CHAPTER 9

Attention-Deficit/Hyperactivity Disorder, Executive Function, and Reading Comprehension

Different but Related

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In the 10 years since the publication of the first edition of the *Handbook of Learning Disabilities*, there has been a marked shift in the focus of research directed at Kennedy Krieger Institute. There is no longer an emphasis on profiles of genetic syndromes that have a high incidence of learning disabilities (LD). Rather, during the period of time leading up to this second edition, the research has been largely school-based and focused on common childhood disorders, specifically, attention-deficit/hyperactivity disorder (ADHD) and various types of reading disabilities (RD). The future directions listed at the conclusion of the first edition's chapter have in fact become the focus of the most recent and current research program. Indeed, as was stated in our chapter in the previous edition of the *Handbook*, "much remains to be understood about the complex interrelationships between executive function, language, and academic skills other than basic reading, such as reading comprehension" (Cutting & Denckla, 2003).

During the period of time leading up to this second edition, research projects within the Center for the Study of Reading Development (CSRD) and in affiliated research grants in the research group all involve the systematic study of the interrelationships between the development of executive function (EF), language, and academic skills in grades 4–8, the stages of academic challenge in which "learning to read" is expected to turn into "reading to learn" (Chall, 1983; Snow, Burns, & Griffin, 1998). In addition, insights gained from directly addressing the topics of interest emanating from the diagnosis of ADHD in girls (with boys as a control group) provided further insights into executive behaviors. For all projects, because further elucidating brain–behavior linkages is the end goal, neuroimaging and behavioral methods (cognitive testing and experimental paradigms) and the correlation between these two levels of inquiry, and data, are utilized. In this chapter, we address research findings that relate to (1) ADHD specifically and, more broadly, (2) EF as it pertains to reading comprehension.

Attention-Deficit/Hyperactivity Disorder

The research agenda in Project 3 within the CSRD (Project 3; E. Mark Mahone, Principal Investigator) and affiliated grants (R01s; Martha B. Denckla and E. Mark Mahone, Principal Investigators) has focused on understanding the learning difficulties associated with ADHD, even when basic academic and oral language skills are within adequate levels of functioning, as well as distinctions between boys and girls with ADHD. The inspirations for the proposed and carried out CSRD ADHD research came from three sources: (1) clinical experience that young children with ADHD and good achievement in kindergarten through second grade "grew into" LD categorization by fourth grade; (2) unpublished data that confirmed the clinical experience, based on Learning Disabilities Research Center (LDRC) 1989–1999 data, with years of follow-up visits demonstrating that "ADHD, no LD" changed into "ADHD and LD" as educational demands increased in reading comprehension and written expression; and (3) a published study from that early LDRC of verbal learning (using the California Verbal Learning Test for Children [CVLT-C]) demonstrating significant verbal retention deficits associated with ADHD (Cutting, Koth, Mahone, & Denckla, 2003). Specifically, despite nearly equivalent encoding of a word list over five trials, children (8–12 years of age) with ADHD who did not have any basic reading or math weaknesses did not retain the information, after a 20-minute delay, as well as their typically developing peers; their grouping strategies were not as well developed and their repetitiousness per trial revealed poor working memory (keeping track of answers already given) and even their "yes–no" recognition trial results revealed poor retention commensurate with retrieval of words on the list. Findings are consistent with clinical experience with the CVLT-C scores of children with ADHD, with internal detail revealing repetitiousness within trials, an indicator of weak working memory (perhaps combined with weak self-monitoring), anecdotally the most consistently reproduced low score.

Working within a model wherein executive function/dysfunction is viewed as the neuropsychological overlap zone between ADHD and LD (Denckla, 1996), Project 3's goal within the CSRD was to operationalize from the "menu" of EFs the factors most probably relevant to reading across grades 4–8, with a specific focus on understanding more about the cognitive and reading weaknesses associated with a population of children with ADHD who had normal word-level and oral language skills. Because of previous research showing that deficits in working memory and processing speed are common to both ADHD and RD (Willcutt, et al., 2001; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005), these two factors were chosen as particular foci of Project 3. These factors lent themselves to linkages spanning psychoeducational, neuropsychological, and neuroimaging domains, and thus allowed for moving translationally into practical educational implications, while moving scientifically into brain systems and circuits.

