there is verbal WM and visuospatial WM.

Some people define WM as holding information in mind while mentally working on either that material

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or any other, or the ability to actively hold information in mind in the face of interference or distraction (Engle and Kane, 2004; Unsworth and Engle, 2007; D'Esposito and Postle, 2015). WM conceived of in this way includes holding in mind a question or comment you want to raise while following what is being said. Here you are not mentally manipulating that question or comment (you are just holding it mind) but while doing that you are actively processing other information. There is agreement that holding information in mind without actively processing that or other information or inhibiting distraction, is short-term memory, not WM.

Inhibitory control involves being able to control one's attention, behavior, thoughts, or emotions to override a strong internal predisposition or external lure, and instead do what you intend to do (Simpson et al., 2012; Wiebe et al., 2012; Diamond, 2013; Watson and Bell, 2013). Thus, it involves resisting a strong inclination to do one thing and, instead, doing what is most needed or appropriate (Diamond, 2011). The two subcomponents of inhibitory control are (a) self-control or response inhibition and (b) interference control. Self-control involves control over one's behavior and control over one's emotions in the service of controlling one's behavior. Self-control is about suppressing a dominant response, or one's first impulse, and giving a more appropriate response instead. The strong inclination might be, for example, to cut in line, grab what you want without asking or paying, reflexively striking back at someone who has hurt your feelings, or blurting out the first thing that comes to mind. Self-control is the opposite of acting impulsively, thinking instead before you speak or act so you do not do something you might regret, waiting before rushing to judgment. It also includes the discipline to stay on task and complete what you started, resisting all the temptations to quit, even if the reward might be a long time in coming.

The subcomponent of interference control involves controlling one's attention and thoughts. At the level of attention it is selective attention, resisting distractions in the environment and sustaining one's focus, as one might need to do in a noisy restaurant or when singing in a round (Driver, 2001). At the level of cognitive inhibition it is resisting internal distraction, such as extraneous or unwanted thoughts, resisting mind-wandering (Anderson and Levy, 2009; Swallwood and Schooler, 2015; Keulers and Jonkman, 2019). When WM is defined as staying focused on what one is holding mind and resisting distractions, it immediately becomes apparent how it is the internal counterpart to selective attention, which involves staying focused on something in the external world and resisting distractions. The close connections and interactions between WM and selective attention, both at the behavioral and neural levels, have been widely documented (Awh et al., 2005; Nobre and Stokes, 2011; Gazzaley and Nobre, 2012; de Fockert, 2013).

Inhibitory control is critical for avoiding social faux pas and for a civil society where people abide by rules and norms (Diamond and Ling, 2016). Choice would not be possible were we not able to resist, at least partially, the pull of external stimuli, our emotions, or old habits of thought or behavior. Without inhibitory control, we would be at the mercy of external stimuli, internal urges, and old habits of thought or action. Inhibitory control makes it possible for us to choose (i.e., exercise voluntary control over) how we react and to change how we behave rather than being "unthinking" creatures of habit or impulse (Diamond, 2013). It does not make it easy, but it makes it possible.

The third core EF, *cognitive flexibility*, is also referred to as set shifting or mental flexibility. One subcomponent of cognitive flexibility is switching between different tasks or mindsets, seeing something from different perspectives, e.g., when you shift from thinking about the economic consequences of an event to thinking about the human consequences or when you shift from thinking about someone's flaws to thinking about that person's virtues or hardships. The other aspect of cognitive flexibility is quickly and flexibly adjusting to change, such as accommodating to a sudden change of topic or finding an alternative route to your goal when the path you intended to take is blocked. The opposite of cognitive flexibility is cognitive rigidity, not being able to see another way of looking at things or being unable to accommodate to change. Alexander Graham Bell gave us an example of poor cognitive flexibility when he said, "When one door closes, another door opens, but we often look so long and so regretfully upon the closed door, that we do not see the ones which open for us."

From these three core EFs, higher-order EFs are built such as reasoning, problem solving, and planning (Collins and Koechlin, 2012; Lunt et al., 2012). Reasoning and problem solving are essentially what fluid intelligence is, and the correlation between WM and fluid intelligence is extremely high (Fry and Hale, 2000; Kane and Engle, 2002; Chen and Li, 2007; Fukuda et al., 2010; Duncan et al., 2012). Thus, fluid intelligence could be considered a higher-order EF.

