MIND, BRAIN, AND EDUCATION

Do Younger Children Benefit More From Cognitive and Academic Interventions? How Training Studies Can Provide Insights Into Developmental Changes in Plasticity

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ABSTRACT— Educational interventions are frequently designed to occur during early childhood, based on the idea that earlier intervention will have greater long-term academic benefits. However, surprisingly little is known about when cognitive and academic skills are most plastic, or malleable, during development. One way to study plasticity is to ask whether learning from targeted practice varies as a function of age. In this review, we summarize behavioral and neuroimaging studies that have tested for age-related differences in cognitive training gains, for executive functions, and for academic skills (reading and math). Findings are mixed, with no clear evidence for an overall younger age benefit. We discuss current challenges and opportunities for leveraging research on cognitive and brain plasticity to inform the timing and content of early academic interventions.

It is commonly argued that educational interventions should occur very early in childhood, in order to yield the best possible outcomes later in life. This argument stems in part from evidence showing that (1) the developing brain is highly malleable, or plastic (Hensch & Bilimoria, 2012), (2) there are large economic benefits to investing in early childhood (Doyle, Harmon, Heckman, & Tremblay, 2009), and (3) early interventions can prevent learning disabilities (Shaywitz, Morris, & Shaywitz, 2008). Motivated by this evidence, intervention programs have been launched with a specific focus on preschool, and recommendations put forth that interventions should be designed for children prior to the age of three (Black et al., 2017). However, from a neuroscience perspective, little is currently known about the timing of peak plasticity in the neural systems that support cognitive and academic skills. Further, there is even some evidence that certain interventions for parenting (Gardner et al., 2019) and social skills (de Mooij, Fekkes, Scholte, & Overbeek, 2020) are not differentially effective during childhood.

Based on research in animal models, we know that there are *critical periods* in development, when specific environmental inputs are required for normal development, as well as *sensitive periods*, when neural systems are particularly malleable (Hensch & Bilimoria, 2012). But to date, we know very little about the timing and duration of such sensitive periods in humans, particularly for higher-level cognitive skills, which have a protracted developmental time course. It is also possible that certain abilities will be more plastic during later stages like adolescence because of changing developmental priorities, for example, social development (Fuhrmann, Knoll, & Blakemore, 2015; Larsen & Luna, 2018). Thus, it is still an open question whether

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intervention programs will necessarily have the greatest benefit in early childhood.

One promising avenue for addressing this question in humans is through training studies, in which individuals receive extended practice in a specific skill. Training studies in developmental populations are particularly useful because not only do they allow us to make inferences about the causal impact of specific enrichment experiences on behavioral outcomes (Thompson & Steinbeis, 2020), but they also help with disentangling experience-based changes from underlying maturational changes (Rosenberg-Lee, 2018; Rosenberg-Lee et al., 2018). Most developmental training studies to date have focused on the question of *transfer*: if individuals are trained on skills like executive functions, does this then have cascading effects on academic achievement (Katz, Shah, & Meyer, 2018; Strobach & Karbach, 2016)? Although there is evidence for near transfer to closely related tasks, studies frequently fail to find improvements on more theoretically distant tasks ("far transfer") (Kassai, Futo, Demetrovics, & Takacs, 2019; Melby-Lervåg, Redick, & Hulme, 2016).

In light of these controversies in transfer research, we instead propose the approach of leveraging training itself as an experimental tool for probing the brain's malleability across development. Specifically, if we compare training gains—the degree of improvement on a training task—across different ages, and simultaneously capture neuroimaging markers of plasticity, we may learn more about the sensitive periods of specific cognitive skills. Neuroimaging has the potential to provide insights that would be difficult to access with behavior alone, such as training-induced brain changes that precede visible behavioral changes. We could then use this basic science framework to design interventions that strengthen cognitive skills at the most effective ages. We discuss selected empirical studies that directly test for effects of age on training gains, as well as meta-analyses of age effects. We first review three basic executive functions (inhibitory control, cognitive flexibility, and working memory). We next review academic skills (reading and math), which rely on structured, hierarchical skills, and therefore present unique challenges for studying windows of plasticity. Finally, we draw insights from the few neuroimaging studies that have examined age as a moderator of training-related brain changes. We provide a theoretical framework to motivate future empirical research on age-related differences in responsiveness to cognitive skills training across development.

