Published in final edited form as:

New Dir Child Adolesc Dev. 2019 May ; 2019(165): 25–54. doi:10.1002/cad.20292.

Cognitive, Intervention, and Neuroimaging Perspectives on Executive Function in Children with Reading Disabilities

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Abstract

The role of executive function (EF) in the reading process, and in those with reading difficulties, remains unclear. As members of the Texas Center for Learning Disabilities, we review multiple perspectives regarding EF in reading and then summarize some of our recent studies of struggling and typical readers in grades 3-5. Study 1a found a bi-factor structure best represented a comprehensive assessment of EF. Study 1b found that cognitive and behavioral measures of EF related independently to math and reading. Study 1c found that EF related to reading, above and beyond other variables, but Study 1d found no evidence that adding an EF training component improved intervention response. Study 1e found that pretest EF abilities did not relate to intervention response. Neuroimaging studies examined EF-related brain activity during both reading and non-lexical EF tasks. In Study 2a, the EF task evoked control activity, but generated no differences between struggling and typical readers. The reading task, however, had group differences in both EF and reading regions. In Study 2b, EF activity during reading at pretest was related to intervention response. Across studies, EF appears involved in the reading process. There is less evidence for general EF predicting or improving intervention outcomes.

Keywords

Executive Function; Reading; MRI; dyslexia; comprehension; review

Executive function (EF) comprises key regulatory processes that are essential for health and cognitive skill formation, support chosen goals, and are critical for the transition from child to adult-like thoughts and behaviors. Because of the importance of EF for life outcomes, researchers have been interested in understanding the relations of EF to academic skills, as

well as the neural bases of normative EF maturation (Banich, 2009; Church, Bunge, Petersen, & Schlaggar, 2017; Engelhardt, Harden, Tucker-Drob, & Church, 2019; McKenna, Rushe, & Woodcock, 2017). To address these issues, the Texas Center for Learning Disabilities (TCLD) has focused on how EF may critically support reading skill acquisition and thus be a source of discrepancy in struggling readers. We selectively review what is known about the relations of EF and reading across cognitive, behavioral, and neuroimaging domains. We first review EF, then the reading process and its associations to EF, before summarizing our recent findings from the TCLD regarding EF across multiple domains.

Executive Function

The study of EF is at once fascinating and frustrating. It is fascinating because at a broad conceptual level, the idea of higher-order cognitive processes that control multiple specific moment-to-moment functions resonates with the acknowledgement that humans' complex cognitive activities are multiply determined and in need of coordination. EF is considered strong when goals are consistently met, especially in the face of obstacles to that goal (e.g., delays, distraction, and barriers). EF is also adaptable and dynamic – cognitive flexibility and inhibition of intentions are required when not all task parameters are known, when task parameters change, or when environmental variables change.

To the extent that this hypothesized control system is tractable from measurement and mechanistic perspectives, then the study of EF has great potential for increasing our understanding of control-demanding processing (which supports nearly all day-to-day activities) (Cirino et al., 2018; Petersen & Posner, 2012; Posner & Petersen, 1990). EF impairments are seen transdiagnostically, and poor EF is related to poorer physical and mental health (Hall, Elias, & Crossley, 2006; Snyder, 2013; Snyder, Miyake, & Hankin, 2015). Further, EF may be particularly essential for activities that are difficult to learn, or that require significant attentional demand. EF may be especially employed or needed by individuals who struggle to a greater extent than most with a given activity (e.g., reading). Alternatively, poor EF could be at the root of academic skill difficulty. Thus, there is strong interest in how EF abilities, and how interventions that target EF may impact educational and academic skill intervention efforts in children who struggle with reading and math.

As studies try and pin EF abilities and relations to academic abilities down, however, numerous obstacles can be encountered, leading to frustration with the concept of EF. First, there is the term EF itself: this paper uses “EF” to refer to an overarching general control capacity of an individual, while recognizing that multiple cognitive processes support that ability, that vary in their associability and dissociability. Across different fields the term EF can mean different things, and different terms can refer to the same or similar cognitive processes or abilities. The term EF is perhaps most closely related to the field of neuropsychology (Burgess, 1997). In neuropsychology, EF is often referred to as those functions that are disrupted by damage to the brain, especially the frontal lobes, including impulsivity and inhibition, inner speech, self-concept, and generative fluency (Cummings & Miller, 2007; Gazzaley & D'Esposito, 2007). In cognitive fields, EF research has largely focused on cognitive skills with or without reference to the brain, including goal-directed behaviors: planning, shifting, inhibition, and working memory updating demands (Miyake et

al., 2000). In developmental or educational psychology, “self-regulation” is a more commonly used umbrella term to refer to EF-related skills such as performance monitoring, solution generating, and meta-cognition (Boekaerts, 1997; Hofmann, Schmeichel, & Baddeley, 2012). In neuroimaging, EF is sometimes characterized as a specific set of behavioral abilities, in line with neuropsychology or cognitive science, while brain supports for EF abilities may be referred to as “executive” or “cognitive control” regions or networks (Church et al., 2017; Dosenbach et al., 2007; Posner & Petersen, 1990). Researchers also vary as to whether they consider these terms entirely overlapping, or whether one of the terms encompasses the other in addition to other abilities (or vice-versa).

Other terms that are used (sometimes interchangeably) with EF include: (a) attentional control (often used to represent inhibitory control in young children, (Allan & Lonigan, 2014)); (b) controlled attention (the aspect of working memory that distributes its resources, Kane, Bleckley, Conway, & Engle, 2001); or (c) executive attention (Engle, 2018; Kane & Engle, 2002; Rueda, Posner, & Rothbart, 2005). Here, we use the term EF to mean a “domain-general ability important for managing goal-directed behavior” (Cirino et al., 2018), but recognize the large gap between such conceptual definitions and the way that EF is captured in empirical studies, where it typically includes a range of (particularly performance-based) manifest measures that purport to measure individual aspects of EF.