A distinction is often made between hot and cool EFs (Zelazo and Carlson, 2012). Hot refers to situations where EFs are needed in a situation where emotions are high, where you really care about the outcome. Cool refers to situations that are more affectively neutral. Cool EFs seem to be more predictive of academic achievement (Brock et al., 2009) whereas hot EFs are more predictive of behavior in socially charged situations (Conner et al., 2008; Kim et al., 2013), although this distinction is not cut and dry. Cool EFs are often impaired in children with serious behavior problems (Hughes et al., 2000) and adults who show deviant behavior (Morgan and Lilienfeld, 2000).

EFs are critical for success in school and in life, physical and mental health, and social harmony (Wong et al., 2010; Miller et al., 2011; Moffitt et al., 2011; Wolfe et al., 2016). EFs are sometimes more predictive of these than are IQ or socioeconomic status (Duckworth and Seligman, 2005; Moffitt et al., 2011). It is difficult to think of any aspect of life where it would not be beneficial to have the presence of mind to give a considered response rather than an impulsive one, be able to stay focused despite distraction, and resist temptations to do inappropriate, ill-advised, self-destructive, or illegal things. Indeed, Hendry et al. (2016) call EFs "the cognitive toolkit of success."

EFs depend on prefrontal cortex and other brain regions with which it is interconnected, such as the anterior cingulate cortex and parietal cortex (Braver et al., 2002; Petrides, 2005; Aron, 2007; Leh et al., 2010; Zanto et al., 2011; Niendam et al., 2012; Takeuchi et al., 2012; McTeague et al., 2017). Prefrontal cortex was the last brain region to evolve and takes the longest to fully mature (Fuster, 1997; Luna et al., 2004; Waxer and Morton, 2011). It is perhaps the most plastic region of the brain. One example of that neuroplasticity is that prefrontal cortex, and the EFs that depend on it, is particularly vulnerable to the damaging effects of environmental factors such as stress, loneliness, or poverty (Baumeister et al., 2002; Cerqueira et al., 2007; Cacioppo and Patrick, 2008; Arnsten et al., 2015; Hackman et al., 2015; Harms et al., 2018). Another example of the neuroplasticity of prefrontal cortex is that EFs can be improved throughout life, from infancy to very old age (Williams and Lord, 1997; Kramer et al., 1999; Diamond et al., 2007; Kovács and Mehler, 2009; Taylor-Piliae et al., 2010; Diamond and Lee, 2011; Wass et al., 2011; Brehmer et al., 2012; Röthlisberger et al., 2012; Tennstedt and Unverzagt, 2013; Stepankova et al., 2014; Gothe and McAuley, 2015; Schonert-Reichl et al., 2015; Lind et al., 2018; Diamond & Ling, 2020).

DEVELOPMENT OF EXECUTIVE FUNCTIONS IN CHILDREN

Infancy (0–2 years)

Just because prefrontal cortex takes a very long time (2 decades) to fully mature does not mean that it is not maturing rapidly during infancy. Indeed, it may show more rapid development during infancy than during any other period of life, and it begins during that period to organize and direct diverse cortical developments elsewhere in the brain (Hodel, 2018).

Visual violation of expectation paradigms have demonstrated that infants as young as 3½–5 months can maintain and update representations of hidden objects (Wynn, 1992; Koechlin et al., 1997; Aguiar and Baillargeon, 2002). By 8–9 months, mental updating abilities extend to more complex calculations (Aguiar and Baillargeon, 1998; Huntley-Fenner et al., 2002; Káldy and Leslie, 2003).

Evidence of planning, WM, inhibitory control, and cognitive flexibility can already be seen in infants' reaching behavior in the second half of the first year of life. Evidence of these can be seen months earlier in infants' looking behavior. Over 80 years ago, Piaget (1954 [1936]) identified the first signs of what we today would call EFs in infants 8–12 months old (Sensorimotor Stage 4). When infants reach for a desired object, it is hard to tell if the external stimulus elicited an automatic reach or the intention was internally generated. However, when an infant searches for an object that is out of sight or acts on an object of no particular interest to obtain a desired object, then Piaget was willing to infer that intentionality was present and the action sequence had been truly goal-directed (i.e., executively controlled). As Piaget pointed out, the emergence of acting on one object to obtain another is also an example of creativity in that it involves adapting behavior (reaching and grasping) for an entirely new end (to obtain not the object of the action, but as a means to obtaining a hidden or distant object). Piaget also took such means–end behavior to indicate planning, since infants seem to intentionally act on the covering or supporting object with the plan that this will make available the object they want.