EXECUTIVE FUNCTIONS

Executive functions (EFs) are goal-oriented cognitive processes that allow people to flexibly manage tasks, engage in higher-level reasoning, plan ahead, and exert top-down regulation over their behavior (Miyake & Friedman, 2012). EFs in early childhood are important for school readiness (Blair, 2002), and predict later literacy and numeracy skills (Fuhs, Nesbitt, Farran, & Dong, 2014). EF improves rapidly during early childhood (Carlson, 2005; Garon, Bryson, & Smith, 2008) until about age 9 or 10 (Akshoomoff et al., 2014), and then continues to improve more gradually into adulthood (Luna, Garver, Urban, Lazar, & Sweeney, 2004). Improvement in EFs is related to changes in the frontoparietal network (Engelhardt, Harden, Tucker-Drob, & Church, 2019), including functional changes like increased connectivity within the frontoparietal network (Shanmugan & Satterthwaite, 2016), as well as structural changes like cortical thinning (Kharitonova, Martin, Gabrieli, & Sheridan, 2013). Below, we review the current evidence for age-related differences in training gains for three EFs: (1) Inhibitory control, (2) cognitive flexibility, and (3) working memory (Figure 1). Because we are proposing that training studies could shed light on sensitive periods in underlying cognitive processes, we focus mainly on studies that trained specific skills, instead of studies that trained multiple EFs simultaneously or took a holistic intervention approach.

Inhibitory Control

Inhibitory control is the ability to suppress distracting information in order to complete a task (Spierer, Chavan, & Manuel, 2013). In one study, 4- and 5-year-olds ($n = 47$) were trained on a variety of inhibition games, and younger children were found to benefit more from training (Volckaert & Noël, 2015). Another study ($n = 123$) provided computerized training to older children (ages 9–10) and adolescents (ages 15–17), including a Stroop task (inhibiting task-irrelevant information) and a stop-signal task (inhibiting an initiated motor response) (Delalande et al., 2020). They found training-related improvements on inhibitory control in children (only boys, not girls), but not in adolescents. This study raises important questions about how the interaction between age and sex differences (e.g., via differences in pubertal hormone development) may influence the timing of sensitive periods (Laube, van den Bos, & Fandakova, 2020).

Cognitive Flexibility

Cognitive flexibility refers to the ability to shift adaptively between changing tasks or mental representations (Buttelmann & Karbach, 2017). Two studies have examined cognitive flexibility training across the lifespan. One study tested three age groups ($n = 168$; 8- to 10-year-olds, 18- to 28-year-olds, 62- to 77-year-olds), and found that children and older adults showed the greatest reduction in