Processing Speed

Two different findings from Project 3 are particularly pertinent to the overall theme of trying to understand more about processing speed (Jacobson et al., 2011; Li et al., 2009). To understand more about why children with ADHD show a slowing on rapid automatized naming (RAN) tasks, researchers (Denckla & Rudel, 1976; Li et al., 2009; Tannock, Martinussen, & Frijters, 2000) examined different components of RAN (colors, numbers, letters) by disambiguating vocal responses into intraindividual pause and articulation times in 31 children (19 children with ADHD and impairment on at least one of three reading comprehension scores but adequate word-level skills, and 12 controls). While RAN deficits are typically thought of as being related to basic reading deficits, children with ADHD who do not have any basic reading or oral language deficits have been found to show a marked slowing on RAN (Tannock et al., 2000). The hypothesized relationship between the slowing on RAN tasks and ADHD is thought to be related to the response time (and associated variability) inherent in RAN tasks, thus capturing the components of "processing speed" that overlap with parts of EF at its most basic level. Findings from Li and colleagues (2009) revealed that pause time *variability* (but not pause time or articulation time per se) for RAN numbers and letters correlated with reading comprehension performance. Additionally, pause times for all conditions (RAN colors, letters, and numbers) were inversely correlated with passage reading fluency scores. Finally, hierarchical regression analyses of combined groups revealed that pause time was a predictor of reading fluency, as well as RAN performance in all conditions; however, there were no significant differences between groups. Therefore, while the results supported the inference that different aspects of RAN performance are related to different aspects of reading fluency and comprehension, these findings were not specific to children with ADHD as an underpinning of their reading comprehension level. Nevertheless, findings suggested that these aspects of RAN serve as a variety of markers, particularly variability in the response time, for the response preparation aspect basic to executive control functions.

In another study focusing on processing speed, Jacobson et al. (2011) undertook an analysis of a Wechsler Intelligence Scale for Children–IV (WISC-IV) processing speed subtest, Coding. The purpose of this study was to take the construct of "processing speed" and to determine which components of executive control underlie the "processing speed deficit" in ADHD, which in turn were thought to be related to reading fluency. Forty-one children with ADHD and 21 controls received both the traditional Coding subtest and a "Copy Code" version (WISC-IV as a process instrument; Wechsler et al., 2004). Measures of reading fluency, working memory, and auditory attention span were also administered. Children with ADHD showed reduced fluency for both oral and silent reading, as well as reduced processing speed; however, when the components of Coding were examined, children with ADHD did not differ from typically developing controls on simple copying speed, which is a measure derived by taking the familiar Coding subtest and simply having children copy the symbols directly below, rather than having to derive a "code" for what was placed in a box for the time sample. Furthermore, after controlling for copying speed, IQ, and severity of ADHD questionnaire-derived scores, slowed "processing speed" was significantly associated with verbal working memory only, not with measures of response control or response inhibition, lexical retrieval speed, reaction time, or intrasubject variability. WISC-IV Coding, dependent on verbal working memory, was an oral reading fluency predictor. Controlling for even more variables, such as ADHD symptom/sign severity, reaction time, lexical and retrieval speed, and inhibition, maintained the finding that WISC-IV Coding, residualized for Copy Speed, was predicted by verbal (not spatial) working memory and in turn predicted oral reading fluency. This again suggests that the "spotlight" is on the output-related (anterior brain–mediated) rather than the attentional or perceptual (posterior brain–mediated) issues seen when a child with ADHD enters into reading. In other words, working memory and response selection abnormalities appear to be those aspects on the output side of so-called "processing speed" that play a role in deficits in reading fluency in ADHD. Since these elements of the output side of "processing speed" are more frontally mediated in the brain, they are potentially more important in determining fluency than are posteriorly mediated problems with either orienting of attention or stimulus discrimination.

In a third study, electrophysiology was employed in the interests of understanding a more direct measure of processing speed (i.e., not requiring motoric output, and actually measuring brain waves while processing information), since functional magnetic resonance imaging, while providing spatial resolution (where in the brain task-related activity occurs), is by its very 4-second lag nature (signals from venous deoxygenated blood) incapable of meaningful time resolution. In an initial study, Ewen and colleagues (2012) examined the choice reaction times after variable interstimulus intervals in 16 children with ADHD and 20 controls, using a psychological refractory period paradigm. The psychological refractory period paradigm involves two stimulus–response tasks (T for task) set up so that response selection for T_1 overlaps with stimulus evaluation for T_2. When the second stimulus onset occurs a long time after the first, T_1 response selection can be completed before second stimulus processing reaches the response selection phase; but if the stimuli overlap, creating a short asynchrony, response selection T_2 is delayed and slows response execution (reaction time). While the effect of stimulus overlap is universal, the magnitude of delay (slowing of reaction time) is significantly greater among children with ADHD. Thus, these results imply that when two perceptual processing streams overlap (as may well happen in rapid silent reading) children with

ADHD are slowed down to a greater extent than their typically developing peers.