Thirty years ago, Diamond (1988, 1990a,b, 1991a,b) similarly identified 7–12 months of age as when "cognitive functions dependent on prefrontal cortex" were first evident in infants' reaching behavior. She showed that infants are able to hold in mind where a desired object has been hidden for progressively longer periods, and are able to inhibit repeating a previously rewarded reach that would now be wrong. That work, using the A-not-B paradigm, has since been greatly elaborated upon by many others, e.g., by providing further evidence of the demand on inhibitory control in the task (Hofstadter and Reznick, 1996) and showing that by using looking rather than reaching similar advances can be detected a few months earlier (Cuevas and Bell, 2010), whereas using walking rather than reaching, similar advances are not detected until a few months later (Berger, 2004), and by progressively increasing the delay, advances on the task can be charted throughout the preschool period (Espy et al., 1999). Holmboe et al. (2008) found that the 9-month-old infants' ability to inhibit looking to peripheral distractors was positively correlated with their performance on the A-not-B task.

Diamond also documented the emergence of detour reaching between 6 and 12 months of age—first around an opaque barrier and then around a transparent one (Diamond, 1988, 1990b,a, 1991b). Detour reaching requires holding a goal in mind, planning, and inhibiting the strong tendency to reach straight for the goal. Indeed, it requires reaching away from the goal object at the outset of the reach. Obviously, a detour reach requires more inhibition when the goal is visible than when it is not, hence detouring around a transparent barrier appears later. To come up with the plan of first reaching to the opening and then to the desired object, infants must grasp the connection between the opening and the desired object, even though these are spatially displaced. Indeed, the farther they are spatially displaced from one another the later in the first year are infants able to come up with, and execute, the plan of reaching to the opening to obtain what they want.

Some effects of experience on EFs are already observable during infancy. Beneficial experiences accelerate how early EF achievements are seen. For example, the benefits of bilingual exposure are evident in better inhibitory control and ability to switch responses at 7–8 months of age (Kovács and Mehler, 2009). Early life stress is well known to produce EF deficits in children, adolescents, and adults (Mueller et al., 2010; Pechtel and Pizzagalli, 2011; Duckworth et al., 2013). The earliest observed effect on EFs has been 2.5 years of age in children who were exposed to horrific neglect in Romanian orphanages (Hostinar et al., 2012).

Preschool period (2–5 years of age)

Children of 2–3 years are marked by notable rigidity; there is only one right way of doing things, one way to look at things, one correct name for a thing, and so on. The transition from 3 to 5 years of age is a period of dramatic improvements in inhibitory control and cognitive flexibility, especially flexibility in changing perspectives. These cognitive advances are expressed in social cognition—theory of mind (Wimmer and Perner, 1983), moral development (Kohlberg, 1963)—and on cognitive tasks such as the dimensional change card sort task (DCCS) (Zelazo et al., 1995), Shape School (Espy, 1997; Clark et al., 2013), ambiguous figures (Gopnik and Rosati, 2001), appearance-reality (Flavell et al., 1986), false belief (Perner et al., 1987), Luria's tapping and hand tasks (Diamond and Taylor, 1996; Hughes, 1998), the day–night Stroop task (Gerstadt et al., 1994), and the grass/snow Stroop task (Carlson and Moses, 2001).

For example, an ambiguous figure can appear to be one thing (such as a duck or an old woman) from one perspective and something quite different from another perspective (perhaps a rabbit or a young woman). Even when informed of the alternatives in an ambiguous figure, children of 3 years remain stuck in their initial way of perceiving the figure; they cannot see the image from the other perspective (Gopnik and Rosati, 2001). When a child of 3 years is presented with a sponge that looks like a rock, the child will usually insist it looks like a rock and really is a rock, or occasionally that it looks a sponge and really is a sponge; but it cannot be both (Flavell, 1986, 1993). By 4–5 years of age, children pass such ambiguous figure and appearance-reality tasks.