Another frustrating aspect of EF, beyond its name, is its definition. If EF refers to a list or set of other abilities (e.g., working memory, inhibition, flexibility), they each can be studied in turn, and different tasks can attempt to elicit more or less EF demand. But, breaking down EF into its constituent factors can result in its “epiphenomenal” characteristics becoming increasingly hard to find. We want to attribute to EF all of its fascinating cognitive control elements, yet still be able to measure it discretely, and to separate it from all other constructs. Task impurity, or inclusion of variance related to non-EF task aspects, as well as task-specific and task-general EF variance can make measurement challenging (Miyake et al., 2000). Additionally, it is well known that some individual measures of EF have internal consistency values that are surprisingly weak. On the other hand, composite or latent EF measures can show rather strong relations with one another, as well as with a range of other cognitive composites, including IQ (Engelhardt et al., 2016), language (Christopher et al., 2012; Unsworth, Spillers, & Brewer, 2011), and visuospatial (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2002) abilities.

Models of EF are now more regularly recognizing and also modeling, a unity and diversity framework, such that different EF tasks generally correlate with each other, reflecting general EF ability, but are also somewhat separable (Miyake & Friedman, 2012), with some specific aspects of EF not separable from general EF. The estimation of EF from multiple tasks can vary from a unitary construct in young children (Wiebe et al., 2011), to a bifactor model in children (Cirino et al., 2018) to a common factor model in children and adults (Engelhardt, Briley, Mann, Harden, & Tucker-Drob, 2015; Miyake et al., 2000), to a hierarchical model in older adolescents and adults (Miyake & Friedman, 2012).

In line with an overarching “unity” model, a consistent set of brain regions has emerged as active during moments in time when control is needed (e.g. task initiation, inhibition, task

maintenance, error processing; Aron, Robbins, & Poldrack, 2004; Dosenbach et al., 2006; Luna, Marek, Larsen, Tervo-Clemmens, & Chahal, 2015; Neta et al., 2015). These brain regions include the anterior cingulate, bilateral frontal operculum, and dorsal aspects of frontal and parietal cortex. Further, these brain regions correlate together at rest, forming putative cingulo-opercular and fronto-parietal control networks (Power et al., 2011; Power & Petersen, 2013; Yeo et al., 2011). Resting-state functional correlations of brain networks may reflect a history of frequent co-activation of these regions in an individual (Power, Schlaggar, & Petersen, 2014).

These common EF brain networks are found to be consistently active across performance of multiple behavioral EF tasks in adults (Niendam et al., 2012) and in children (Church et al., 2017; McKenna et al., 2017; Engelhardt, Harden, Tucker-Drob, & Church, 2019). Structural brain changes in the same regions may relate to ongoing behavioral improvement of EF skills throughout adolescence and young adulthood. Protracted maturation (e.g. synaptic pruning) of gray matter is observed in prefrontal cortex from inferior-medial to superior-dorsal regions (Paus, 2005). Concurrently, long-range white matter pathways connecting prefrontal subregions with other brain areas undergo maturational changes in myelination and fiber density, presumably supporting the functional control network communication just described (Gogtay et al., 2004; Lebel & Beaulieu, 2011; Sowell et al., 2004).

A challenge in EF research is moving beyond overlap/shared variance with related constructs to discern what is unique about EF in terms of the role it may play in an academic skill or intervention-focused context. Recent work from the TCLD examines the role EF plays in struggling readers, both at baseline and related to intervention outcome (see studies below).

Reading

The Reading Brain

It is well known that reading is a non-evolutionary skill, co-opting visual and language brain processes to decipher written words. Our understanding of what happens in the “reading brain” is fairly well known and nuanced, but it is not the primary focus here. Thus, we provide a simplified overview. Word reading-related brain regions include three bilateral (but often stronger on left) swaths of cortex: (1) a ventral system involving the occipital region extending to the basal surface of the temporal lobe (occipito-temporal) that permits rapid processing of orthographic (visual) features of words; (2) a dorsal sublexical system involving the posterior portion of the superior and middle temporal gyri, extending into inferior parietal areas (temporo-parietal), that is thought to map phonemes and graphemes (sound correspondence to letter forms); and (3) inferior frontal lobe regions, which are thought to be critical to subvocal articulation processes (Dehaene, 2009; Price, 2012; Pugh et al., 2000). The ventral and dorsal systems are typically underactivated in readers with poor decoding abilities, with less consistent reports of either underactivation and overactivation in the frontal regions of poor readers (Cutting et al., 2013; Hancock, Richlan, & Hoeft, 2017; Richlan, Kronbichler, & Wimmer, 2011). Some studies have reported a difference of activation in struggling readers in regions that overlap with the EF literature, including right frontal regions or inferior parietal cortex. Differences in these putative

executive control regions has increased interest in elucidating the role EF differences may play in struggling readers (Hoeft et al., 2007) .

Imaging studies using sentence-level tasks in struggling readers are less common but they appear to find similar activation patterns as single words in the two reading areas described above (phonology and orthography), as well as in semantic-related regions (Harm & Seidenberg, 2004; Seidenberg, 2017; Taylor, Rastle, & Davis, 2013). However, sentence level tasks also tax comprehension abilities more than single-word reading, and comprehension abilities have been shown to rely more on non-language-specific abilities, potentially indicating a stronger role of EF (Anderson et al., 2018; Berninger, Richards & Abbott, 2017; Kronbichler et al., 2006; Langer, Benjamin, Minas, & Gaab, 2015; Rimrodt et al., 2009; Schulz et al., 2008; Schulz et al., 2009). Consistent with greater control demand, neuroimaging studies of sentence reading have found activation differences related to reading ability in fronto-parietal and cingulo-opercular control networks (Aboud, Bailey, Petrill, & Cutting, 2016; Meyler, Keller, Cherkassky, Gabrieli, & Just, 2008; Roe et al., 2018).

