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The Development of Executive Function: Mechanisms of Change and Functional Pressures

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ABSTRACT

This developmental account of executive function (EF) argues that domain-general analogical processes build a functional hierarchy of skills, which vary on a continuum of abstraction, and become increasingly differentiated over time. The paper begins by showing how a functional hierarchy can capture important aspects of EF development, including incrementalism, partial differentiation, and a shift from reactive to proactive control. It then details how children construct this hierarchy in development, by showing how they make functional analogies between similar EF problems, in a bottom-up incremental fashion. This results in EF structure which becomes differentiated into components which are more suited to solving some goal-directed problems than others. The developmental implications of this are that children eventually acquire task-general EFs while also retaining goal-specific skills sensitive to wider beliefs, values, norms, preferences, relevant motor, procedural, and embodied knowledge. There is discussion of how this approach is similar to and different from existing accounts, and how it relates to broader issues of training and transfer, group and individual differences, overlapping EF functions and domain-general learning. The developmental mechanisms advocated under this account intentionally draw on neuropsychological, learning and cognitive processes that have been demonstrated in other domains, so that EF theory can benefit from the lessons learned elsewhere and become more integrated with other areas of cognition.

Introduction

The path from problem to solution is rarely straightforward. Along the way there are time-wasting distractions to resist, dead-end strategies that need to be switched in favor of better ones, and unforeseen obstacles that demand a new plan. There is effort associated with this approach, as the easiest option would be to give into temptation, to repeat what has been done before and only consider one thing at a time. However, the benefit of being flexible, controlled, and focused, is behavior which is much more likely to achieve the end goal. The collection of cognitive skills that keeps goal-directed behavior on track are known as executive functions (EFs), and they offer just-in-time solutions to questions like “where should I focus my attention next?”, “what actions do I need to inhibit?” and “what information do I need to update?”

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Not all problems are created equal, however, for example, resisting eating a marshmallow has more in common with resisting kicking someone, than it does with following a topic of conversation. The fact that some problems are more alike than others, cause EF to develop specialized components that are more suited to answering some problems than others. There is some general agreement that at a macro level these components can be organized into three partially dissociable functions: suppressing goal-irrelevant actions or thoughts through *inhibitory control*, maintaining and updating information in *working memory*, and shifting between many tasks or mental operations with *cognitive flexibility*. The evidence for this, in adults at least, is that there is some variance in EF behavior that is uniquely attributable to each component (e.g., Miyake & Friedman, 2012; Miyake et al., 2000), and on a more granular level, some variance uniquely attributable within components too, for example, cognitive inhibition (suppressing prepotent mental representations) dissociating with delay of gratification (suppressing an immediate reward for a later one) (e.g., Diamond & Lee, 2011; Engelhardt, Nigg, Carr, & Ferreira, 2008). The outputs of these all these components combine at the most general level of EF, which support higher-order cognitive processes like reasoning, planning and fluid intelligence.

As other papers in this special issue demonstrate, a closer dialogue between EF theory and developmental processes can offer a corrective critique for one another and benefit both perspectives. For example, if EF theorists are describing an adult end state with no plausible account of how children get there, then they need to rethink what the adult content of EF is. Likewise, if developmentalists are plotting an acquisition trajectory toward an end state that has little empirical support in the adult EF literature, then they need to rethink where the trajectory is aiming at. In that spirit, this paper sets out some of the important underlying mechanisms of acquisition and functional pressures on cognition that explain why adult EF eventually looks the way it does. In particular, this account argues that domain-general analogical processes build a functional hierarchy of EF skills, which vary on a continuum of abstraction, and become increasingly differentiated over time. The developmental implications of this are that children eventually acquire task-general EFs (e.g., Carlson & Moses, 2001; Miyake & Friedman, 2012) while also retaining goal-specific skills sensitive to wider beliefs, values, norms, knowledge and preferences (Doebel, 2020).

This paper is organized into three parts; first, a brief characterization of what develops in EF, including how the current account captures the facts of development; second, an incremental description of how analogical reasoning constructs a hierarchy and how the differentiation of EF skills can be seen as a by-product of functional pressures acting on goal-directed behavior over time, and third, an exploration of some of the predictions of this account, and how it relates to wider challenges and issues in EF research, followed by some general conclusions.

Part I. What develops

Inhibitory control is a multifaceted construct, which generally describes the capacity to defocus a stimulus, block a prepotent response and keep attention focused on a goal (Nigg, 2000; Simpson & Carroll, 2019). New-born infants primarily allocate their attention in a reflexive way to marked perceptual contrasts in the environment, focusing on objects, patterns and actions that change size, intensity, shape, color or are in some other way a departure from the familiar (Colombo, 2002). When young infants attend to some aspect

of the scene, they often have difficulty disengaging from it, displaying so-called “sticky fixation” (Haith, 1980). Within a couple of months though, the expansion of the visual field, physiological changes in the retina and cortical visual pathways, and moderation of inhibitory mechanisms that caused sticky fixation, all allow infants more voluntary control over their attentional resources (e.g., Courage, Reynolds, & Richards, 2006). Infants become increasingly able to intentionally direct their attention to aspects of their environment that interest them most and resist distractors that do not, as they come to recognize, categorize and sort their experience of objects, actions, patterns and people.

Young children show an ever-greater ability and willingness to engage in more sustained periods of attention, moving from 5- to 10-seconds at 3-months-of age to several minutes or more over the first two years (Ruff & Capozzoli, 2003). In these episodes of sustained attention, information is processed with greater depth and with more efficiency, as well being associated with a state of arousal – decreased heart rate, activation of the noradrenergic and cholinergic neurochemical systems – that is optimal for learning and performance. In these longer periods of attention infants are also less distractible by information in the periphery and slower to orientate to it (Reynolds, Courage, & Richards, 2013).

Inhibitory control was once thought to emerge only in middle to late childhood, as the demand to perform more complex, higher-order integrative tasks becomes more frequent and more intense (Golden, 1978). However, research now suggests inhibitory control emerges in a stable form as early as 6 months-of-age (Holmboe, Bonneville-Roussy, Csibra, & Johnson, 2018) and is visible in the inhibition of neonatal reflexes and reaching responses throughout the first year of life (Diamond, 1990). The development of such behavior is associated with the increased activation in the second-half of the first year of life in the prefrontal cortex; an area of the brain whose function is thought to support a range of self-regulating behaviors including inhibitory control (Diamond, 2002).

Early inhibitory control performance appears to have a profound effect later on in life. For example, children who were better at waiting their turn, less easily distracted, more persistent, and less impulsive, were found to be more law abiding, have better educations, higher salary and more favorable mental and physical health 30 years later, even after controlling for IQ, gender, social class, and family circumstances growing up (Moffitt et al., 2011). Beyond this peak of inhibitory control in early adulthood there is a notable decline in inhibition in older adults, as part of what seems to be a normal aging process (e.g., Darowski, Helder, Zacks, Hasher, & Hambrick, 2008).

With respect to memory, the speed and efficiency with which infants encode information, rapidly increases in the first few months. For example, it typically takes 2-month-olds, four and a half minutes to learn the relationship between the action of kicking and the effect it has on an object. By 4-and-a-half-months old this has typically reduced to two minutes (Hill, Borovsky & Rovee-Collier, 1988). Between 2 and 18-months of age, infants’ memory storage also rapidly improves, such that older infants show retention over longer intervals than their younger counterparts regardless of the number of opportunities they have to encode the information (Hsu, 2010). However, being able to hold many things in mind or do any kind of mental manipulation, a hallmark of working memory, is far slower to develop and is a multifaceted construct (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006; Müller & Kerns, 2015). Several factors are thought to shape its developmental trajectory, including changes in children’s speed of forgetting and processing speed, a global increase in cognitive resources, an increase in attention bandwidth, acquisition of

maintenance strategies, long-term knowledge and the ability to keep in mind the goal of the task (e.g., Camos & Barrouillet, 2018; Fitamen, Blaye, & Camos, 2019). Alongside these developments, memory span is also rapidly improving from 4 to 8 years-of-age, with more gradual improvement thereafter up to approximately 12 years-of-age, when performance levels off to adult levels (Gathercole, 1999). This shape of development is seen for both verbal and visuospatial information and for short-term memory and complex memory tasks (e.g., Luciana, Conklin, Hooper, & Yarger, 2005). The most recent work on working memory shows that it is improving significantly from 3 years right the way through to adolescence (Ahmed, Ellis, Ward, Chaku, & Davis-Kean, 2022).