At 2–2½ years of age, most children can do within-dimension switching (also called reversal learning); e.g., learning first that reaching for the card with a boat instead of a truck is always rewarded, and then learning that the reward contingencies have reversed so reaching for the truck is always rewarded and never the boat (Hughes and Ensor, 2005) or switching from the boats always go in Bin A and the trucks always go in Bin B to the trucks go in Bin A and the boats go in Bin B (Perner and Lang, 2002; Brooks et al., 2003). The ability to switch stimulus–response mappings (as in reversal tasks), without needing to change what aspect of a stimulus (e.g., shape or color) is relevant develops earlier than the ability to change how the stimuli are thought of or change what aspect of the stimuli one is attending to. By 3½–4 years of age, most children can switch from sorting by color to sorting by shape if, and if, color and shape are not properties of the same thing (e.g., the cards are red or blue and the shape on the cards is a black truck or a black boat). That is, they can do card sorting if the dimensions they need to use are separated on the cards (Diamond et al., 2005; Kloo and Perner, 2005). At 4½–5 years, for the first time, children can switch from thinking about something one way (e.g., as a truck) to thinking about it another way (e.g., as something that is blue), and thus they can succeed at the DCCS task (Zelazo, 2006). Flexibly switching back and forth randomly comes in later, but a simple single switch from always sorting by color or shape to always sorting by the other is within the ability of most 4½–5 year olds.

From a different perspective, all of the above tasks can be thought of as taxing inhibitory control in that they require inhibiting a strong perceptual pull (as in conservation, appearance-reality, or Stroop-type tasks), inhibiting a way of thinking about the game or the stimuli that the child has been successfully using (as in card sorting, Shape School, or interpreting ambiguous figures), or inhibiting the answer that the child knows is correct in order to report what someone else would say or what he himself had said earlier (as in theory of mind or false belief tasks). Thus, for example, children can succeed earlier at appearance-reality tasks if the stimuli are out of sight when the child is queried (Heberle et al., 1999) so the strong perceptual pull to give the wrong answer is absent. They succeed earlier on the DCCS task if the cards are sorted face down, reducing the perceptual pull to continue sorting by the previously correct dimension (Kirkham et al., 2003).

Other tasks that do not have an element of switching perspectives, but place high demands on inhibitory control, are also able to detect marked developmental improvements between 3 and 5 years of age, such as the Simple Simon task (Reed et al., 1984; Jones et al., 2003), bear/dragon task (Reed et al., 1984), less is more task (Carlson et al., 2005), and the windows task (Russell et al., 1991). For example, it takes inhibitory control to point to the lesser amount of candy to get the greater amount because of course the child wants to point at what he or she really wants (the greater amount of candy). Not surprisingly, if the perceptual pull is less intense, so that the number of candies is represented by a number and the child sees the number two vs the number five rather than two candies vs five candies, more children are able to succeed at a younger age.

Toddlers and preschoolers will often fail a task, on which they otherwise would have succeeded, when irrelevant information, which they should just ignore, is added (Diamond, 1991b; Brooks et al., 2003; Zelazo et al., 2003; Richland et al., 2006). They often try to hold too much in mind so that, for example, babies of 12 months can find a toy they see hidden at the right or left, but toddlers cannot find a toy they see hidden in a container and watch the container being moved to the right or left, though the memory load should be the same (the toy is at the right or left). Duncan et al. (2008) have found that in adults this inefficient use of one's mental workspace, by holding too much information or irrelevant information in mind, characterized most participants in their study whose fluid intelligence score was more than one standard deviation below the population mean and almost no one whose fluid intelligence score was above the mean.

Children of 2–4 years of age show a marked lack of planfulness. For example, they show reactive inhibitory control (exercising inhibitory control when the situation calls for it at that moment) but not proactive inhibitory control (planfully exercising inhibitory control in preparation for when the situation will require it; Chatham et al., 2009; Munakata et al., 2012; Chevalier et al., 2013; Chevalier et al., 2015; Doebel et al., 2017). An initial shift from reactive to proactive control appears between 5 and 8 years of age. Another example of a lack of planfulness can be seen if a game requires uncovering two cards that match. Instead of first turning over a new card and then finding its match from cards they have previously turned over, children of 2–3 years will start with a card they had previously turned over (Mir et al., in prep.).