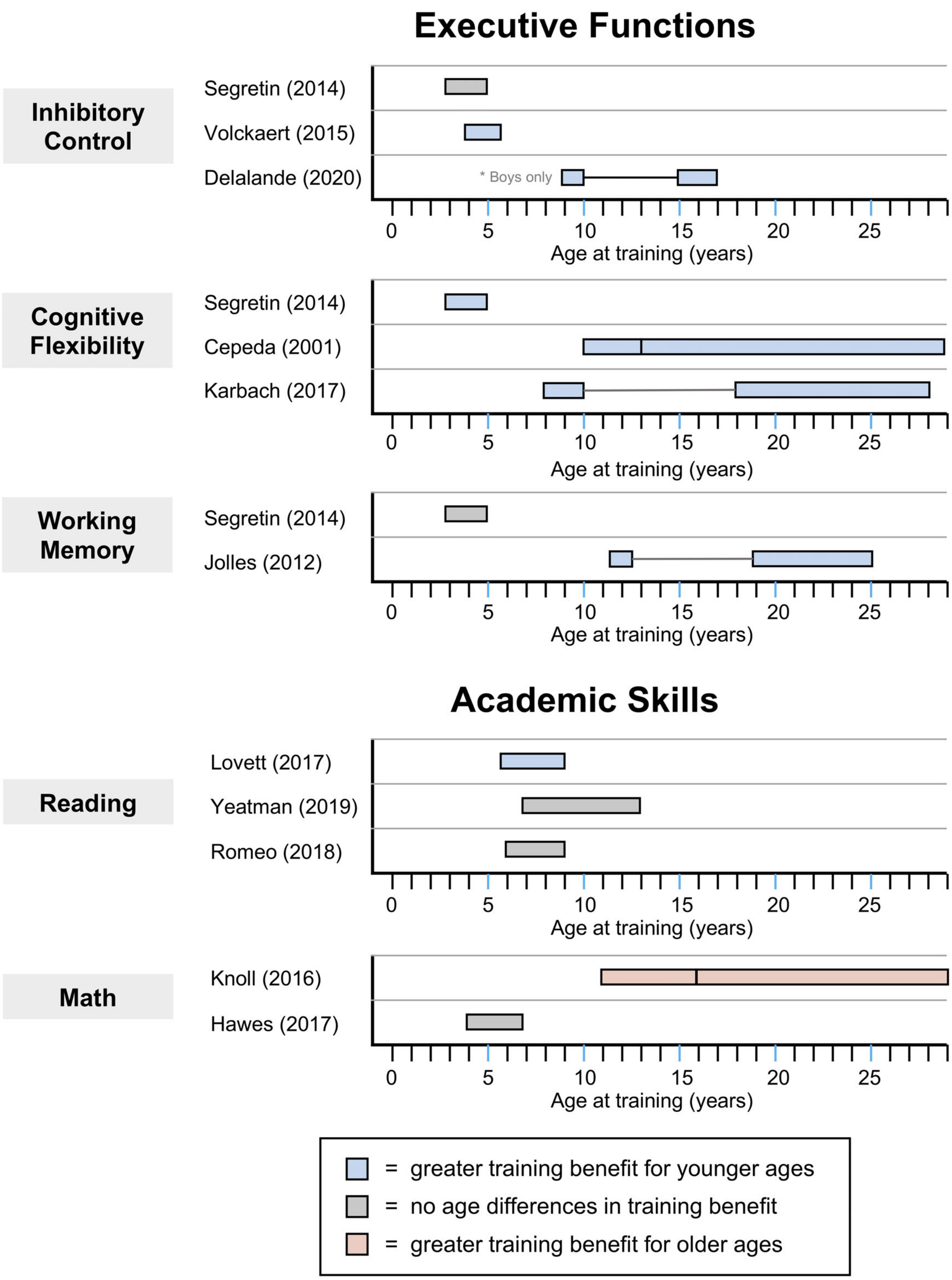

Fig. 1. Developmental training studies that test for a moderating effect of age. The figure presents empirical studies (by first author) that test for a moderating effect of age, within the domains of executive functions (EFs) (inhibitory control, cognitive flexibility, and working memory), and academic skills (reading and math). Blue indicates that the younger participants in the study showed greater training improvements, red indicates that older participants improved more, and gray indicates no age difference. Rows with a single rectangle show studies that tested for a moderating effect of age within a continuous age range, while rows with two rectangles show studies that tested for differences between two age groups. See the main text for discussion of meta-analyses, which are not shown in the figure.

switch costs, compared to young adults (Karbach, Könen, & Spengler, 2017); another study included the full lifespan ($n = 152$, ages 7–82), and found the greatest improvement for 10- to 12-year-olds (Cepeda, Kramer, & Gonzalez de Sather, 2001). Next, we highlight a randomized controlled study that directly compared age effects on different EF skill modules (Segretin et al., 2014). In this study, 3- to 5-year-old children were trained as part of a broader intervention program for children living in poverty, with modules on cognitive flexibility, inhibitory control, working memory, attention, and planning. For cognitive flexibility ($n = 329$), younger age was associated with greater training gains; no moderating effects of age were found for any of the other cognitive skills. This study illustrates how future research could systematically train different EF subcomponents and directly compare training gains as a function of age.

Working Memory

Working memory refers to the ability to manipulate and maintain a limited amount of information (Constantinidis & Klingberg, 2016). There is some evidence for younger individuals showing greater improvements on untrained, closely related tasks ("near transfer") (Melby-Lervåg & Hulme, 2013; Wass, Scerif, & Johnson, 2012), but do younger children also show greater responsiveness to training itself? A recent meta-analysis of working memory training studies in typically developing children and adolescents (mean ages 4–15) found no effects of age on training gains (Sala & Gobet, 2020). On the other hand, in meta-analyses that include children with learning disabilities, findings are mixed for whether children younger or older than age 10 show greater improvements (Melby-Lervåg & Hulme, 2013; Peijnenborgh, Hurks, Aldenkamp, Vles, & Hendriksen, 2016). This discrepancy underscores the importance of examining both typically developing and clinical populations, as there may be factors like disorder-related differences in plasticity or in beliefs about the value of training that additionally interact with age.