Finally, cognitive flexibility, the ability to change perspective, switch tasks and set shift, also has a protracted development (Garon, Bryson, & Smith, 2008). Children as young as 3 years-of-age, have no difficulty sorting objects by either color or shape, for example (Kirkham, Cruess, & Diamond, 2003). But when they are asked to switch the sorting criteria halfway through the task, from color to shape or vice versa, they struggle to adopt the new rule and stick with the old one, even though they know what they should do. The effect is not just limited to using sorting rules of the type, if x then y , but a much more general inability to change perspectives, as evidenced by young children's difficulty when asked to see an ambiguous figure as anything other than their initial way of perceiving it, even when they are shown the alternative (Gopnik & Rosati, 2001).

By 4–5 years-of-age most children have significantly improved on these tasks, but it is not until 7–9 years-of-age, that they can switch flexibly on a trial-by-trial basis (Gupta, Kar, & Srinivasan, 2009). Speaking to just how protracted the acquisition of cognitive flexibility is, the cognitive cost of changing tasks persists into adulthood, as indicated by greater response times for switch trials, regardless of whether adults are informed of the upcoming switch or whether there is a gap between trials (Diamond & Kirkham, 2005).

From this brief developmental sketch of EF, there are several recurrent themes that any developmental model needs to capture (Table 1).

Table 1. How the functional hierarchy advocated by this paper accommodates the developmental facts.

Developmental phenomena	How a functional hierarchy captures the phenomena
Incrementalism. Smaller first-acquired parts of EF are gradually assembled into larger, later-acquired more coherent wholes, in a cascade of skill acquisition (e.g., Bornstein et al., 2006).	Structure emerges in a piecemeal fashion from the bottom-up. Generalized skills (e.g., complex reasoning, problem-solving and planning) are made possible by first acquiring more specific skills (e.g., inhibition, and working memory and cognitive flexibility) which are generalized over even more specific skills (e.g., not eating a marshmallow)
Partial differentiation. EFs are <i>partially</i> dissociable both on a macro level (working memory vs. inhibitory control vs. cognitive flexibility) and on a granular level (e.g., cognitive inhibition vs. delay of gratification). (Miyake et al., 2000; Miyake & Friedman, 2012; Engelhardt et al., 2008; Diamond & Lee, 2011).	Goal-directed behavior drives the hierarchy to be somewhat clustered (some problems are more alike than others) and somewhat distributed (some skills are generalizable). Differentiation (and overlap) of the hierarchy emerges as the result of functional pressures over time.
Reactive to proactive. There is a shift from a reactive mode of control, characterized by the recruitment of executive processes in the face of immediately unfolding events, to a proactive mode of control, where children anticipate and actively prepare for probable upcoming events, and later on develop more internal, self-initiated forms of inhibition and attentional deployment (Berger, 2011; Chevalier, James, Wiebe, Nelson, & Espy, 2014).	Functional hierarchies become increasingly better at prediction over time because knowledge of instances becomes more schematized and generalizable to novel events (Bar, 2007; Bar, 2009). They also become more under voluntary control, because an increasingly complex hierarchy allows more flexible application of top-down commands.

Part II. The development of EF hierarchies

Many previous studies have found that information representation in the brain demonstrates a hierarchical structure, with simple sensations and perceptions processed close to cortical inputs and more abstract, symbolic, or deep concepts processed more distant from sensory inputs, or deeper in the brain's structural network (e.g., Felleman & Van Essen, 1991). Indeed, it has been argued hierarchical aggregation and progressive functional abstraction over network depth is a fundamental organizational principle of human cortical networks and cognition (Taylor, Hobbs, Burroni, & Siegelmann, 2015). The functional reason for this is that if two problems have similar solutions, one efficient way to store and process this relationship is to cluster them close together in a structured hierarchy in a way that supports generalization. By knowing some properties of a category, other *unobserved* properties can be inferred at a small cost, because of the way attributes and relations of a category cluster together, and that free information is useful in predicting behavior and making smart behavioral responses. The way in which this hierarchy incrementally emerges over time can be characterized as in Figure 1, and in what follows, this view of EF development is motivated by discussion of the relevant EF developmental findings and domain-general learning mechanisms.

Information hierarchies have been used to explain such diverse behavior as categorization (Anderson, 1991), feature learning (Griffiths & Austerweil, 2008), theory formation (Kemp, Tenenbaum, Niyogi, & Griffiths, 2010), classical conditioning (Gershman, Blei, & Niv, 2010), and word segmentation (Goldwater, Griffiths, & Johnson, 2009). As EFs are similar goal-driven behaviors to these, we might expect they recruit similar cognitive structures, and indeed some theories of EF have explicitly incorporated hierarchies into their models. For example, in Cognitive Complexity and Control (CCC) theory, the development of EF can be understood in terms of age-related increases in the complexity of a hierarchy of if-then conditional statements (Zelazo et al., 2003). A child might start out with the reflection, "If I see a mailbox, then I need to mail this letter," and later on, learn to embed this proposition in a more complex structure, "If it is before 5 p.m., then if I see a mailbox, then I need to mail this letter, otherwise, I'll have to go directly to the post office." CCC is especially well suited to characterize the kind of cognitive flexibility needed to perform on tasks that require a switch in rules, like the Dimensional Change Card Sort (i.e., "if red then sort here").

The proposal here is also functionally motivated, but generalizable to much broader class of EFs and admits a much wider repertoire of concepts into the EF hierarchy than if-then conditionals. This includes relevant motor, procedural, and embodied knowledge (e.g., Goldstein & Lerner, 2018) and wider beliefs, values, norms, knowledge and preferences (Doebel, 2020). In short, it includes whatever is predictive in the environment that serves the goal at that time. How does an infant know what is predictive or relevant? As with other areas of children's development (Gopnik, 2020), there is reason to suggest that children apply an explore-then-exploit strategy to their EF learning. For example, children start out using a distributed attention strategy that explores a broad hypothesis space of possibilities, precisely because they don't know yet what the predictive dimensions are that serve their goals. Then later on, they narrow their attention once they stumble across what is relevant to achieving their goal, and exploit this to the exclusion of other information (a general class of optimization solutions also known as simulated annealing). This strategy, in the context