There is a fair bit of evidence to suggest that WM and inhibitory control are not differentiated during the preschool period and become increasingly differentiated during primary school (Senn et al., 2004; Wiebe et al., 2008, 2011; Hughes et al., 2010; Shing et al., 2010; Willoughby et al., 2010, 2012; Mungas et al., 2013). For example, Shing and colleagues found that the correlations between WM and inhibitory control were 0.98 in children 4–7 years old, 0.81 in children 7–9½ years old, and 0.32 in children 9½–14½ years old. Such findings are consistent with Johnson's (2011) emphasis on early brain development as reflecting experience-dependent neural specialization. More recent studies, however, have concluded that even in preschool-age children EFs are best characterized by the two-factor model in which inhibitory control and WM are dissociable (Miller et al., 2012; Schoemaker et al., 2012; Gandolfi et al., 2014; Garon et al., 2014; Lerner and Lonigan, 2014; Mulder et al., 2014; Usai et al., 2014; Skogan et al., 2016).

Middle childhood (6–11 years of age)

Improvements in inhibitory control, WM, cognitive flexibility, and planning are all evident during the early school years.

Many teachers and educators assume that if children know what they should do, they will do it. Therefore, not solving a problem correctly or not behaving properly is thought to indicate either ignorance, lack of understanding, or willful misbehavior and defiance. However, young children can fail tests or not behave correctly not because they do not understand the concepts or are choosing to be defiant, but because they lack the inhibitory control to demonstrate their understanding on the tests or to behave in accord with what they know to be correct. An example of the kind of cognitive challenge that requires inhibitory control in school subjects is whether to use a singular or plural verb when the subject of a sentence is "the friends of my brother" or "the dog of the neighbors." Another example is whether to add or subtract when told, "James has 20 stickers. He has 5 more than Ryan. How many stickers does Ryan have?" or "Betsy, who is 10 years old, is 4 years older than Emily. How old is Emily?" Here the relational terms ("more than" or "older than") suggest addition when the correct operation is really subtraction. Houdé, Borst, and their colleagues have shown that when the inhibitory demand is reduced, children are more successful at such problems (Lubin et al., 2013; Houdé and Borst, 2015; Cassotti et al., 2016).

Another example of improved inhibitory control during middle childhood, is improved performance on the antisaccade task. On that task, as soon as a target appears, participants are to look in the opposite direction. This requires inhibiting the strong tendency to look toward a target—the response that is correct on prosaccade trials. Children can barely do this at all until they are 6–7 years old and improve dramatically over the next few years, not reaching peak performance until their early 20s (Munoz et al., 1998; Luna et al., 2004; Luna, 2009).

Inhibitory control is disproportionately difficult for young children compared to adults. For example, the difference in both the speed and accuracy of children's performance at all ages from 4 to 9 between (a) always responding on the same side as a stimulus (the Heart Block) and (b) inhibiting that prepotent tendency and always responding on the side opposite of a stimulus (the Flower Block) of the Hearts and Flowers task is greater than the difference in their speed or accuracy for (a) holding two stimulus–response associations in mind vs (b) holding six stimulus–response associations in mind (Davidson et al., 2006). That is true whether the same-side trials come before or after the opposite-side ones (Wright and Diamond, 2014). The reverse is true for adults. It is far harder for us to hold six associations in mind rather than only two, but it is no harder for us to always respond on the side opposite a stimulus than to always respond on the same side as a stimulus (our speed and accuracy for each are equivalent; Lu and Proctor, 1995; Davidson et al., 2006). Inhibitory control continues to mature during adolescence.

Marked improvements in WM are consistently seen between 5 and 11 years of age on complex span tasks that require updating and/or manipulating information held in mind under high-interference conditions requiring interference control, such as the counting span and spatial span tasks (Case et al., 1982). A meta-analysis by Case (1992) of 12 cross-sectional studies showed remarkably similar developmental progressions on both of those complex span tasks. Continuous and marked improvements are seen from 4½ to 8 years, with more gradual improvement thereafter. The pattern span task is similar to the spatial span. The child gets a quick look at the pattern of shaded cells in a matrix. At the test, one of the cells that had been shaded is now unshaded and the child is to point to that cell. Performance on the pattern span task improves greatly between 5 and 11 years of age, when it starts to plateau (Wilson et al., 1987; Miles et al., 1996). The listening span task (Daneman and Carpenter, 1980) requires processing spoken sentences while retaining, in correct temporal order, the last word of each preceding sentence. Performance on this improves from 6 years until at least 15 years and probably longer (Siegel, 1994).