Neuroimaging Studies of Executive Function Training

To our knowledge, very few studies have directly tested for age-related differences in how the brain responds to EF training in childhood. In a pilot study with functional magnetic resonance imaging (MRI), Jolles, van Buchem, Rombouts, and Crone (2012) studied working memory training in 12-year-olds ($n = 11$) and young adults ($n = 15$), and found that the children were able to reach adult-like performance, and showed increases in frontoparietal activation. In an attention training study, Rueda, Rothbart, McCandliss, Saccomanno, and Posner (2005) compared 4-year-old ($n = 49$) and 6-year-old ($n = 24$) children and found that 4-year-olds showed a greater reduction in reaction time on an independent executive attention task, suggesting steeper improvement in resolving attentional conflict. Electroencephalography (EEG) recordings were simultaneously collected: following training, 4-year-olds showed patterns in executive attention brain regions that were similar to that of 6-year-olds, whereas the 6-year-olds became more similar to adults. This study reveals training-induced brain changes that recapitulate typical maturational improvements in executive attention. However, the magnitude of brain changes was not compared between groups. In a training study of inhibitory control, Delalande et al. (2020) compared children (ages 9–10) and adolescents (ages 15–17) using structural MRI. They found that boys but not girls in the child group showed improvements in inhibitory control, while the adolescent group did not. Behavioral improvement was related to a complex pattern of structural brain changes, such as changes in the inferior frontal gyrus, a region of prefrontal cortex that is associated with inhibitory control.

In sum, few EF training studies have directly tested for age effects on responsiveness to training. Meta-analytic evidence of working memory training in children and adolescents finds no effect of age (Sala & Gobet, 2020). Also, we note that a recent meta-analysis broadly examining EF training in 3- to 6-year-olds did not find evidence for an age effect (Scionti, Cavallero, Zogmaister, & Marzocchi, 2019), suggesting that the assumption of an overall younger age benefit may be more complicated than previously thought. Additional empirical studies are needed to more systematically test for peak periods of sensitivity.

ACADEMIC SKILLS

Reading

Early reading ability is pivotal for later academic success (Cunningham & Stanovich, 1997). Learning to read is a complex process that builds upon lower-level perceptual and language-related skills, including orthographic processing (visualizing written language) and phonological awareness (processing the sound structure of words) (Hulme & Snowling, 2013). In the domain of speech perception, it has been suggested that there may be staggered and cascading sensitive periods for subcomponent skills, with downstream effects on language outcomes (Werker & Hensch, 2015). Similarly, in order to design better reading interventions, it may be useful to examine whether there are sensitive periods for underlying reading-related skills.

Earlier remediation of reading difficulties has been shown to lead to better outcomes (Gabrieli, 2009; Shaywitz et al., 2008). One study found that children who met a low-achievement criterion for reading disabilities showed better reading outcomes if they received reading support in first or second grade (ages 6–8), as compared to third grade (age 8) and onwards (Lovett et al., 2017). However, two meta-analyses in grade-school children with reading difficulties did not find that children's grade at the time of reading intervention was predictive of improvements, for kindergarten through third grade (ages 5–9) (Lam & McMaster, 2014; Wanzek et al., 2016), and fourth to ninth grade (ages 9–15) (Wanzek et al., 2013). This suggests that children from a broad range of ages may stand to benefit from reading interventions.

In addition to assessing reading interventions holistically, it is also informative to examine interventions that target specific underlying skills (Melby-Lervåg & Lervåg, 2014). Meta-analyses of phonological awareness instruction find that preschoolers and kindergarteners (ages 4–6) benefit more than older grades, perhaps because they start out with the least amount of experience and have more room to grow (Bus & Van Ijzendoorn, 1999; Ehri et al., 2001), or because their auditory systems are more plastic (Werker & Hensch, 2015). Similarly, another meta-analysis found that phonics-related interventions are more effective in kindergarten and first grade (ages 5–7), while comprehension-related interventions are more effective starting around third grade (age 8) (Suggate, 2010). This underscores the importance of considering the role of hierarchical skill development (i.e., how learning complex skills depends on successful learning of earlier, more basic skills). Thus, we acknowledge that mapping out windows of plasticity may be challenging in the academic domain, and that it may be more fruitful to focus on perceptual precursors of reading success, like phonological awareness, rather than on content-based skills like reading comprehension. Sensitive periods for reading-related skills and for EFs will also undoubtedly interact, as EFs are integral to the academic context.