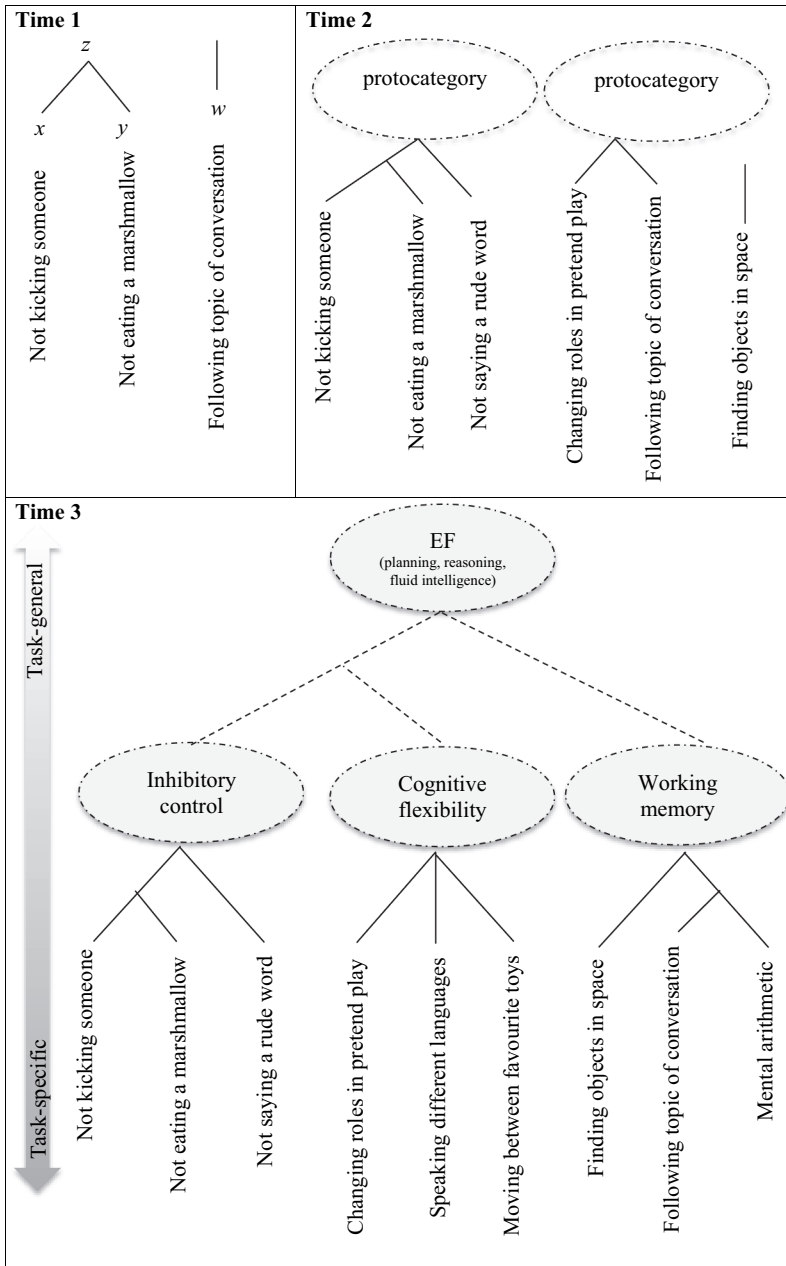


Figure 1. Time 1. “Not kicking someone” (x) is like “not eating a marshmallow” (y) in that they both require effortful resistance of some prepotent response (z), and both are more similar to one another than either are to “following a topic of conversation” (w) with the demands that places on working memory. The depth of the hierarchy is shallow at this stage because experience limits the generalizations that are possible over concrete events or tasks. **Time 2.** As experience accumulates, new experiences are clustered with similar old ones on the basis of functional analogy, and as the depth of the hierarchy increases, it supports more abstract generalizations. The hierarchical structure is subject to dynamic reorganization such that some of these emergent proto-categories are temporary generalizations on the way to more stable and entrenched representations of mature EFs. **Time 3.** An adult-like functional hierarchy of EFs, where individuals retain both task-general (abstract) and task-specific (concrete) EF information.

of cognitive control, appears to protect children from learning traps (i.e., failing to realize that what they ignore carries important information) although at the cost of slower learning to begin with (Blanco, Turner, & Sloutsky, 2022).

The fundamental process that constructs the hierarchy, is making analogies, which broadly speaking, maps novel concepts onto familiar ones, allowing children to transfer learning across contexts, to extract relevant information from everyday learning experiences on the basis of relational similarity and to make inferences about new experiences. It is widely considered an essential, implicit mechanism underpinning a wide range of abilities including perception, reasoning, and communication (Gentner, 1983; Goswami, 2001). For example, in usage-based approaches to language acquisition, children do not start out with abstract adult-like grammatical components and learn to connect these to the concrete utterances they experience. Rather, utterances are the starting point, and through a combination of general-purpose analogy-making processes and specific communicative intention-reading skills, more adult-like abstract language structure emerges incrementally and in a piecemeal fashion from the bottom-up (Bybee, 2010; Goldberg, 2005; Tomasello, 2003). Likewise with EF, the argument here is that children do not start out with fully formed abstract components of EFs, rather, more adult-like structure emerges incrementally from the bottom-up as a result of functional pressure on the system over time.

In support of this view, a meta-analysis of 98 studies showed a clear trend toward greater EF differentiation with age, or in other words, the older children needed more top-level components of EF (i.e., working memory, cognitive flexibility and working memory) to explain the variance in EF performance than the younger children (Messer et al., 2022 with data from; Lee, Bull, & Ho, 2013; Karr et al., 2018; St. Clair-Thompson & Gathercole, 2006 and the citations therein). It could be that this trend toward differentiation is an artifact of different age-appropriate tasks being administered at different times, rather than reflecting an underlying cognitive change. As part their meta-analysis, Karr et al. (2018) report that some of the studies they analyzed used different tests of EF across different ages; some used the exact same task or a highly similar task (e.g., Digit Span Backward); and some used a variation which involved different stimuli, but with similar task demands (e.g., Boy-Girl Stroop, Day-Night Stroop, and Color-Word Stroop). Using a mixture of the same, similar, or different tasks is common across meta-analyses and makes it difficult to precisely estimate how much task effects are contributing to the overall developmental trend, but more studies that use the same or very similar measures of EFs across a broad age range would help to clarify this. On a biological level, the general idea of EF specialization is supported by the fact that infant and child brains are more plastic, less modular than the adult brain, where cognitive processes are not as discretely mapped to specific neural regions in young children relative to adults (e.g., Jacobs, Harvey, & Anderson, 2011; Tooley et al., 2022). On a more general cognitive level, it is consistent with the idea of modularization being the result of functional developmental pressures over time, rather than modules organized in advance of experience (Karmiloff-Smith, 1992).

Returning to analogical reasoning, young children seem to start out by making analogies based on concrete lower-level attributes rather than deeper relational ones: aligning kitten to puppy and dog to cat on the basis of size, to use a categorization example. While the distinction between attributes and relations is far from clear and, at the very least, is highly context dependent, at some point in development there appears a “relational shift” where children begin to reason more on the basis of deeper relational features (e.g., aligning cat to

kitten and dog to puppy on the basis of parent-offspring), although the precise timing of this shift depends on children's familiarity with the domains involved (Rattermann & Gentner, 1998). The fundamental developmental reason for this shift is that relational inferences require more data, and the higher levels of the hierarchy that support higher level generalizations emerge only when there is enough experience for them to work. Applied to EFs, this means development starts out with fixed behavioral responses to relatively narrow environmental situations that are quite task specific, low-level and concrete (Figure 1, time point 1) and over time, as experience accumulates, new instances of EF are categorized on the basis that they are analogous to previous ones. For example, improvements in children's cognitive flexibility can be understood as the result of an expanding repertoire of control strategies as well as more effective coordination of this repertoire (Chevalier, 2015). So somewhat paradoxically, the key to more flexible and adaptive behavior in the future is not to use fewer fixed behavioral responses, but to pack the mind with more of them, with more niche task-routines and routine blends, that make generalizations over tasks possible.