Improvements in cognitive flexibility (set shifting) are seen during this period on the Wisconsin Card Sort Test (WCST) and on task-switching paradigms. The WCST is one of the classic tests of prefrontal cortex function in adults (Stuss et al., 2000). Participants must deduce the sorting criterion, which can be color, shape, or number, and must flexibly switch sorting rules when the sorting criterion changes without warning, based on the feedback they receive on their sorting. Children improve on the WCST from 5 to 11 years, though they do not reach adult levels until perhaps 20 years of age (Chelune and Baer, 1986; Chelune and Thompson, 1987; Welsh et al., 1991; Rosselli and Ardila, 1993).

Task-switching requires a participant to flexibly switch back and forth between two rule sets and two sets of response mappings. In a paradigm devised by Meiran (1996), participants must indicate whether a cue is in the left or right half of a square or the top or bottom half of the square, one key being used to indicate left or top and the other to indicate right or down. On this task, by 4 years, children can begin to switch back and forth, but only poorly. The cost of having to switch back and forth declines continuously through at least age 11. Even at 11 years, children showed more of a reduction in speed and accuracy when required to switch back and forth (compared to single-task blocks) than do adults (Cohen et al., 2001).

Another task-switching paradigm that has been used with children requires that they switch between identifying whether the stimulus display contains a 1 or a 3 (Task A), and whether the number of digits displayed is 1 or 3 (Task B). Hence, for Task A, the correct response to a stimulus display of "1 1 1" is one, but for Task B for the same display the correct response is three. As on Meiran's task, participants are cued about which task to do on each trial. Cepeda et al. (2001) found that performance was better at 10–12 years than at 7–9 years, but that children do not reach peak levels until the early 20s. Crone et al. (2006) found that children of 7 or 8 years show a greater cost than adults on trials where the task switches but the site of the correct response does not, though the age difference decreases with more time between trials.

Planning and organizational skills develop rapidly between 7 and 10 years of age (Krikorian et al., 1994; Anderson et al., 1996) and continue improving more gradually through adolescence (Welsh et al., 1991; Krikorian et al., 1994). Young children utilize simple strategies that are usually inefficient, haphazard, or fragmented, but between 7 and 11 years strategic behavior becomes more systematic, organized, and efficient (Waber and Holmes, 1985; Levin et al., 1991; Anderson et al., 2001). Early work by Piaget (1976) showed school-age children not performing very well on versions of the Tower of Hanoi. Subsequent research has confirmed that performance on tower tasks follows a protracted developmental course. Developmental improvements on the Tower of London have been described between 4 and 12 years by Luciana and Nelson (1998), between 6 and 13 years by Injoque-Ricle et al. (2014) and between 7 and 12 years by Culbertson and Zillmer (1998).

Speed of processing and developmental improvements in EFs

The relation between speed of processing and EF performance is strong and well replicated (Duncan et al., 1995; Fry and Hale, 1996; Salthouse, 2005). Processing speed increases markedly throughout infancy and childhood and then improves more gradually until early adulthood (Rose et al., 1982, 1989, 2003, 2012; Kail, 1991; Fry and Hale, 1996; Miller and Vernon, 1997).

Individual differences in processing speed emerge in early infancy and those differences, already at 5–7 months of age, predict later EFs. Rose et al. (2012) found that differences in processing speed at 7–12 months (e.g., time needed to process a stimulus as indicated by mean look duration) predicted performance on WM and set-shifting tasks at 11 years of age. Cuevas and Bell (2013) found that those infants, who at 5 months, had a faster speed of processing (as indicated by needing to look at novel stimuli a shorter time) exhibited better EFs throughout early childhood (at 2, 3, and 4 years of age).