Reading Predictors

Much is already known about the behavioral correlates of reading, how to provide reading instruction, and how to address reading difficulties (Fletcher, Lyon, Fuchs, & Barnes, 2018; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Of the many processes that have to come together for fluent reading, phonological skills are strongly implicated in developing word level identification skills (Wagner & Torgesen, 1987; Wagner et al., 1997). Phonology and word-level identification skills have bidirectional relations with one another (Wagner et al., 1994). Phonological skills are multifaceted and develop in complexity over childhood (e.g., Anthony et al., 2002; Lonigan et al., 2009). Other early skills (print awareness, letter identification, environmental exposure) help bootstrap phonological skills in the preschool years (e.g., Lonigan, Allan, & Phillips, 2017; Whitehurst & Lonigan, 1998). There is recognition that phonological training impacts reading itself, but that it does so in a more forceful way when print is incorporated (National Reading Panel, 2000).

As young children pass through their early elementary years, sound and word identification give way to fluency, and the language predictors that capture the ability to quickly recognize symbolic print (e.g., rapid automatized naming) also promote reading skill (e.g., Norton & Wolf, 2012; Wolf, Bowers, & Biddle, 2000). As word reading skill becomes automatic, there is increased focus on reading comprehension, and the reliance on additional language and cognitive processes generically characterized as listening comprehension becomes increasingly important, above and beyond individual word reading itself (e.g., as espoused by the Simple View of Reading; Gough & Tunmer, 1986; Torppa et al., 2016; see a recent special series in Remedial and Special Education, Vaughn, 2018). Vocabulary size tends to be a consistent reading predictor throughout development (Lee, 2011), though its effects are not always discernable in the context of the other language predictors mentioned above.

Because reading comprehension is a more complex process than reading individual words, predictors of comprehension are more varied than for word level skills, and include skills beyond the domain of language. An important non-language domain skillset that potentially

relates to reading comprehension performance is EF. Because comprehension is complex, it seems plausible that addressing difficulties of comprehension might lean on the supervisory and coordinating aspects of EF. There is clear agreement that there are relations between EF and reading (e.g., Follmer, 2018; Jacob & Parkinson, 2015), and strong theoretical reasons for these relations, particularly for comprehension (Aboud et al., 2016; Butterfuss & Kendeou, 2017; Cutting, Bailey, Barquero, & Aboud, 2015). EF abilities have been shown to predict reading comprehension performance on school assessments (Fuhs, Nesbitt, Farran, & Dong, 2014; Gathercole, Pickering, Knight, & Stegmann, 2004) and in experimental studies (e.g. Borella, Carretti, & Pelegrina, 2010; Swanson, 2011), regardless of the ages studied or the types of tasks used to measure both constructs (Follmer, 2018). However, many of the studies examined small samples and/or specific populations, or typical readers (Follmer, 2018). Struggling readers may need to rely more on EF to coordinate disparate cognitive functions to facilitate the fluent reading process.

Reading Intervention

When considering struggling readers, efficacious interventions are a necessary research and practical priority. For young students with reading difficulties (e.g., K to 3rd), there is agreement surrounding effective remediation characteristics, including systematic and explicit instruction of graded intensity and a focus on extending the range of print materials (National Early Literacy Panel, 2008; Wanzek & Vaughn, 2007). Yet, this approach to intervention shows a decreasing gradient of effectiveness with older students (Kamil et al., 2008; Scammacca et al., 2016; Vaughn et al., 2010). Potential reasons for this decrease in effectiveness include an increasing emphasis over age on comprehension of complex materials, failure to respond to earlier interventions (resulting in greater severity or intractability of older children's reading difficulties), and/or an increased reliance on non-language skillsets, like inference-making and background knowledge as reading becomes a primary means for instruction in multiple fields (Barnes, Ahmed, Barth, & Francis, 2015; Compton, Fuchs, Fuchs, Elleman, & Gilbert, 2008; Kieffer, Vukovic, & Berry, 2013).

Despite what is known about intervening to enhance reading, there are pieces that remain surprisingly sparse, including the way that EF might intersect with intervention for struggling readers. For example, there is little evidence that training programs focused on EF outside the context of reading promote reading outcomes (Jacob & Parkinson, 2015). Where EF has been evaluated as a cognitive training method, it has typically been done via working memory training, seeking to boost the underlying cognitive skill (memory) rather than the academic outcome. Given the purpose of many such studies, academic outcomes are not always measured, though when they are, EF training studies show little transfer to academic skill (Melby-Lervåg & Hulme, 2013; Shipstead, Redick, & Engle, 2012). While training underlying EF components is one way to go about attempting to improve reading skills, fewer studies have attempted to incorporate EF explicitly into text-based reading intervention. However, it is important to note, that there is an entire related literature on self-regulated learning and its potential for improving academic outcomes, including reading (Dignath, Buettner, & Langfeldt, 2008), writing (Graham & Harris, 1997), and math (Fuchs et al., 2003). This literature underscores our earlier discussion regarding the differences in terminology surrounding EF and EF-related processes; many of the studies just noted do not

use the term “EF”, but may have important relevant findings to the relation between EF and reading ability.

Overview of TCLD

One of the overarching goals of the Texas Center for Learning Disabilities (TCLD) 2011-2017 was to address several of the above issues regarding EFs and reading, particularly in terms of its potential influence in struggling reader brain and behavior, and on the role of EF in reading intervention. For example, our cognitive project aimed to clarify the structure of EF, to use EF to predict important reading outcomes, and to evaluate the role of EF in intervention, both on a small scale, and in the context of our larger intervention project. The imaging project addressed EF from a complementary perspective; it sought to evaluate whether executive control networks in the brain differed in struggling readers in structure or function, and whether struggling readers who experienced gains in reading from intervention engaged EF regions differently.