Neuroimaging Studies

One notable study directly examined the impact of an intensive reading intervention program on white matter plasticity changes in 7- to 13-year-olds with dyslexia or parent-reported reading difficulties (Yeatman & Huber, 2019). The intervention consisted of 8 weeks of the Seeing Stars program, which focuses on training orthographic and phonological processing skills. Contrary to their predictions, the authors found that in this age range, younger and older children showed equivalent gains in reading accuracy and reading rate, and also showed white matter changes of similar magnitude and time course. The authors give the caveat that there could be a sensitive period earlier in development, prior to age 7. It may also be that intensive reading interventions are still effective even in older children, perhaps suggesting plasticity over a broader age range than previously anticipated. Another study using the same reading intervention program in 6- to 9-year-olds with reading disabilities ($n = 65$) similarly found no effects of age (Romeo et al., 2018).

Math

Like reading, learning math is important for success in school, as well as for engagement in science, technology, engineering, and mathematics (STEM) fields later in life (Duncan et al., 2007). Early numeracy skills are important predictors of math achievement (Libertus, Feigenson, & Halberda, 2011; Raghubar & Barnes, 2017), and interventions have been developed to support children with math-related difficulties (Dowker, 2017). Recent evidence suggests that nonsymbolic numerical representations, referred to as the approximate number system (ANS), may act as a scaffold for later symbolic math achievement (Dehaene, 2011). Also, meta-analytic evidence finds that the correlation between nonsymbolic numerical understanding and math achievement is strongest in children younger than age 6 (Fazio, Bailey, Thompson, & Siegler, 2014). It would therefore be informative to probe whether the ANS is most trainable at particular ages.

Some studies have found that ANS training results in improved math performance in children (Bugden, DeWind, & Brannon, 2016; Park, Bermudez, Roberts, & Brannon, 2016; Szkudlarek & Brannon, 2018) (although note a recent failure to replicate; Bugden, Szkudlarek, & Brannon, 2021). One study examined participants across a broad age range (ages 11–33, $n = 229$) for multiple types of training, including ANS numerosity discrimination (Knoll et al., 2016). The numerosity discrimination training involved looking at dot arrays composed of two different colors, and indicating the color of the more numerous dots. Greater training gains were found for older adolescents and adults, compared to younger adolescents (although the authors note that these results weakened after controlling for design-related confounds). It could be that plasticity of the ANS is sustained over a broad age range, or could reflect better use of strategy in older participants. One caveat is that this study had no participants who were younger than age 11.

In addition to nonsymbolic number skills, spatial skills (e.g., mental rotation, geometry) are another important component of mathematics education. A 1-year classroom geometrical and spatial thinking intervention in 4- to 7-year-olds ($n = 39$) found that spatial skill improvements did not vary by age (Hawes, Moss, Caswell, Naqvi, & MacKinnon, 2017). Relatedly, meta-analyses on spatial skills training in childhood (0–8-year-olds; Yang, Liu, Chen, Xu, & Lin, 2020) and spanning childhood to young adulthood (Uttal et al., 2013) also did not find age effects. Spatial skills appear to be malleable across a wide age range.

Neuroimaging Studies

In a study by Rosenberg-Lee et al. (2018), 8- and 9-year-olds (n = 19) went through an intensive one-on-one math intervention designed to improve arithmetic skills, and participated in MRI scanning before and after the intervention. Exposure to the math intervention resulted in increased activity in the hippocampus, as well as increases in functional connectivity between the hippocampus and the intraparietal sulcus (a region implicated in math skills). These training effects recapitulated developmental brain changes, suggesting that training on this particular skill led to earlier maturation rather than to compensatory effects. However, because the age range was so narrow, age effects on training responsiveness could not be evaluated.