Age-related improvements in speed of processing are highly correlated with developmental improvements on complex span tasks in school-age children (Case et al., 1982; Kail, 1992; Hitch et al., 2001) and individual differences in speed are highly correlated with WM capacity as assessed by complex span tasks (Fry and Hale, 1996). The empirical relation between performance on complex span tasks and speed of processing might be due to any number of reasons. Faster processing might make better WM possible. Items would not need to be held in mind as long. The faster people can repeat back the word they just heard, the more words they can hold in mind. As the speed of word repetition improves, so too does word-span memory. When the speed at which adults and 6-year-olds can repeat back words is equated by presenting adults with unfamiliar words, children and adults show equivalent word-span memory (Case et al., 1982). Similarly, when the speed at which adults and children can count is equated by requiring adults to count in a foreign language, equivalent counting span memory is found in adults and 6-year-olds. Individuals who have shorter naming times (within and between ages) have larger memory spans. People can generally name a digit faster than a word, and people generally have larger spans for digits than for words. Similarly, words can usually be identified faster than pictures, and people generally have larger spans for words than pictures (Mackworth, 1963). Item recognition speed also improves with age (Samuels et al., 1975–1976; Chi, 1977) and the speed of item identification is related to the number of items (span) that can be held in mind and retrieved (Dempster, 1981).

EVALUATION OF EXECUTIVE FUNCTIONING IN CHILDREN

It is always important to remember that any test or assessment is an imperfect indicator of the underlying ability it is intended to assess. Queried one way a child might look impaired, while when queried a different way the child might show advanced ability. Low scores on any assessment measure can be obtained for any number of reasons other than a problem with the ability one intended to assess. Difficulties on EF tasks may reflect an EF impairment, but might also reflect an impairment in vision, hearing, speed of processing, or attention, or occur because the child did not understand what was being asked of him or her, got little sleep the night before, was preoccupied with something else, or has been experiencing stress. It is extremely important to bear in mind that stress can cause any child to looks as if he or she has an EF impairment (like ADHD) when that is not the case. A case history should always be taken and severe stress should be ruled out before diagnosing ADHD.

As mentioned earlier, problems with inhibitory control can cause children to look like as if they have a problem with any of the other EFs or are intentionally misbehaving when that is not the case. Development proceeds both from the acquisition of skills and from the increasing ability to inhibit inappropriate reactions that can get in the way of demonstrating skills already present. Between knowing the right answer or knowing what correct behavior entails and demonstrating that in one's behavior, another step, long ignored, is often needed. When a strong competing response is present, that response needs to be inhibited. Adults do not always appreciate how inordinately difficult inhibitory control can be for young children because it is so much less difficult for us adults (Davidson et al., 2006).

Almost no EF measure requires only one EF. A child might fail a WM task because of problems with inhibitory control (not WM), fail an inhibitory control task because of WM problems, or fail a cognitive flexibility, planning, or reasoning task because of problems with inhibitory control or WM.

Since neuropsychologic assessments are typically done in settings with minimal distraction and with the examiner providing support and encouragement, continually bringing the child back to the task (Shordone, 2000), a child with EF problems, especially problems with distractibility and not staying on task, might look fine and show few EF problems from that assessment when serious EF problems are indeed present.

Most objective measures of EFs use laboratory-based measures unrelated to real life. Parent and teacher rating scales, on the other hand, are subjective and vulnerable to diverse biases, such as different meanings of the scale scores to different respondents, but they have the advantage of being related to real life. Mischel's delay of gratification task is a measure of children's ability to strategize to circumvent inhibitory demands rather than a measure of inhibitory control, and children who trust adults to keep their word are more likely to wait than children who have learned adults cannot be trusted, independent of any difference in EFs (Callan et al., 2009;

Michaelson et al., 2013; Michaelson and Munakata, 2016). Most measures of delay discounting for children ask children what they would do in a hypothetical situation. That is very different from actually foregoing a small reward now for a larger one later in a real situation.

Some people still refer to one or another test of short-term memory as a test of WM, which is incorrect. Forward digit span requires only holding information in mind and, therefore, is not a measure of WM. Backward digit span or reordering digit span ("Say the numbers back in numerical order") *are* tests of WM. It is unfortunate that the WISC-IV combines scores for forward and backward digit span. Forward spatial span (like the Corsi Block task) requires only holding information in mind and, therefore, is not a measure of WM. If a masking stimulus is used on each trial between stimulus presentations and when a response can be made, then the task would fit the definition of WM as holding information in mind and exercising interference control (see the first section above).