Our focus on the relations of reading and EF, and in particular the consideration of struggling readers, was relevant for several reasons. First, reading is a goal-directed activity – precisely one of those complex cognitive activities that requires coordination of other systems. This coordination is especially needed for reading comprehension, for which EF has been considered to play a strong role (Butterfuss & Kendeou, 2017; Hudson, Scheff, Tarsha, & Cutting, 2016). Second, as noted earlier, individuals who have particular difficulty learning how to read could potentially also have weaker EF ability undergirding that difficulty or conversely may rely on stronger EF ability to compensate for language skill deficits. Third, most attempts at directly improving EF have occurred via working memory training in isolation, rather than combining EF training activities to target transfer skills, including reading and other aspects of academic achievement. Fourth, the cognitive correlates of reading are well established (Fletcher, Lyon, Fuchs, & Barnes, 2018), and the prominent brain circuitry involved in many aspects of reading is also increasingly understood (Seidenberg, 2017), thus providing a strong context in which to evaluate the role for EF in reading. Below, we summarize results of several studies involving EF and reading in middle childhood.

1. Behavioral Studies of EF and Reading

Study 1a (Cirino et al., 2018)—As noted from the review above, EF is conceptualized in differing manners that include not only the type of measures utilized (e.g., the behavioral and performance measures such as those employed in Gerst, Cirino, Fletcher, & Yoshida, 2017, described below, but also including overlap of EFs with other constructs including self-regulated learning and metacognition, as noted in the developmental and educational literatures (Cirino et al., 2017; Connor et al., 2016). The premise of this study was that components of EF could be separated from one another (and that more than the three components of (Miyake et al., 2000) – updating, inhibition, and shifting – could be distinguished), but also that these components share varying degrees of overlap versus separability. Until recently, structural understanding of EF had focused primarily on children prior to or concomitant with the onset of schooling (e.g., Wiebe et al., 2011; Willoughby,

Blair, Wirth, & Greenberg, 2010) or in adults (e.g., Miyake et al., 2000), leaving open many questions about the structure of EFs in middle childhood.

This study included 846 students across grades 3 to 5, across 2 urban school districts. The sample was diverse, and included a large sample of struggling readers, reflecting the sample overlap with the large TCLD intervention study (Vaughn, Solis, Miciak, Taylor, & Fletcher, 2016). Twenty-seven measures of EF were administered (with planned missingness) to fully represent all considered domains. While not all hypotheses were confirmed (e.g., latent relations among individual components were much stronger than anticipated), a bifactor model provided a strong fit with the data. In the model, in addition to a common EF factor, five individual factors were also identified (two that involved working memory, one of these focused on updating; one each in generative fluency, self-regulated learning, and metacognitive ratings). Notably, this model fit better than corresponding models that focused on method variance. Shifting and inhibition latent variables were absorbed into common EF, which was not particularly surprising, especially with respect to inhibition (Friedman et al., 2008; van der Sluis, de Jong, & van der Leij, 2004), and consistent with other models that have previously combined these two factors (e.g., Lee, Bull, & Ho, 2013; van der Ven, Kroesbergen, Boom, & Leseman, 2013). Notably, manifest indicators overall correlated quite poorly with one another (median $r = .15$), although examination of other factor analytic studies (e.g., Lee et al., 2013; Miyake et al., 2000; Wiebe, Espy, & Charak, 2008) revealed only slightly higher intercorrelations. These results support the continued viewing of EF as unity in the face of diversity; the general coherence was strong, but the most separable components were those of self-regulated learning, metacognition, and working memory as updating. Future measurement studies might more strongly disambiguate such factors, with contrasting methodology (e.g., crossing type of measure with factor), and studies using the framework need to relate this structure to relevant outcomes (e.g., achievement), as well as consider its utility for what it might mean for how components might be considered within an intervention context. A recent effort in our work to relate EF ability to achievement is described next.

Study 1b (Gerst et al., 2017)—The premise of this study was that because EF is measured in multiple ways, and because these contrasting types of measures tend to not relate well to one another (Toplak, West, & Stanovich, 2013), it was unclear which EF aspects or measures would best predict academic outcomes. This study included an unselected sample of 93 students in grades 4 and 5 from a large, diverse, urban school district, who provided multiple measures of both behavioral ratings of EF by teachers and performance measures of EF, as well as assessments of reading comprehension and math calculations. Specifically, four domains of EF were included: working memory, inhibition, shifting, and planning. Behavioral ratings of EF provided by teachers were much more strongly related to one another (range $r = .72$ to $.91$) than were performance measures (range $r = .22$ to $.48$); notably, cross-domain relations (e.g., behavioral ratings of working memory and performance measures of working memory) were low (range $r = .19$ to $.40$). On their own, both performance and behavioral EF measures related significantly to both reading and math achievement outcomes. Even when multiple relevant covariates (demographics as well as language variables) were included, EF measures contributed uniquely to both reading

comprehension (R^2 of 8%), and particularly, math computations (R^2 of 23%). At least one behavioral EF measure, and at least one performance EF measure uniquely predicted both reading comprehension and math computations. Thus, the conclusion from this study was that not only do both behavioral and performance measures of EF measures relate to academic success, but that they relate in a complimentary manner. We next delved deeper into the impact of EF measures on reading success.