DISCUSSION

When is the best time to intervene to improve children's cognitive and academic skills? Is younger truly better across the board, or can we tailor interventions to target cognitive systems during windows when there will be greater benefits? In this review, we discussed studies that explicitly tested for age-related differences in training gains, in EFs and academic skills (reading and math). So far, a few meta-analyses of EF training studies in children and adolescents have found no age effects (Sala & Gobet, 2020; Scionti et al., 2019), raising the possibility that there may not be a clear overall younger age benefit as previously suggested. In the academic domain, complex reading interventions may show plasticity over wider age ranges than previously thought (Yeatman & Huber, 2019). On the other hand, in studies that individually targeted skills like phonological awareness, there is some evidence from meta-analyses for a benefit to intervening at early grade levels (Bus & Van Ijzendoorn, 1999; Ehri et al., 2001), while interventions for more complex abilities, like reading comprehension, become more important later on (Suggate, 2010). In the domain of math learning, a few studies on numerosity discrimination and spatial skills training suggest malleability across a broad age range (Knoll et al., 2016; Uttal et al., 2013). However, more work is needed to tease apart whether we should nonetheless prioritize early intervention for foundational skills that serve as gatekeepers for later academic abilities.

Challenges

To our knowledge, only a few studies have directly tested for moderating effects of age on training gains. Some studies compared older children or adolescents with adults (Cepeda et al., 2001; Jolles et al., 2012; Karbach et al., 2017; Knoll et al., 2016), but did not include younger children, meaning that we lack data on the very age group that could be more plastic. Future studies could address this gap in knowledge by designing training studies that are well-suited for a broad age range. Another methodological approach would be to perform meta-analyses to rigorously test for age differences across existing training studies.

However, there are major challenges to examining a behavioral construct across many ages. Studies differ widely on factors like the duration, adaptiveness, or "gamification" of the training task (Green et al., 2019), which could introduce age-related confounds. It can also be unclear whether younger children are approaching the training task in the same way as older participants. For example, children may vary in their strategies, underlying motivations (e.g., external vs. intrinsic rewards), or higher-order beliefs about the trainability of particular skills (Jaeggi, Buschkuehl, Shah, & Jonides, 2014; Kinlaw & Kurtz-Costes, 2007; Schroder et al., 2017). This can complicate our assessment of the neuroplasticity of a specific cognitive skill, as other neural systems are also undoubtedly involved, each with their own complex developmental trajectories. Relatedly, the hierarchical nature of academic interventions presents challenges for studying plasticity, that is, older children may show larger gains not because of greater plasticity, but because they had more time and opportunity to develop the prerequisite skills, or could better leverage effective strategies. On the flipside, there may be domains where younger children show larger gains because they have more room to grow, compared to older children who are at ceiling performance (Karbach et al., 2017). When comparing across development, it is possible that both patterns could be present, making it challenging to differentiate between training gains that are attributable to strategy selection versus true neuroplasticity (Lövdén, Brehmer, Li, & Lindenberger, 2012).

Finally, although here we have emphasized isolating specific cognitive skills, in the real-world children's cognitive abilities do not operate or develop independently. Rather, interventions may be maximally effective when they incorporate support for children's emotional and social development (Diamond, 2012). Thus, while narrowly defined training studies provide the methodological rigor needed for identifying sensitive periods, they may come at a cost to ecological validity. Future work should therefore additionally investigate whether there are age-related differences in the likelihood of *transfer* (i.e., whether there are specific ages where critical ingredients like social support and motivation tend to encourage meaningful boosts to cognition in the real world).

Opportunities

By designing studies that systematically test for age-related differences in training gains, we can develop a better understanding of when intervention programs will be effective (Figure 2). Some skills might show early peaks in plasticity