Importantly, as children acquire abstract generalizations they also retain task-specific knowledge. To use a previous example, just because a child acquires the ability to make relational analogies (cat is to kitten as dog is to puppy), this does not imply they forget how to make more surface-levels analogies (cat is to dog as kitten is to puppy). A similar debate about the abstractness of knowledge representations has been played out in developmental literature on language acquisition (Ibbotson, 2020; Chapter 3). That debate has reached the conclusion, for many researchers, that adult speakers have both a massive reservoir of lower-level linguistic knowledge (i.e., lexically specific, multiword chunks) and higher-level knowledge (i.e., highly schematic form-meaning constructions). Likewise, in the categorization literature, the argument has been over whether knowledge is best understood as a complex interconnected network of specific exemplars or as some abstracted prototypes over exemplars, or probably a blend of both (Ibbotson, 2020). With respect to EF, Doebel argues (2020), "children start out deploying their basic EF skills in the service of specific, concrete goals, such as avoiding hitting a playmate who takes one of their toys or working out the amount of change to give to a customer" (p.946). However, the developmental story does not end there because not all goals are created equal. The developmental implications of this are that children eventually construct domain-general component processes *as well as* also retaining more task-specific knowledge. Sometimes more abstract knowledge will be required, if a new task is almost totally unfamiliar or requires a radically new combination of skills to achieve the goal; other times, when there is a close analogue to previous experience, more task-specific knowledge is appropriate.

Other EF theories have also appealed to a continuum of concrete to abstract EF representations. For example, Munakata, Snyder, and Chatham (2012) argue that children's goal representations shift from concrete objects toward increasingly abstract goals and become more robust in the face of distraction and delay, particularly with respect to goal-relevant representations in working memory. Garon et al. (2008) suggest that skills underlying EF develop hierarchically, with basic skills needed for component EFs emerging first, followed by an integrative period in which basic skills become coordinated. The approach here also uses a continuum of EF representations that vary in their level of abstraction, but I flesh out in more detail the dynamic processes that give rise to those abstractions, emphasizing the role of functional analogy, a domain-general process that has been relatively overlooked in this context. Diamond has highlighted the importance of making

analogies at higher levels of cognition, for example “fluid intelligence . . . involves being able to figure out the abstract relations underlying analogies (Diamond, 2013, p. 151),” but the current proposal argues that analogy is also at work in much low-level EFs, that analogy need not be an explicit strategy as it is in fluid intelligence, and plays a more widespread role in the construction of EFs themselves rather than being a by-product of them.

As the hierarchy develops, there are likely to be phases of reorganization such that aspects of the EF structure might look quite different from that of the adult end-state (see Karmiloff-Smith, 1979 for a similar notion of representational redescription in development). For example, in Figure 1, time point 2, “changing roles in pretend play” and “following topic of conversation” have been brought under the same emergent proto-category, which have been treated as analogous in some respect. Perhaps both events occurred in close proximity in development for that child or they had other lower-level attributes that caused these events to cluster together, like involving the same people. The point is that some of these emergent proto-categories are temporary generalizations on the way to more stable and entrenched representations of mature EFs (the dynamic nature of the hierarchy has some implications for training and transfer, discussed in Part III). A similar reorganization can be seen in over- or under-extension of category acquisition, for example when a child goes through a phase of referring to all mammals as dogs, or more rarely, all dogs as mammals (Kay & Anglin, 1982).

The general trade-off involved here, as with any classification hierarchy, is between specificity and sensitivity: grouping all experiences into a single cluster in a hierarchy where they are represented by some abstract summary statistics is maximally simple, but at the cost of losing a significant amount of detail. Having a separate cluster for each experience accurately captures the nuances of those experiences, but is maximally complex. So how should children form clusters? The short answer is that there is no guaranteed way of knowing in advance of experience; children need to work out the means that achieve their goals through play, trial-and-error, observational learning, explore-then-exploit learning (Gopnik, 2020) and embodied interactions within a social context (Müller & Kerns, 2015). The central role of experience and interaction advocated here fits with a view of development, where children are not passive recipients of an invariant EF maturational schedule, but active participants in constructing EFs to fit their ecological niche. For example, Werchan and Amso (2017) argue that the development of the prefrontal cortex, an area associated with EFs, is best understood as a process of adaptation to the environment, that organizes learning and action, particularly in social, linguistic, and emotional domains relevant to infants.

The payoff of a functional hierarchy is that it allows an individual to make rapid use of experience and select which aspects of cognition are most appropriate for achieving the goal. As the hierarchy becomes more complex, the generalizations or predictions it makes become more nuanced and allow more flexible behavior in the face of obstacles. And without such abstractions it is not immediately clear how children would ever get better over time on novel EF measures tasks, where analogies between EF tasks allow children to transfer learning across contexts and to make inferences about new experiences. The final time point, 3, in Figure 1, is of course a massive oversimplification, with a more realistic hierarchy incorporating many tens of thousands of EF events, and likely a much richer classification structure with many more sub-categories and branches. Nevertheless, the account does try to capture something plausible about how children could incrementally

get from “here to there” in development using domain-general learning strategies and cognitive structures applied to situations that demand EFs. Following this characterization of EF development, in what remains I focus on other aspects of EF that a functional hierarchy can capture or predict.

Part III. Challenges, predictions and remaining issues

Group and individual differences in EF

Data driven, bottom-up functional hierarchies naturally accommodate group and individual differences because, regardless of how abstract the structures become, they are always grounded in concrete experience of goal-directed behavior, and these goals can vary across time and space. For example, at the group-level, Yanaoka et al. (2022) assessed children who delayed gratification for different rewards across two cultures that differed in their customs around waiting. They found that Japanese children delayed gratification longer for food than for gifts, whereas American children delayed longer for gifts than for food. This suggests culturally-specific habits support delaying gratification: waiting to eat is emphasized more in Japan than America, whereas waiting to open gifts is emphasized more in America than Japan.

On an individual level, there is evidence that the most optimal way to engage EFs varies as a function of individual traits (e.g., working memory capacity) and states (e.g., motivation, fatigue, emotions). For example, strategies that demand much working memory are most adaptive for individuals with greater capacity for working memory when they are not fatigued, and children with lower processing speed are less likely to use verbal strategies spontaneously and thus benefit more from incentives to do so (Chevalier, 2015). Werchan and Amso (2017) have also argued that the prefrontal cortex does not mature according to a strict timetable, rather, early childhood adversity, variations in socioeconomic status, and early life deprivation can modulate the development of the prefrontal cortex differently for different children, and thus the EFs that are supported by them. The fact that such individual differences exist allow us to ask to what extent individuals who are particularly strong in one aspect of EF, are also relatively good on a different task that requires the same underlying ability. In this context, Ibbotson & Kearvell-White, (2015) tested 81 English-speaking 5-year-olds using two classic tests from linguistics and psychology: the Past Tense Generalization Test and the Stroop Test. They predicted that if language and cognition share similar cognitive resources and routines, then children who are good at inhibiting on a visual Stroop-test (saying “moon” to a picture of the sun and vice versa) should also be the same children who are good at inhibiting saying “flyed” when the correct response was “flew,” for example. That is exactly what they found, and the most parsimonious explanation for the correlation in individual differences seems to be that providing the correct behavioral response in both tests (and domains) requires using a common cognitive capacity to inhibit unwanted competition (see for Yuile & Sabbagh, 2021; Gandolfi & Viterbori, 2020; Gandolfi, Usai, Traverso, & Viterbori, 2022 for replications of the same pattern with different languages and over different developmental periods). So, either by systematic variation between cultures, societies or families, or by unsystematic random variation, different children are likely to experience different EF events with different values attached to them or in a different sequence, and this will lead them to follow different

developmental trajectories and display different strengths and weaknesses in adult EF. Any particular view of adult EF structure (e.g., Garon et al., 2008; Miyake et al., 2000) must acknowledge that therefore there will be significant individual and group differences.