Study 1c (Cirino et al., in press)—Although approximately a dozen studies have evaluated multiple aspects of EF in relation to multiple aspects of reading, none have done so on a large scale (with regard to EF coverage, sample size), while controlling for multiple robust demographic and cognitive covariates. Beyond covariates per se, the Simple View of Reading (SVR; Gough & Tunmer, 1986; Catts et al., 2006; Foorman, Petscher, & Herrera, 2018) has had a strong influence on understanding reading; it was important to conceptualize any role for EF in predicting reading, while also considering SVR variables. If EF were considered alone, it would be unclear if any such effects would remain after accounting for what are known to be robust correlates of reading performance. It was expected that common EF would have the strongest predictive value, and that the role of EFs would be stronger for comprehension than more basic types of reading. In addition, a possible interaction of EFs with the SVR variables was also hypothesized. This study utilized the same sample as (Cirino et al., 2018; Study 1a), and applied its findings to multiple reading outcomes, including single word reading, fluency, and two types of reading comprehension.

For all reading outcomes, EFs provided a unique contribution above and beyond robust language and demographic variables. This contribution was particularly relevant given that baseline models without EFs accounted for 50% to 70% variance in reading performance. The type and amount of unique influence varied. For single word reading, the group of EF variables added 3% additional variance, but did not interact with language variables, and notably, common EF was not one of the significant predictors (only metacognition was a unique predictor). EF variables added a similar amount of variance for single word fluency, and included various EF variables (with the largest unique contribution for specific working memory), but again EF variables did not interact with language variables. However, for comprehension, while the unique added variance was similar (~3%), common EF was a strongest unique predictor, and the overall proportion of variance was higher than for single word models. Common EF and working memory (with aspects of complex span and manipulation, combined with planning, or as updating) were the only variables to interact with SVR variables, which is perhaps not surprising given the large literature that implicates working memory for the reading process, particularly for comprehension (e.g., Follmer, 2018; Peng et al., 2018). The interaction effects were the most novel finding from Cirino et al. (in press). For example, for the Gates-MacGinitie Reading Test of reading comprehension (MacGinitie, MacGinitie, Maria, & Dreyer, 2000), the EF effect appeared to be compensatory. That is, SVR variables showed an interaction with one another only when common EF was low. This result implies that reading comprehension performance is dominated by these language variables; at higher levels of EF, strong reading comprehension might be achieved even when one of the core SVR components is weak. In other cases, the

EF effect seemed to be one of “thresholding” where the interaction of specific EF (as working memory, either as updating, or as span/manipulation) with SVR components occurred only when EF was high, suggesting that its effect was to amplify the impact of these variables, particularly on listening comprehension skills.

While these results are intriguing, replication is necessary. Of note, EF exhibited substantial shared variance with other variables in these prediction models (particularly with language measures). This means that despite clear unique contributions, employing EF in interventions will be complicated by the difficulty in manipulating EF components independently. These results also indicate that perhaps the most promising way to utilize EF for intervention is within the context of well-established interventions rather than outside of them. We examined this idea in the next study.

Study 1d (Cirino et al., 2017)—This analysis directly tested whether EF components could in fact be manipulated to improve reading. The goal was to build specific self-regulated learning principles into an already conceptually strong reading intervention approach to test for an additional boost in learning gains. Struggling readers (defined on the basis of comprehension, $n = 75$) were randomized into a text-based reading condition (TB), a second condition where self-regulated learning/EF components were added (TB+EF), or to business-as-usual control. This design reflected two assumptions. First, that targeting pure cognitive aspects of EF was not likely to be fruitful, given the results of meta-analytic work (Melby-Lervåg & Hulme, 2013); further, the process of self-regulated learning (invoking components of forethought, performance, and reflection; Zimmerman, Abrams, Giuliano, Denckla, & Singer, 2000) lends itself well to reading for understanding. Second, we assumed it relevant to contrast any intervention with added EF components with a more recognized approach that did not remove any “naturally occurring” self-regulated learning components. For example, motivation, monitoring of performance, and directing attention are commonplace in individualized and small group tutoring, such that it would be artificial to remove such elements to create a “low EF” condition. Nonetheless, we hypothesized that the TB+EF would outperform the TB group, who would in turn outperform the control group on tasks related to taught and untaught text comprehension.

The results did not support our hypotheses. That is, although background knowledge on topics contained within taught intervention texts improved significantly in both intervention groups relative to controls ($d = +.94$ for TB; $+1.09$ for TB+EF), and similarly significantly improved with regard to comprehension of taught texts ($d = +.71$ and $+.42$, respectively), these results showed little transfer to untaught texts and topics. Such transfer was weak and nonsignificant for both topically related text learning ($d = +.42$ and $+.23$, respectively), and for unrelated text learning, where effect sizes were negligible.

These results, while disappointing, are an important piece in understanding how to incorporate and evaluate aspects of EF training in reading interventions. First, we recognized the artificiality of a “low EF” or “non EF” comparison condition, as many instructional components that may be construed as “EF training” must also be recognized as fundamental to all teaching tasks (i.e., motivating students, directing attention, and monitoring comprehension). It is possible that more robust EF impacts would have been obtained if the

point of comparison was an artificially low EF intervention that contained no emphasis on self-regulatory input, but we contend such a comparison is minimally informative. The critical instructional question is whether the systematic inclusion of explicit EF training activities can improve intervention outcomes beyond that which might occur naturally within typical instruction. Thus, we situate the findings of this study among others that find generally weak support for specifically addressing EF skills in intervention, while acknowledging that the corpus of such studies is small. The last behavioral study we summarize here tests how EF ability may relate to the propensity to respond to an in-school reading intervention.