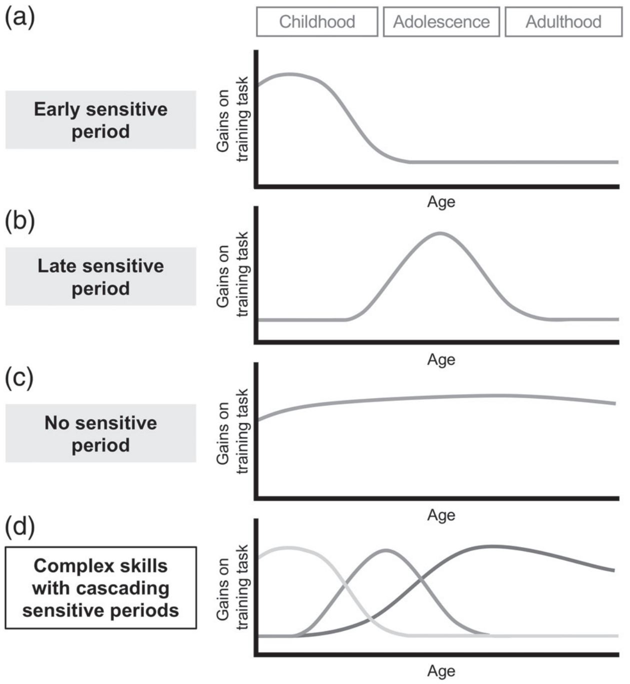

Fig. 2. Schematic illustrating possible patterns of training task gains, which could be useful for identifying sensitive periods in cognitive functions. Individual skills may be more easily targeted during specific developmental windows, as certain skills could be (a) more malleable early in development, (b) more malleable late in development, or (c) malleable across much of development with no clear sensitive period. Empirical training studies can address this hypothesis by directly testing for moderating effects of age on training gains. (d) It is thought that certain complex abilities have subcomponent skills with cascading sensitive periods that build on each other, as in the case of language development (Werker & Hensch, 2015), and in structured, hierarchical academic domains like reading and math.

(Figure 2a). For example, inhibitory control is thought to mature earlier than cognitive flexibility and working memory (Best & Miller, 2010; Crone & Steinbeis, 2017; Huizinga, Dolan, & van der Molen, 2006). Other skills may be better targeted in older children (Figure 2b), or may remain malleable throughout development (Figure 2c). Domains with hierarchical, cumulative skill development may show cascading sensitive periods (Figure 2d). For example, complex cognitive skills like reasoning first build off of more basic EFs like working memory and processing speed (Fry & Hale, 1996). Training certain higher-level cognitive functions at younger ages may therefore not be sustainable. There are also many other complex abilities beyond basic cognitive skills that are critical for boosting children's learning, and it should be explored whether they have sensitive periods of their own. Examples include meta-cognitive skills (which also draw upon lower-level EFs) and socioemotional processing, as well as behaviors like curiosity that emerge from the interaction between learning, memory, and motivational systems.

In addition to the timing of sensitive periods, we could also learn more about their *limits* by examining age-related differences in the *maintenance* of training gains. If certain ages are less likely to maintain benefits over time, does this actually suggest that they are in a stage of greater plasticity for that particular skill? For example, a study by Kray and Fehér (2017) found that younger adults were less likely than older adults to maintain their training gains on a cognitive flexibility task. Future studies could model learning curves for individual participants (Bürki, Ludwig, Chicherio, & de Ribaupierre, 2014) in order to see how rapidly gains are lost after the end of training. It may be possible to time interventions such that they fall toward the later end of a sensitive period, so that the training benefits will be more likely to become "locked in." However, we should also be mindful of additional factors that can shape intervention fadeout, such as broader environmental contexts, like socioeconomic status, that can either support or impair the maintenance of training gains (Bailey, Duncan, Odgers, & Yu, 2017). Indeed, early experiences of stress and cognitive enrichment are hypothesized to alter the pacing and plasticity of brain development (Colich, Rosen, Williams, & McLaughlin, 2020; McDermott et al., 2021; Tooley, Bassett, & Mackey, 2021).

Finally, neuroimaging methods provide the unique opportunity to expand upon behavioral training studies, by revealing early brain changes that have not yet manifested in behavior, and potentially improving predictions about when and how individual children respond best to intervention (Cooper & Mackey, 2016). While a number of studies have collected neuroimaging data before and after cognitive training in children (Astle, Barnes, Baker, Colclough, & Woolrich, 2015; Jolles & Crone, 2012), few have explicitly tested for a moderating effect of age on training-induced brain changes. Future training studies would be well-served by drawing from animal models of neural mechanisms of plasticity. Windows of plasticity are constrained by factors like increased growth of myelin and increased inhibitory neurotransmission, and enhanced by neurotransmitters like dopamine and acetylcholine (Hensch & Bilimoria, 2012). We can use MRI to generate novel proxy measures of plasticity that quantify myelination in humans, with techniques like cortical thickness (Natu et al., 2019), the ratio of T1-weighted and T2-weighted MRI intensities (Glasser & Van Essen, 2011), and myelin water fraction (Deoni et al., 2016). While less well-understood, inhibitory neurotransmission processes may be related to the functional segregation of brain networks, which can be measured using resting-state functional MRI methods (Kraft et al., 2020). Neuroimaging can also capture the development of neuromodulatory systems like dopamine (Larsen et al., 2020). Taken together, we can leverage neuroimaging methods to track developmental changes in biomarkers that reflect constraints on plasticity.