This presupposes some meaningful difference between a common (if not universal) psychological *process* of analogical reasoning on the one hand, and the variable *content* on which the process operates, on the other, and it predicts both group-level and individual differences in EFs, because content varies between individuals and groups. There is a limit to this variation however, because we inhabit a similar social and physical world where similar problems, such as walking, talking, and living in three-dimensional space, require similar solutions. The emergent functional hierarchy view of EF acknowledges both exogenous cultural influences as well as endogenous factors, and sees individual differences in EF emerging from a dynamic interaction between the two (e.g., Müller, Baker, & Yeung, 2013). The key point for a functional hierarchy is that whatever content goes into a EF category – physical, social, emotional – the predictive benefits of forming a category must offset the cognitive costs of maintaining one. For example, to use a categorization example from language acquisition, young infants can distinguish a wider range of sounds than is present in their native language, but they lose this ability somewhere between 6 and 12 months of age (Werker & Tees, 1984). They lose this ability as they get older because forming and maintaining categories that make no useful predictions about the way their world works (e.g., a language they haven't heard in the first 12 months) is an expensive thing for the brain to do.

Training and transfer

Beyond the evidence that training can directly improve EF (Diamond & Lee, 2011), it has been claimed that training one aspect of EF, can indirectly improve another, untrained, aspect of EF or cognition. This is particularly relevant here because, with enough examples of this kind of cognitive transfer, we can build up a picture of how EFs relate to one another and broader cognition. Using a similar model to that of spreading activation in priming studies, it is argued that functions that are close to each other in a network or hierarchy are more likely to prime or transfer one another compared with ones far away. One prediction based on the development of EF structure sketched out in Part II, is that what constitutes “near by” will be subject to some group and individual variation, and will change over time, as children respond to experience by reorganizing their functional hierarchies (e.g., the proto-categories of Time 2, Figure 1). The consequence of this is that there are different transfer and priming possibilities for children than there are for adults.

So-called near transfer has been demonstrated with spatial WM training transferring to other measures of spatial WM but not to visual WM or other EF subcomponents (Bergman-Nutley et al., 2011). And far-transfer has been demonstrated with training task switching to an untrained task-switching task and also inhibition, verbal and nonverbal WM, and reasoning (Karbach & Kray, 2009). In a recent demonstration of far transfer, Roque-Gutierrez and Ibbotson (2022) tested several hypotheses about the relation between syntax and working memory. Using a pre- posttest randomized control trial, 104 native Cuban Spanish-speaking children took part in either syntax training in their first language; syntax training in their second language; working memory training or no training (control). Compared to the control group, children in the training conditions showed cognitive

transfer from working memory to syntax, but not from syntax to working memory. The result was most striking in the case of their first language, where working memory training was as effective as language training in boosting syntactic performance. As well as establishing cognitive transfer at the group level, they also found individual differences in working memory performance, both at baseline and in training, predicted the extent to which children's syntax improved. The directionality of transfer, the group-level and individual-level results, established in the context of a randomized control design, all point to a strong causal role for domain-general cognition in the processes of language acquisition.

Even though it is not entirely clear why there was transfer in only one direction, one possibility is that the subject-verb agreement WM, that was taxed in syntax training, is more task-specific than the visual N-back WM, so that, broadly speaking, transfer is more likely from the general to the specific rather than vice versa. This possibility needs to be addressed in future studies, as it implies an asymmetry in the functional hierarchy of cognition, where training can transfer along one branch, but not another (for more on the general relationship between EF and language see Müller & Kerns, 2015; Shokrkon & Nicoladis, 2022).

In previous work, it has been demonstrated that working memory training has transferred to language abilities in children with Attention Deficient Hyperactivity Disorder (ADHD) (Klingberg et al., 2005); children with Developmental Language Disorder (DLD) (Delage, Stanford, & Durreleman, 2021a) and most recently, in children with Autistic Spectrum Disorder (ASD) (Delage, Eigsti, Stanford, & Durreleman, 2021b). Delage and colleagues (2021b) assessed the impact of 12 hours of WM training (simple and complex span tasks) across 8 weeks in 30 children with ASD, aged 5 to 11. Results showed direct improvements on untrained WM tasks, as well as transfer effects to syntax (root question accuracy and clitics), an effect that was still present three-months after the posttest.

Despite this, the very existence of far transfer effects remains hotly contested (Kassai, Futo, Demetrovics, & Takacs, 2019; Melby-Lervåg, Redick, & Hulme, 2016). The findings of their meta-analytic study led Gobet and Sala (2022) to conclude that transfer effects could be explained as an artifact of methodological shortcomings, including sampling error, publication bias and types of control group. Note their review did not (or could not) include the transfer effects reported here of Delage and colleagues (2021a, 2021b); Klingberg et al. (2005) or Roque-Gutierrez and Ibbotson (2022). Most recently, in one of the biggest training studies to date with 17,648 children, Judd and Klingberg (2021) demonstrated positive transfer from spatial cognition training to mathematical learning. What seems necessary for transfer, but perhaps not sufficient, is a clear functional mapping between the training domain and target domain. For example, Roque-Gutierrez and Ibbotson specifically chose two domains that were likely to share a common functional hierarchy – that is, they call upon similar cognitive resources to get the job done (Carroll, 1993; see also Ibbotson et al., 2015 in this respect). Their test sentences were of the type “The girl in the red pajamas under the stairs is hiding,” where the subject “the girl” needed to be held in mind while “in the red pajamas under the stairs” was simultaneously processed, so that it agreed with the following verb “is” – compare “are hiding.” Likewise, the N-back test required participants to hold some information in mind, the sequence of the visual stimuli, while simultaneously performing a different task, matching stimuli N trials before. Where positive transfer effects are reported, they tend to be consistent with skill-based theories of transfer that argue training tasks require the establishment or refinement of a cognitive routine that is not already fully developed in either target or source domain (Gathercole,

Dunning, Holmes, & Norris, 2019). These accounts might also predict why the populations in which we have the strongest evidence for transfer (i.e., children, ADHD, DLD and ASD) have the greatest headroom for training. As others have argued, WM limitations are likely to impact the acquisition of complex syntax and improving WM capacities via a dedicated training program, as they could free up cognitive resources to deal more effectively with syntax. In this regard, children represent a particularly promising group to target transfer because of their greater neuroplasticity (Klingberg, 2010).

Overlapping functions

The fact that EFs are *partially* clustered and partially distributed in a hierarchy, captures the fact that in practice, it is often difficult to isolate a “pure” task that requires just one EF but not the other. For example, to relate multiple ideas or facts together in working memory, a child must be able to inhibit focusing exclusively on just one thing, and to inhibit one action over another, implies two or more things are held in mind at the same time in working memory. This might be two sides of the same capacity-limited function, or it might be that one component is a by-product of another. For example, if the goal is strongly in focus, by definition it implies other goals are defocused and there is perhaps no independent motivation for inhibition. Whatever the outcome of that particular debate, functional hierarchies naturally accommodate the fuzziness between EF components because experience is fuzzy: over time the hierarchy becomes densely clustered when problems are alike, and sparsely clustered when problems require more general skills.

Domain-general learning

The mechanisms advocated under this developmental account of EF have intentionally adopted the neuropsychological, learning and cognitive processes that have been independently motivated of EF. These include:

- A hierarchical aggregation and progressive functional abstraction over network depth as a fundamental organizational feature of the brain (Felleman & Van Essen, 1991; Taylor et al., 2015) cognition and behavior (Anderson, 1991, Sanborn et al., 2010; Griffiths & Austerweil, 2008; Kemp et al., 2010; Gershman et al., 2010; Goldwater et al., 2009).
- Analogical reasoning as an essential, implicit mechanism underpinning a wide range of abilities including perception, reasoning, and communication (Gentner, 1983; Goswami, 2001).
- Domain-general approaches to learning dilemmas such as an explore-then-exploit strategy (Gopnik, 2020).
- Abstract generalizations over usage events emerging incrementally and in a piecemeal fashion from the bottom-up (e.g., Bybee, 2010; Goldberg, 2005; Ibbotson, 2020; Tomasello, 2003).
- Environmental prediction as a domain-general principle of flexible behavior organized into a hierarchical cascade of forecasts at different levels of granularity across the brain (Bar, 2007, 2009) and perceptual narrowing of categories that are ecologically valid (Werker & Tees, 1984).