Study 1e (Miciak, Cirino, Ahmed, Reid, & Vaughn, 2018)—In the final behavioral study, we sought to investigate the role of EF in predicting how struggling readers respond to intensive reading interventions. In educational research fields, there is considerable interest in the cognitive and behavioral characteristics of students who inadequately respond to generally effective, evidence-based interventions (Al Otaiba & Fuchs, 2002; Nelson, Benner, & Gonzalez, 2003), because students with academic difficulties demonstrate heterogeneous educational experiences, and there are multiple potential etiologies for observed learning difficulties (Fletcher & Vaughn, 2009). Studies of the cognitive and behavioral characteristics of inadequate responders evaluate individual students' response to a standardized intervention in an attempt to better understand whether individual characteristics like EF are associated with differential individual response (Fletcher et al., 2011; Miciak, Taylor, Denton, & Fletcher, 2015). These data are useful in educational contexts because knowledge of differential intervention response may help identify students who are unlikely to respond to standardized interventions, facilitating earlier changes to their intervention regime and potentially improving academic outcomes. Additionally, because the focus of intensive academic interventions is not EF training per se, such analyses test a different hypothesis about how EF may relate to academic outcomes like reading. That is, the test is whether domain general cognitive control processes like EF facilitate acquisition of domain-specific skills in the presence of robust instruction.

In study 1e, we evaluated whether students who responded adequately and inadequately to an intensive reading intervention differed in EF skills at pretest. Data were generated from students who participated in both the large measurement study of EF (study 1a, Cirino et al., 2018) and an intensive reading intervention study (Vaughn et al., 2016; $n = 231$). Participants from the intervention study were classified as Adequate Responders ($n = 64$) and Inadequate Responders ($n = 167$) based on post-intervention performance on two standardized measures of reading comprehension. We also included 74 students without reading difficulties who completed the large measurement study and were evaluated at the end of school-year posttest as a comparison group or benchmark (Typicals). The three groups (Inadequate Responders, Adequate Responders, and Typicals) were compared on factor scores derived from the large EF measurement study and reflecting the final bifactor EF model described in study 1a from (Cirino et al., 2018): common EF + five factors (Metacognition, Fluency, Self-Regulated Learning, Working Memory/Planning, and Working Memory/Updating). Few differences between the three reader groups emerged, and there were no statistically significant differences between the Inadequate Responder group

and the Adequate Responder group; EF performance at pretest was not predictive of responder status.

Results across these five studies suggest further complexity in how we must interpret the composition of EF (study 1b), and the role of EF in reading and reading intervention among struggling readers. While studies 1a and 1c found a clear, unique role for EF in predicting reading achievement at a single time point, this study (and study 1d) suggest that the role of EF as an intervention (1d) or assessment (1e) may be of limited utility in educational contexts.

2. Imaging Studies of EF and Reading

Study 2a (Roe et al., 2018)—The goal of this neuroimaging study was to test whether the brain EF network differences some studies have observed in struggling readers for reading tasks generalized to non-reading tasks. The extent of any EF brain network differences is important for clarifying the extent of any EF effects observed in struggling readers. We investigated activation in reading and EF-related brain regions during both a sentence comprehension task, and a non-lexical inhibitory control task (a visual stop-signal task). Using a subset of the 3rd-5th grade TCLD sample who participated in pre-intervention neuroimaging at our two sites, we collected high resolution structural MRI scans, diffusion tensor imaging (DTI), and functional scans (both task and rest fMRI) from struggling (n=74) and non-struggling (n=32) readers. Here, we compared brain engagement during a sentence comprehension task, where participants indicated by button press whether a sentence “made sense” or not, to brain engagement when children were successful at inhibiting (“stopping”) a prepotent “go” response to the direction of single arrows presented on the screen. Both datasets were corrected for motion (Siegel et al., 2014), and used data from participants who performed above chance (for details, see Roe et al., 2018).

The sentence comprehension task successfully elicited brain activity in reading and EF-related regions. During the task, struggling readers had significantly less activation than non-struggling readers in the left posterior temporal cortex, consistent with other studies of sentence reading, and the general neuroimaging literature of reading and language studies. Struggling readers also had greater suppressed activity (relative to fixation) in bilateral inferior parietal regions from the applied fronto-parietal EF control network; greater negative activation related to poorer reading ability measured by the TOWRE-2 task outside of the scanner. Better performance on the Woodcock Johnson Passage Comprehension task (WJ-III PC) (Woodcock, McGrew, & Mather, 2001) was associated with less anterior cingulate activity during the sentence comprehension scanner task. The anterior cingulate is part of the cingulo-opercular EF network, and this result indicates that struggling readers needed to rely on greater cingulate activity to perform the sentence comprehension task (Figure 1a,b). However, during the non-lexical EF task, the stop-signal task, despite adequate engagement in the expected brain control regions, there were no group differences between struggling and non-struggling readers, including in applied control networks (Figure 1c). Thus, differences in EF engagement in struggling readers in this study were found to be specific to reading, rather than indicative of a general EF brain network difference across tasks in children with reading difficulties. This specificity is potentially

critical information for EF-related interventions interested in improving reading. If struggling readers engagement of EF processes are typical outside of reading-related tasks, then focusing EF-related practice to reading tasks may be more optimal than a general EF intervention. Next, we studied effects in control networks related to reading intervention.

Study 2b (Nugiel et al., 2019)—In this second EF-related study, we used four standardized reading measures (TOWRE-2, WJ-III PC, WJ-III Letter Word ID, and the Gates-MacGinitie Reading Test) collected before and after the intervention treatments to evaluate expected versus actual gain in reading scores for struggling readers over time. Those struggling readers who demonstrated growth on at least 2 of the 4 measures over the school year, above what was expected for age, were grouped as “improvers” relative to those who only gained on 1 or none of the tests – “non-improvers”. We could then look at individuals who had high quality imaging data both after the 16-week interventions (“improvers” (n=15) and “non-improvers” (n=8) and prior to those interventions by back-applying these improvement labels (“future improvers” (n=19) and “future non-improvers” (n=27)). The struggling readers were pulled from the same imaging set as Study 2a (Roe et al., 2018), and thus performed the same sentence comprehension and stop-signal tasks in the scanner. We examined whether any EF brain regions related to future reading gains (at pre-intervention), or to growth in reading (at post-intervention).