Considerations for Future Research

To aid researchers in designing future training studies, we close by describing potential age-related confounds that could obscure evidence for true developmental differences in plasticity.

Training Task Design

Younger children may differ from older children in their engagement during training. For example, longer or more complex tasks might fatigue or lose the attention of younger children, increasing attrition. Different ages may also vary in their familiarity with touch-screens and laptops, and in their fine-motor abilities. Careful piloting should be performed to ensure that the training task is similarly engaging and accessible across different ages. One method would be to use an adaptive design, where the task is tailored to each individual child's training trajectory, which would additionally help researchers avoid floor or ceiling effects (e.g., younger children having more room for improvement compared to older children who have maxed out). In order to make inferences about specific cognitive skills, the task should be narrowly targeted to the intended task processes, that is, making it harder to circumvent training with unrelated higher-order strategies.

Experimental Design

Researchers should carefully consider how choice of recruitment mechanisms and broader training context could introduce age-related confounds. For example, a group of teenagers recruited through social media could be demographically different from a group of college students recruited from a psychology course. Conducting the training in a classroom environment could be subject to grade-related differences in factors like level of structure, noise, and so on, whereas if training occurs at home, parents may be more or less likely to intervene during training sessions depending on child age. Researchers could also consider the time scale of training (e.g., days, weeks), and how this might interact with the pace of brain maturation or with study attrition at different ages. Longitudinal designs could improve inferences about developmental differences in plasticity by studying age effects within, rather than across, children (i.e., children could practice the same task for 1 week at age 5, and again at age 6 or 7). Finally, it is important to carefully design active and passive control conditions that can help separate out the effects of cognitive training versus maturational processes. Participants should be kept as blind to condition as possible, to mitigate age-related differences in expectations about training.

Neuroimaging Outcome Measurement

Developing novel neuroimaging markers of plasticity is still a nascent area of research, but researchers can leverage existing technologies, like MRI, EEG, and functional near-infrared spectroscopy to capture pre-/post-training brain changes. Neuroimaging measures are sensitive to motion artifacts, which could confound training-related age effects because younger children move more than older children. Depending on the studied age range, younger children may have smaller heads than older children, and therefore their brains might be further from coil elements, reducing image contrast and sensitivity. Repeated scanning can also be useful for capturing nonlinearities in brain reorganization following training. For example, cognitive training can lead to initial increases in gray matter, followed by decreases (Wenger et al., 2017). Researchers could consider ways to make repeated scanning more tractable, as younger children might be less likely to tolerate multiple scans.

Statistical Methods

Although training studies will ideally prevent age-related confounds during the design process, statistical methods can also be leveraged to help address concerns like the fact that younger children may have more room to grow. Methods like structural equation modeling (e.g., latent change models) can more rigorously address how age-related differences in baseline abilities relate to training gains (Karbach et al., 2017).

Reporting Results

Going forward, researchers conducting developmental training studies should provide effect sizes by age (i.e., not just averaging across a wide age range or comparing children vs. adolescents). Clinical training studies should report detailed age effects separately for the clinical group and for the healthy control group. Providing these results will be useful for future meta-analyses testing for age as a moderator of training gains (Yaple & Arsalidou, 2018).

CONCLUSION

There are still many open questions about windows of plasticity for specific cognitive processes, and little clear evidence for an overall younger age benefit. We argue that it would be useful for future studies to explicitly test for age-related moderation of training effects in broad age cohorts, in the hopes of putting together a more complete picture of sensitive periods for cognitive and academic skills. This is important for several reasons. First, we could use this knowledge to develop interventions that are more sensitive to the developmental timing and malleability of specific cognitive abilities (i.e., designing curricula that target skills at ages when long-term benefit is more likely). Second, by discovering which cognitive skills are most malleable, we can make more informed decisions about the kinds of interventions to invest in. There are always trade-offs to consider when deciding how a child's time should be spent in educational settings, and it would be helpful to know which cognitive functions are the most promising targets, beyond the blanket statement of "younger is better." Third, rigorously combining neuroimaging and cognitive training studies can yield basic science insights into mechanisms of brain plasticity during human development. Ultimately, a better understanding of the shape of sensitive periods will be important for investigating risk and resilience in early childhood: How can we implement positive changes when they are most likely to be maintained, and how can we best protect children from negative influences when they are most susceptible.

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