For children 2–5 years of age, the new Minnesota Executive Function Scale (MEFS) (Carlson, 2017) looks promising. It is computerized, easy to administer, short, is beginning to accumulate substantial normative data, and includes reversal, separated-dimensions card sorting, and the dimensional change card sort, referred to earlier, among other measures. Another widely used behavioral scale that goes down to the preschool range is the NEPSY (Korkman, 1988; Stinnett et al., 2002; Scherrer, 2018). Other objective behavioral scales of EFs for the preschool period that have been used primarily by those who developed them are Shape School (Espy, 1997; Clark et al., 2013), a novel EF battery for preschoolers (Garon et al., 2014), and an EF test battery for 2-year-olds (Mulder et al., 2014).

For children 4½–6 years of age, the Head–Toes–Knees–Shoulders (HTKS) task provides a fun way of assessing inhibitory control and cognitive flexibility through a movement game somewhat akin to Simon Says. McClelland et al. (2014) found that it predicted growth in mathematics over four time points between prekindergarten and kindergarten. HTKS has recently been adapted for work with older adults (Cerino et al., 2018).

For parent report, the Behavior Rating Inventory of Executive Function–Preschool Version (BRIEF-P) (Isquith et al., 2005; Gioia et al., 2008; Duku and Vaillancourt, 2014; Garon et al., 2016; Skogan et al., 2016), for children 2–5½ years old, is the most widely used, is norm-referenced, and has the most research backing. For children 6 and older, the same can be said for the Behavior Rating Inventory of Executive Function (BRIEF) (Gioia et al., 2000, 2015; Isquith et al., 2013, 2014; Jiménez and Lucas-Molina, 2018). The Childhood Executive Functioning Inventory (CHEXI) is another questionnaire measure of EFs that can be used for children aged 4–12 (Thorell and Nyberg, 2008; Thorell et al., 2010; Catale et al., 2013). Although not as widely used or researched as the BRIEF, the CHEXI is relatively short (26 items), has been translated into multiple languages, and is free.

For school-age children, the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001, 2004) is the best behavioral battery in my opinion. It is norm-referenced with nine verbal and nonverbal EF tasks that are appropriate for use with children and adults (age 8–89 years). It is nuanced and tries to get at why a child is performing at one level or another. Another widely used behavioral battery that is computerized is the Cambridge Neuropsychological Test Automated Battery (CANTAB) (Luciana and Nelson, 2002; De Luca et al., 2003; Luciana, 2003; Syväoja et al., 2015).

The NIH Toolbox Cognition Battery (CB) is designed for use with ages 3–85 and contains two EF measures—the dimensional change card sort test (a measure of cognitive flexibility) and a flanker task (a measure of inhibitory control in the context of selective visual attention). These two measures are sensitive to developmental change across childhood, have excellent reliability, and good convergent validity (Zelazo et al., 2013).

The Test of Everyday Attention for Children (TEA-Ch) assesses both selective and sustained attention in children 6–15 years old (Manly et al., 2001). It takes about an hour and has two parallel forms. Heaton et al. (2001) found that children with ADHD performed worse than clinical controls on TEA-Ch subtests of sustained attention but not on subtests of selective attention. A version (TEA-Ch(J)) has been adapted for use with 5-year-olds (Underbjerg et al., 2013). The TEA (the version for adults) not only assesses selective and sustained attention but also mental shifting.

For individual EF tasks with school-age children, the Tower of London is particularly sensitive to individual differences and the effect of interventions or programs (Krikorian et al., 1994; Anderson et al., 1996; Manjunath and Telles, 2001; Alesi et al., 2016). A modified version, Tower of LondonDX, has not been widely used but seems worth looking into (Culbertson and Zillmer, 1998; MacAllister et al., 2018). For children 8 years or older, the Stroop task, either the color-word version or the numerical version, is an excellent measure of inhibitory control (Heine et al., 2010; Ikeda et al., 2011; Penner et al., 2012; Sachs et al., 2017). For assessing WM in the sense of maintaining information in mind and resisting interference, complex span tasks are excellent for children and adults. Many complex WM span tasks exist for use with school-aged children and those older, such as operational, reading, counting, running, and visual pattern span tasks (Daneman and Carpenter, 1980; Collette et al., 2007; Foster et al., 2015). They share similar underlying methodologies even though they differ in terms of the information retained and the specific processing operations required (Case et al., 1982; Conlin et al., 2005; Conway et al., 2005; Hitch, 2006; Unsworth et al., 2009).

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