We found that prior to intervention, struggling readers who go on to improve had greater engagement of the right fusiform gyrus relative to struggling readers who do not go on to improve. We also found a similar right fusiform region correlated with change in reading ability over intervention across all post-intervention struggling readers (continuous measures were used due to small group sizes). However, these results were limited to the sentence comprehension task; there were no group differences in regional brain activity for the stop-signal task even though the expected cognitive control regions were engaged by the task. Further, also during the sentence comprehension task, we found greater suppression of precuneus activity in future improvers relative to non-struggling readers, a region of the default-mode network. While not an executive control network, greater suppression of default mode network activity has been associated with greater engagement of attentional resources (Leech, Kamourieh, Beckmann, & Sharp, 2011; McKiernan, Kaufman, Kucera-Thompson, & Binder, 2003; Pearson, Heilbronner, Barack, Hayden, & Platt, 2011). Finally, a fronto-parietal control network region, the right middle temporal gyrus, was more suppressed in future non-improvers relative to non-struggling readers. Thus, struggling readers who did not go on to experience reading growth were displaying less activity in an EF brain region prior to intervention, but only in the sentence task. These results support and extend the pre-intervention results reported in Study 2a (Roe et al., 2018): changes to EF brain networks in struggling readers appear specific to a reading-related task, and do not extend to a control-demanding but non-lexical task. Subtle differences in engagement of brain regions not specific for reading (EF, default), during reading, may relate to potential response to subsequent reading intervention, but much more work is needed in this area.

Discussion

A role for EF ability in reading

The measurement, intervention, and neuroimaging studies we just reviewed converge along some important dimensions. EF plays a role in reading both behaviorally and in the brain, but less evidence was seen on both behavioral and neuroimaging fronts when relating EF to intervention outcomes. EF was variably related to different components of reading, across behavioral (both ratings and performance measures) and imaging modalities. We find this contextual effect even though EF can be reliably measured, and Study 1a supports a bi-factor model with both a common and several specific factors. Moreover, there was evidence that the common EF factor played a role in predicting reading skills via both behavioral rating and performance assessment approaches. There was an interesting interaction showing that stronger performance on the EF general factor was associated with better outcomes in poor decoders. However, the interaction was small; while the behavioral and cognitive measures predicted independently from well-known language and demographic predictors, the added variance of EF was relatively small (about 3%). In our other studies that involved intervention (Studies 1d and 1e), neither prior EF ability nor an EF training component produced differences in intervention outcomes.

The lack of robust EF differences between groups in relation to intervention response may appear contradictory to our finding of significant EF variance relating to reading skills. In Study 1b (Gerst et al., 2017), cognitive and behavioral measures of EF related independently to math and reading, with cognitive measures more related to math and with behavioral measures more related to reading. In Study 1c above and beyond language and demographic variables, EF did relate to reading skills (Cirino et al., in press). However, we found that, when investigating the intervention side of the EF-reading relation, EF components did not work well for promoting reading gains. This was true when directly testing addition of EF training components to an intervention (Study 1d; Cirino et al., 2017), and when examining pre-intervention EF ability on outcomes from a large intervention study (Study 1e; Miciak et al., 2018). To reconcile this pattern of results, it is important to parse the different analytic goals of the studies—an illustration of the complexity inherent to a program of research attempting to improve understanding of the relation between broad factors like EF and reading comprehension. In study 1b, the goal was to evaluate the relations of EFs to reading comprehension at a single point in time and within a sample that demonstrates a wide range of comprehension ability. In contrast, Study 1e, (Cirino et al., 2018) attempted to find associations between EF and individual response to an intensive reading intervention. Study 1e's goal was a more demanding one because there is typically less variance associated with changes in reading performance. Yet, analyses of this nature help to answer important questions about whether knowledge of individual students' EF profile can help predict who will or will not respond to intensive interventions, or whether routine assessment of EF is advisable for intervention planning. The negative results from Study 1e are consistent with earlier studies that question the utility of routine assessment of cognitive processes for intervention planning even though they largely did not include specific measures of EF (Fletcher & Miciak, 2017; Miciak et al., 2015; Miciak et al., 2016; Stuebing et al., 2015).

Brain EF activation differences in struggling readers are limited to reading-related tasks

Our behavioral results converged somewhat with the functional neuroimaging studies. We chose to measure brain activity in struggling readers using a non-lexical task of a specific EF (inhibitory control) that has demonstrated a significant (but weak) relation with reading comprehension (Arrington, Kulesz, Francis, Fletcher, & Barnes, 2014). This stop-signal task activated expected EF brain networks, but this activity was not related to reading comprehension ability and did not differ between struggling and non-struggling reader groups. In contrast, a sentence reading task activated regions implicated in both reading and EF demand, and some EF-related brain regions did correlate with reading ability (Roe et al., 2018). Activation of some of these regions also predicted a positive intervention response (Nugiel et al., 2019). As such, the findings are consistent with a recent study (Aboud, Barquero, & Cutting, 2018) that found that activation of both reading and cognitive control regions during a lexical decision task predicted intervention response in a group defined with poor decoding. Our groups were identified largely by poor decoding fluency and reading comprehension, showing convergence not only in struggling readers defined with different criteria, but also across single word and sentence-level fMRI tasks. While Aboud and colleagues did not have a non-lexical EF task in their study, they proposed that the interaction of brain regions involved in EF and reading tasks was necessary for a positive intervention response (Aboud et al., 2018). Our studies support this proposal, but add a critical specification: these EF activation differences in struggling and typical readers may be limited to the context of reading.