In each case, the intention has been to learn from debates that have already been played out in other areas of development (e.g., exemplar vs prototype in the categorization literature; concrete vs abstract constructions in linguistics), to better integrate EF development with other areas of cognitive development, and to fully exploit the explanatory capacity of existing, independently motivated processes, before recourse to EF-specific ones. In support of the idea that EF is recycling domain-general cognition we find both longitudinal and cross-sectional contingencies between children in their EF and general cognitive development, in cases where both abilities are hypothesized to recruit the same underlying cognitive skills (Białecka-Pikul, Kosno, & Byczewska-Konieczny, 2016; Bornstein et al., 2006; Gandolfi et al., 2022; Gandolfi & Viterbori, 2020; Ibbotson et al., 2015; Roque-Gutierrez & Ibbotson, 2022; White, Alexander, & Greenfield, 2017; Woodard, Pozzan, & Trueswell, 2016; Yuile & Sabbagh, 2021).

Conclusions

This paper aimed at setting out a plausible account of how children get from “here” to “there” with their EFs, arguing that domain-general analogical processes build a functional hierarchy of EF skills, which vary on a continuum of abstraction, and become increasingly differentiated over time. The approach agrees with other accounts that argue EFs are best viewed functionally, as an outcome, not an explanatory construct (e.g., Zelazo et al., 2003), and that rather than being on a fixed maturational time-course, EF development and the neurological functions that underpin it, can be delayed or accelerated in response to environmental demands (Werchan & Amso, 2017). It also goes further than these accounts in detailing the mechanisms that build a hierarchy and the functional pressures that act on the system in development. Because of this focus on the developmental processes, there is less emphasis on defending a particular view of what content an adult hierarchy includes, for example, whether EF is best thought of as a central attention system that is involved in all EF component operations (Garon et al., 2008) or a unitary construct with partially dissociable components of working memory, response inhibition, and shifting (Miyake et al., 2000).

What is more relevant, is that EF development has either been characterized as the emergence of a set of domain-general component processes that are relatively insensitive to context (e.g., Carlson & Moses, 2001; Miyake & Friedman, 2012) or the development of goal-specific skills sensitive to wider beliefs, values, norms, knowledge and preferences (Doebel, 2020). This article has attempted to show why these are not necessarily alternatives we need to choose between, indeed there are good empirical and theoretical reasons for integrating both accounts.

In conclusion, this approach has set out the underlying mechanisms and developmental sequences that explain how children move from task-specific to task-general knowledge. Specifically, functional analogies between specific EF goals are made on the basis of contextual similarities and the cognitive routines employed to succeed at the task. According to this approach executive function skills systematically build on each other in development in an incremental fashion, where abstract components of executive function exist to the extent that they represent similar processing solutions to similar environmental problems. The differentiation of executive function components in development is then seen a by-product of differential functional pressures on cognition over time.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

- Ahmed, S. F., Ellis, A., Ward, K. P., Chaku, N., & Davis-Kean, P. E. (2022). Working memory development from early childhood to adolescence using two nationally representative samples. *Developmental Psychology, 58*(10), 1962–1973. doi:10.1037/dev0001396
- Anderson, J. R. (1991). The adaptive nature of human categorization. *Psychological Review, 98*(3), 409. doi:10.1037/0033-295X.98.3.409
- Bar, M. (2007). The proactive brain: Using analogies and associations to generate predictions. *Trends in Cognitive Sciences, 11*(7), 280–289. doi:10.1016/j.tics.2007.05.005
- Bar, M. (2009). The proactive brain: Memory for predictions. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1521), 1235–1243. doi:10.1098/rstb.2008.0310
- Berger, A. (2011). *Self-regulation: Brain, cognition, and development*. Washington, DC, USA: American Psychological Association.
- Bergman-Nutley, S., Söderqvist, S., Bryde, S., Thorell, L. B., Humphreys, K., & Klingberg, T. (2011). Gains in fluid intelligence after training non-verbal reasoning in 4-year-old children: A controlled, randomized study. *Developmental Science, 14*, 591–601.
- Bialecka-Pikul, M., Kosno, M., & Byczewska-Konieczny, K. (2016). Where was it? Working memory as a predictor of passive vocabulary development in the third year of life. *Polish Psychological Bulletin, 47*(1), 92–102. doi:10.1515/ppb-2016-0010
- Blanco, N. J., Turner, B. M., & Sloutsky, V. M. (2022). The benefits of immature cognitive control: How distributed attention guards against learning traps. *Journal of Experimental Child Psychology, 226*, 105548. doi:10.1016/j.jecp.2022.105548
- Bornstein, M. H., Hahn, C. S., Bell, C., Haynes, O. M., Slater, A., Golding, J., & Wolke, D.; ALSPAC Study Team. (2006). Stability in cognition across early childhood. A developmental cascade. *Psychological Science, 17*(2), 151–158. doi:10.1111/j.1467-9280.2006.01678.x
- Bybee, J. (2010). *Language, usage and cognition*. Cambridge: Cambridge University Press.
- Camos, V., & Barrouillet, P. (2018). *Working memory in development*. UK: Routledge.
- Carlson, S. M., & Moses, L. J. (2001). Individual differences in inhibitory control and children's theory of mind. *Child Development, 72*(4), 1032–1053. doi:10.1111/1467-8624.00333
- Carroll, J. B. (1993). *Human cognitive abilities*. Cambridge: University Press.
- Chevalier, N. (2015). The development of executive function: Toward more optimal coordination of control with age. *Child Development Perspectives, 9*(4), 239–244. doi:10.1111/cdep.12138
- Chevalier, N., James, T. D., Wiebe, S. A., Nelson, J. M., & Espy, K. A. (2014). Contribution of reactive and proactive control to children's working memory performance: Insight from item recall durations in response sequence planning. *Developmental Psychology, 50*(7), 1999–2008. doi:10.1037/a0036644
- Colombo, J. (2002). The development of visual attention in infancy. *Annual Review of Psychology, 52*(1), 337–367. doi:10.1146/annurev.psych.52.1.337
- Courage, M., Reynolds, G., & Richards, J. (2006). Infants' attention to patterned stimuli: Developmental change from 3 to 12 months of age. *Child Development, 77*(3), 680–695. doi:10.1111/j.1467-8624.2006.00897.x
- Crone, E. A., Wendelken, C., Donohue, S. E., van Leijenhorst, L., & Bunge, S. A. (2006). Neurocognitive development of the ability to manipulate information in working memory. *Proceedings of the National Academy of Sciences, USA* (vol. 103 pp. 9315–9320).
- Darowski, E. S., Helder, E., Zacks, R. T., Hasher, L., & Hambrick, D. Z. (2008). Age-related differences in cognition: The role of distraction control. *Neuropsychology, 22*(5), 638–644. doi:10.1037/0894-4105.22.5.638