EF interventions may not result in reading improvement

All of the studies discussed here have important implications for the development of reading interventions. Consistent with meta-analytic studies of broad EF interventions (Jacob & Parkinson, 2015) and specific training of working memory (Melby-Lervåg & Hulme, 2013), there is little evidence that interventions focused on EFs in isolation of specific academic skills generalize to distal outcomes involving reading and math abilities. The use of stimulant medication in children who have comorbid reading difficulties and ADHD appears to improve behavior with little evidence of generalization to improved reading (Tamm et al., 2017). Even a skill strongly associated with reading development, phonological awareness, does not lead to improved reading if trained as an isolated auditory skill with no print component (Foorman et al., 2003).

Yet, it is important to note that all effective reading interventions include a self-regulation component embedded in the context of reading, math, and writing. The embedding of self-regulation across interventions can make it challenging to differentiate from other aspects of the intervention. It is hard to imagine an effective intervention program without a self-regulation component that teaches cognitive and behavioral strategies and promotes generalization outside the intervention context. But, as isolated training of any cognitive skill to improve academic skills lacks support, the data thus far call for interventions to focus EF-related components within the context of the academic skill needing improvement.

Conclusions and Future Directions

The issue of how EF relates to academic outcomes is far from settled, if for no other reason than the hypothesis itself remains compelling, and because it is apparent that those who struggle need help with self-regulation ability. There is a clear need for more work to further delineate how EF, whether manifest in brain metrics or behavioral performance, plays a role in the reading process. How well these components can be isolated is open to further research. It may be that future work may uncover more clever or efficient means of manipulating EF that will find better purchase in an intervention context. It may also be the case that if consistent mediators or moderators of treatment are identified that include more specific components of EF, then these specific components would be the prime ones to manipulate in an experimental context to increase reading gains.

There are some caveats to our studies. First, in the neuroimaging context, we only studied a non-lexical task that primarily tapped inhibitory control. It is possible that larger differences would be seen through tasks that push more on working memory-updating or cognitive flexibility. However, examining patterns of activity during this inhibitory EF task and comparing these patterns to those in the reading task, within the same participants, was useful and showed results that complemented one another and aligned with the behavioral studies. It may be useful to use neuroimaging to examine other aspects of EF in struggling readers, both in and out of the context of reading. Second, our studies only involved children in grades 3 to 5; additional longitudinal studies across the age range using a similarly broad approach to assessment may yield different results, and would be useful. Third, although our sample was diverse, it is possible that relations may differ among subgroups of poor readers. In particular, EF is an important issue in bilingualism. Examining behavioral and neuroimaging patterns in a large sample of English learners who vary in reading skills may be illuminating.

The treatment of EF across behavioral and imaging domains, as evaluated by the TCLD in its prior instantiation, may also provide a guide for evaluating other cognitive components of academic success. Other relevant domain general cognitive factors (e.g., attention, processing speed) may benefit from systematic evaluation of their structure, relations to outcomes, and potential for influencing intervention outcomes. To be sure, there is overlap of these constructs with EF (e.g., as noted above with the use of terms such as controlled attention, attentional control, and executive attention), but this overlap is not always examined explicitly. Because EF is conceptually quite broad, but typically measured narrowly, this mismatch can cause interpretive difficulties. To this end, the latest version of the TCLD (2018-2023) focuses on attention, which has a more mature theoretical basis than EF (e.g., Chun et al., 2011; Cooley & Morris, 1990; Dennis et al., 2008; Mirsky et al., 1991; Posner & Peterson, 1990) – the term itself is older, and the components of attention have been studied in some detail. Moreover, attention has multiple manifestations (e.g., behavioral, cognitive, neural) that may impact reading in differential ways from EF. For example, in the taxonomy of Chun et al. (2011), internal and external attention are distinguished, focused on the source of attentional interference. During reading, a loss of focus arising either endogenously or exogenously can disrupt the processes necessary to maintain meaning. In addition, the latest TCLD focuses exclusively on English learners

(Spanish-English), offering a window on this important, growing population in United States schools that has high rates of academic difficulty and is little studied.

Overall, our studies show the value of integrating studies of cognition, behavior, neuroimaging, and intervention within the same cohort. Although some sacrifices have to be made in the depth of some studies, the findings may permit a more integrated understanding of the issues underlying success and failure in the development of academic skills.

ACKNOWLEDGEMENTS

We would like to thank the Imaging Research Center at UT Austin, and the Core for Advanced MRI (CAMRI) at Baylor College of Medicine. We would like to thank the Texas Institute for Measurement, Evaluation, and Statistics, especially David Francis and Pat Taylor for their roles in the TCLD project. We would also like to thank the UT Meadows Center for Prevention of Educational Risk, especially Gregory Roberts, Garrett J Roberts, and Stephanie Stillman for their critical roles in the intervention and assessment arms of the TCLD project. We thank Mary Abbe Roe, Tehila Nugiel, Joel E. Martinez, and Annie Zheng for neuroimaging project assistance with collection and analysis. We thank Tehila Nugiel for feedback on earlier drafts. The authors declare no conflicts of interest.

FUNDING

This research was supported by grant P50 HD052117, Texas Center for Learning Disabilities, from the Eunice Kennedy Shriver National Institute of Child Health and Human Development (NICHD). The opinions expressed in the paper do not necessarily reflect the opinions of the NICHD or the National Institutes of Health.

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Figure 1.

Control activity relates to reading ability during a reading fMRI task, but not during a non-lexical EF task. A) Brain regions in the fronto-parietal (yellow regions) and cingulo-opercular (purple regions) control networks, including the dorsal anterior cingulate region of interest (ROI). B) blood oxygenation signal change in the dACC ROI during sentence comprehension correlates with out of scanner measurement Woodcock-Johnson III Passage Comprehension scores (p-value reflects FDR correction). C) Brain signal change does not correlate with Passage Comprehension scores during a non-lexical inhibition task, the Stop Signal Task (SST). Figure adapted from Roe et al., 2018.