- Delage, H., Eigsti, I. M., Stanford, E., & Durrleman, S. (2021b). A preliminary examination of the impact of working memory training on syntax and processing speed in children with ASD. *Journal of Autism Developmental Disorders*, 52(10), 4233–4251. doi:10.1007/s10803-021-05295-z
- Delage, H., Stanford, E., & Durrleman, S. (2021a). Working memory training enhances complex syntax in children with developmental language disorder. *Applied Psycholinguistics*, 42(5), 1341–1375. doi:10.1017/S0142716421000369
- Diamond, A. (1990). Developmental time course in human infants and infant monkeys, and the neural bases of inhibitory control in reaching. *Annals of the New York Academy of Sciences*, 608(1), 637–676. doi:10.1111/j.1749-6632.1990.tb48913.x
- Diamond, A. (2002). Normal development of prefrontal cortex from birth to young adulthood: Cognitive functions, anatomy, and biochemistry. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 466–503). New York, NY: Oxford University Press.
- Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, 64(1), 135–168. doi:10.1146/annurev-psych-113011-143750
- Diamond, A., & Kirkham, N. Z. (2005). Not quite as grown-up as we like to think: Parallels between cognition in childhood and adulthood. *Psychological Science*, 16(4), 291–297. doi:10.1111/j.0956-7976.2005.01530.x
- Diamond, A., & Lee, K. (2011). Interventions and programs demonstrated to aid executive function development in children 4–12 years of age. *Science*, 333(6045), 959–964. doi:10.1126/science.1204529
- Doebel, S. (2020). Rethinking executive function and its development. *Perspectives on Psychological Science: a Journal of the Association for Psychological Science*, 15(4), 942–956. doi:10.1177/1745691620904771
- Engelhardt, P. E., Nigg, J. T., Carr, L. A., & Ferreira, F. (2008). Cognitive inhibition and working memory in attention deficit/hyperactivity disorder. *Journal of Abnormal Psychology*, 117(3), 591–605. doi:10.1037/a0012593
- Felleman, D. J., & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral Cortex. New York*, 1, 1–47.
- Fitamen, C., Blaye, A., & Camos, V. (2019). Five-year-old children's working memory can be improved when children act on A transparent goal cue. *Scientific Reports*, 9(1), 15342. doi:10.1038/s41598-019-51869-4
- Gandolfi, E., Usai, M. C., Traverso, L., & Viterbori, P. (2022). Inhibitory control and verb inflection in Italian preschool children. *Journal of Child Language*, 1–17. doi:10.1017/S0305000922000058
- Gandolfi, E., & Viterbori, P. (2020). Inhibitory control skills and language acquisition in toddlers and preschool children. *Language Learning*, 70(3), 604–642. doi:10.1111/lang.12388
- Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin*, 134(1), 31–60. doi:10.1037/0033-2909.134.1.31
- Gathercole, S. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences*, 3(11), 410–419. doi:10.1016/S1364-6613(99)01388-1
- Gathercole, S., Dunning, D., Holmes, J., & Norris, D. (2019). Working memory training involves learning new skills. *Journal of Memory and Language*, 105, 19–42. doi:10.1016/j.jml.2018.10.003
- Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science*, 7(2), 155–170. doi:10.1207/s15516709cog0702_3
- Gershman, S. J., Blei, D. M., & Niv, Y. (2010). Context, learning, and extinction. *Psychological Review*, 117(1), 197. doi:10.1037/a0017808
- Gobet, F., & Sala, G. (2022). Cognitive training: A field in search of a phenomenon. *Perspectives on Psychological Science*, 174569162210918. doi:10.1177/17456916221091830
- Goldberg, A. (2005). *Constructions at work: The nature of generalization in language*. New York: Oxford University Press.
- Golden, C. J. (1978). *Stroop color and word test: A manual for clinical and experimental uses*. Chicago, IL: Stoelting Co.
- Goldstein, T. R., & Lerner, M. D. (2018). Dramatic pretend play games uniquely improve emotional control in young children. *Developmental Science*, 21(4), e12603. doi:10.1111/desc.12603

- Goldwater, S., Griffiths, T. L., & Johnson, M. (2009). A bayesian framework for word segmentation: Exploring the effects of context. *Cognition*, *112*(1), 21–54. doi:10.1016/j.cognition.2009.03.008
- Gopnik, A. (2020). Childhood as a solution to explore-exploit tensions. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *375*(1803), 20190502. doi:10.1098/rstb.2019.0502
- Gopnik, A., & Rosati, A. (2001). Duck or rabbit? Reversing ambiguous figures and understanding ambiguous representations. *Developmental Science*, *4*(2), 175–183. doi:10.1111/1467-7687.00163
- Goswami, U. (2001). Analogical reasoning in children. In D. Gentner, K. J. Holyoak, & B. N. Kokinov (Eds.), *The analogical mind: Perspectives from cognitive science* (pp. 437–470). Cambridge, MA: MIT Press.
- Griffiths, T. L., & Austerweil, J. (2008). Analyzing human feature learning as nonparametric Bayesian inference. *Advances in Neural Information Processing Systems*, *21*, 97–104.
- Gupta, R., Kar, B. R., & Srinivasan, N. (2009). Development of task switching and post-error-slowness in children. *Behaviour and Brain Function*, *5*(1), 38. doi:10.1186/1744-9081-5-38
- Haith, M. (1980). *Rules that babies look by: The organization of newborn visual activity*. Hillsdale, NJ: Erlbaum.
- Hill, W. L., Borovsky, D., & Rovee-Collier, C. (1988). Continuities in infant memory development. *Developmental Psychobiology*, *21*(1), 43–62. doi:10.1002/dev.420210104
- Holmboe, K., Bonneville-Roussy, A., Csibra, G., & Johnson, M. (2018). Longitudinal development of attention and inhibitory control during the first year of life. *Developmental Science*, *21*(6), e12690. doi:10.1111/desc.12690
- Hsu, V. C. (2010). Time windows in retention over the first year-and-a-half of life: Spacing effects. *Developmental Psychobiology*, *52*(8), 764–774. doi:10.1002/dev.20472
- Ibbotson, P. (2020). *What it takes to talk: Exploring developmental cognitive linguistics*. Berlin/Boston: DeGruyter Mouton.
- Ibbotson, P., & Kearvell-White, J. (2015). Inhibitory control predicts grammatical ability. *Plos One*, *10*(12), e0145030. doi:10.1371/journal.pone.0145030
- Jacobs, R., Harvey, A. S., & Anderson, V. (2011). Are executive skills primarily mediated by the prefrontal cortex in childhood? Examination of focal brain lesions in childhood. *Cortex*, *47*(7), 808–824. doi:10.1016/j.cortex.2010.06.002
- Judd, N., & Klingberg, T. (2021). Training spatial cognition enhances mathematical learning in a randomized study of 17,000 children. *Nature Human Behaviour*, *5*(11), 1548–1554. doi:10.1038/s41562-021-01118-4
- Karbach, J., & Kray, J. (2009). How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science*, *12*(6), 978–990. doi:10.1111/j.1467-7687.2009.00846.x
- Karmiloff-Smith, A. (1979). Micro- and macro-developmental changes in language acquisition and other representational systems. *Cognitive Science*, *3*(2), 81–118. doi:10.1207/s15516709cog0302_1
- Karmiloff-Smith, A. (1992). *Beyond Modularity: A developmental perspective on cognitive science*. Cambridge, MA: MIT Press.
- Karr, J. E., Areshenkoff, C. N., Rast, P., Hofer, S. M., Iverson, G. L., & Garcia-Barrera, M. A. (2018). The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies. *Psychological Bulletin*, *144*(11), 1147–1185. doi:10.1037/bul0000160
- Kassai, R., Futo, J., Demetrovics, Z., & Takacs, Z. K. (2019). A meta-analysis of the experimental evidence on the near- and far-transfer effects among children's executive function skills. *Psychological Bulletin*, *145*(2), 165–188. doi:10.1037/bul0000180
- Kay, D., & Anglin, J. (1982). Overextension and underextension in the child's expressive and receptive speech. *Journal of Child Language*, *9*(1), 83–98. doi:10.1017/S0305000900003639
- Kemp, C., Tenenbaum, J. B., Niyogi, S., & Griffiths, T. L. (2010). A probabilistic model of theory formation. *Cognition*, *114*(2), 165–196. doi:10.1016/j.cognition.2009.09.003
- Kirkham, N. Z., Cruess, L., & Diamond, A. (2003). Helping children apply their knowledge to their behavior on a dimension-switching task. *Developmental Science*, *6*, 449–467.
- Klingberg, T. (2010). Training and plasticity of working memory. *Trends in Cognitive Sciences*, *14*(7), 317–324. doi:10.1016/j.tics.2010.05.002

- Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlström, K., Gillberg, C. G., Forsberg, H., & Westerberg, H. (2005). Computerized training of working memory in children with ADHD—a randomized, controlled trial. *Journal of the American Academy of Child and Adolescent Psychiatry*, 44(2), 177–186. [10.1097/00004583-200502000-00010](https://doi.org/10.1097/00004583-200502000-00010)
- Lee, K., Bull, R., & Ho, R. M. H. (2013). Developmental changes in executive functioning. *Child Development*, 84(6), 1933–1953. doi:[10.1111/cdev.12096](https://doi.org/10.1111/cdev.12096)
- Luciana, M., Conklin, H. M., Hooper, C. J., & Yarger, R. S. (2005). The development of nonverbal working memory and executive control processes in adolescents. *Child Development*, 76(3), 697–712. doi:[10.1111/j.1467-8624.2005.00872.x](https://doi.org/10.1111/j.1467-8624.2005.00872.x)
- Melby-Lervåg, M., Redick, T. S., & Hulme, C. (2016). Working memory training does not improve performance on measures of intelligence or other measures of “Far transfer”: Evidence from a meta-analytic review. *Perspectives on Psychological Science: a Journal of the Association for Psychological Science*, 11(4), 512–534. doi:[10.1177/1745691616635612](https://doi.org/10.1177/1745691616635612)
- Messer, D., Kearvell-White, J., Danielsson, H., Faulkner, D., Henry, L., & Ibbotson, P. (2022). The structure of executive functioning in 11 to 14 year olds with and without special educational needs. *British Journal of Developmental Psychology*, 40(3), 453–470. doi:[10.1111/bjdp.12418](https://doi.org/10.1111/bjdp.12418)
- Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: Four general conclusions. *Current Directions in Psychological Sciences*, 21(1), 8–14. doi:[10.1177/0963721411429458](https://doi.org/10.1177/0963721411429458)
- Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, 41(1), 49–100. doi:[10.1006/cogp.1999.0734](https://doi.org/10.1006/cogp.1999.0734)
- Moffitt, T.E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R.J., Harrington, H., . . . Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, 108(7), 2693–2698. doi:[10.1073/pnas.1010076108](https://doi.org/10.1073/pnas.1010076108)
- Müller, U., Baker, L., & Yeung, E. (2013). A developmental systems approach to executive function. *Advances in Child Development and Behavior*, 45, 39–66.
- Müller, U., & Kerns, K. (2015). The development of executive function. In L. S. Liben, Müller, U., Lerner, R. M. (Eds.), *Handbook of child psychology and developmental science*, Cognitive processes (7th ed., vol.2, pp. 571–623). Hoboken, NJ: Wiley.
- Munakata, Y., Snyder, H. R., & Chatham, C. H. (2012). Developing cognitive control: Three key transitions. *Current Directions in Psychological Science*, 21(2), 71–77. doi:[10.1177/0963721412436807](https://doi.org/10.1177/0963721412436807)
- Nigg, J. T. (2000). On inhibition/disinhibition in developmental psychopathology: Views from cognitive and personality psychology and a working inhibition taxonomy. *Psychological Bulletin*, 126(2), 220–246. doi:[10.1037/0033-2909.126.2.220](https://doi.org/10.1037/0033-2909.126.2.220)
- Rattermann, M. J., & Gentner, D. (1998). More evidence for a relational shift in the development of analogy: Children’s performance on a causal-mapping task. *Cognitive Development*, 13(4), 453–478. doi:[10.1016/S0885-2014\(98\)90003-X](https://doi.org/10.1016/S0885-2014(98)90003-X)
- Reynolds, G. D., Courage, M. L., & Richards, J. E. (2013). The development of attention. In D. Reisberg (Ed.), *The Oxford Handbook of cognitive psychology* (pp. 1000–1013). New York: Oxford University Press. <https://doi.org/10.1093/oxfordhob/9780195376746.013.0063>
- Roque-Gutierrez, E., & Ibbotson, P. (2022). Working memory training improves children’s syntax ability but not vice versa: A randomized control trial. *Journal of Experimental Child Psychology*, 227, 105593. <https://doi.org/10.1016/j.jecp.2022.105593>
- Ruff, H., & Capozzoli, M. (2003). Development of attention and distractibility in the first 4 years of life. *Developmental Psychology*, 39(5), 877–890. doi:[10.1037/0012-1649.39.5.877](https://doi.org/10.1037/0012-1649.39.5.877)
- Shokrkon, A., & Nicoladis, E. (2022). The directionality of the relationship between executive functions and language skills: A literature review. *Frontiers in Psychology*, 13. doi:[10.3389/fpsyg.2022.848696](https://doi.org/10.3389/fpsyg.2022.848696)
- Simpson, A., & Carroll, D. J. (2019). Understanding early inhibitory development: Distinguishing two ways that children use inhibitory control. *Child Development*, 90(5), 1459–1473. doi:[10.1111/cdev.13283](https://doi.org/10.1111/cdev.13283)

- St. Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition and working memory. *Quarterly Journal of Experimental Psychology*, 59(4), 745–759. doi:10.1080/17470210500162854
- Taylor, P., Hobbs, J. N., Burroni, J., & Siegelmann, H. T. (2015). The global landscape of cognition: Hierarchical aggregation as an organizational principle of human cortical networks and functions. *Scientific Reports*, 5(1), 18112. doi:10.1038/srep18112
- Tomasello, M. (2003). *Constructing a language. A usage-based theory of language acquisition*. Cambridge, MA: Harvard University Press.
- Tooley U.A., Park, A.T., Leonard, J.A., Boroshok, A.L., McDermott, C.L., Tisdall, M.D., Bassett, D.S., Mackey, A.P. (2022). The age of reason: Functional brain network development during childhood. *The Journal of Neuroscience : the Official Journal of the Society For Neuroscience*: 42(44), 8237–8251. doi:10.1523/JNEUROSCI.0511-22.2022.
- Werchan, D. M., & Amso, D. (2017). A novel ecological account of prefrontal cortex functional development. *Psychological Review*, 124(6), 720–739. doi:10.1037/rev0000078
- Werker, J., & Tees, R. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, 7(1), 49–63. doi:10.1016/S0163-6383(84)80022-3
- White, L. J., Alexander, A., & Greenfield, D. B. (2017). The relationship between executive functioning and language: Examining vocabulary, syntax, and language learning in preschoolers attending head start. *Journal of Experimental Child Psychology*, 164, 16–31. doi:10.1016/j.jecp.2017.06.010
- Woodard, K., Pozzan, L., & Trueswell, J. C. (2016). Taking your own path: Individual differences in executive function and language processing skills in child learners. *Journal of Experimental Child Psychology*, 141, 187–209. doi:10.1016/j.jecp.2015.08.005
- Yanaoka, K., Michaelson, L. E., Guild, R. M., Dostart, G., Yonehiro, J., Saito, S., & Munakata, Y. (2022). Cultures crossing: The power of habit in delaying gratification. *Psychological Science*, 33(7), 1172–1181. doi:10.1177/09567976221074650
- Yuile, A. R., & Sabbagh, M. A. (2021). Inhibitory control and preschoolers' use of irregular past tense verbs. *Journal of Child Language*, 48(3), 480–498. doi:10.1017/S0305000920000355
- Zelazo, P. D., Müller, U., Frye, D., and Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development*, 68(3), vii–137. doi:10.1111/j.0037-976X.2003.00260.x