The tasks used to derive the psychological refractory period are as follows: The specific task is experimental in nature, with yet-to-be-established psychometrics. Children were seated 3 feet away from a liquid crystal display (LCD) monitor, holding a controller such as that used for video games. In each trial, two stimuli were presented, separated by a variable stimulus onset asynchrony (SOA). The first stimulus, a colored square, was blue or yellow, while the second stimulus was a letter, either "O" or "X." Each stimulus was displayed for 100 milliseconds and the SOA consisted of three different durations (50 milliseconds, 150 milliseconds, and 750 milliseconds). Increasing the length of the longest SOA helps younger subjects respond to each task as it comes. SOA levels were varied randomly within each block. Each square color was presented with a 50/50 probability, while the letter stimuli were presented, with one occurring more frequently than the other, in a 2/1 ratio. The setup was chosen to elicit a P300 response during electroencephalographic (EEG) recording, which would further elucidate "processing speed" during stimulus evaluation. These P300 results were reserved for a separate analysis and publication. For the task, the children were instructed to press a button with the left ring finger for a blue square, another button with the left middle finger for the yellow square, another button with the right ring finger for the letter "O," and yet another button with the right middle finger for the letter "X." The participants were told to be as accurate as possible while responding as quickly as they could. They were given three practice blocks to ensure that they understood the instructions. The use of "X" and "O" frequently or infrequently was counterbalanced within subjects between blocks. The reaction times were recorded in milliseconds between the stimulus and corresponding response. Therefore, the reaction time for the first was recorded at the time between the stimulus for the first trial and the second trial, and the measurement for the second trial was performed similarly.

The results of our studies using the psychological refractory period paradigm were as confirmatory of the hypothesis as expected. Children with ADHD show a prolonged "bottleneck" in stimulus–response processing, as indicated by a prolonged psychological refractory period effect compared with that of age-matched typically developing children. In other words, simultaneous processing of two stimulus–response tasks brings with it a higher cognitive cost in children with ADHD. This could have relevance to reading in terms of the fact that reading does involve often overlapping stimulus and response while perceiving a second stimulus (written word); therefore, there could be a greater cognitive cost to children with ADHD, especially if they are expected to read rapidly.

Working Memory and Localization by Functional Magnetic Resonance Imaging

Working memory functional magnetic imaging (fMRI) research within Project 3 of the CSRD, led by Stewart Mostofsky, was focused specifically on understanding the neural correlates of working memory in ADHD, then relating these findings to reading comprehension. Specifically, in a task modeled from D'Esposito and colleagues (1998), Muschelli and colleagues (2012) examined activation of brain regions during the maintaining and manipulating phases of verbal working memory (alphabet letters were the stimuli). In the MRI scanner, children (10 with and 10 without ADHD) were shown sets of three letters for 2.5 seconds, followed by a 1.5-second word of instruction—"same" (remember the identical sequence) or "alphabetize" (recognize the three letters in alphabetical order)—and responding "yes" (right button) or "no" (left button) to a subsequent letter set probe. Activation of interest was in the delay (between initial set and probe set display) for each condition and both conditions. During any/both delay(s) all children activated a frontal region (Broca's area [BA 9]), as well as left supplementary motor area and left posterior parietal lobe. These findings are consistent with other studies from Mostofsky and colleagues that, although devoted to motor proficiency, show similar results, such that posterior brain regions are "recruited" for what is a motor, predominantly anteriorly mediated accomplishment for typically developing children (Mostofsky & Simmonds, 2008). Muschelli and colleagues also found, however, that children with ADHD activated the left parietotemporal association areas (supramarginal and angular gyri). Using all children's data, activations in the "same" delay condition correlated modestly with a reading comprehension measure (Comprehension from the Gray Oral Reading Test—IV; Wiederholt & Bryant, 2001). Additionally, children with ADHD (unlike controls) showed a positive correlation between left inferior parietal (BA 40) activation and reading comprehension. Overall, these findings suggest that for children with ADHD, the working memory that is utilized during reading is also drawing upon neural circuitry associated with their deficits in basic motor proficiency.

Anatomical Findings

Several anatomical findings (e.g., looking at structural components of the brain, such as gray and white matter) related to ADHD have also been found. For example, Mahone and colleagues (2011) reported on finely, functionally subdivided frontal lobe regions as seen on anatomical MRIs of 42 children with ADHD (half boys, half girls) and 44 controls (23 boys, 21 girls) using a method developed by Walter Kaufmann in collaboration with Stewart Mostofsky. Findings revealed that boys and girls with ADHD showed reduced gray and white matter in the left supplementary motor complex. Girls with ADHD, however, showed reduced volume of gray matter in the left lateral premotor cortex, while boys with ADHD showed reduced volume of white matter in the left medial prefrontal cortex. Some behavioral task correlations were found, such that commission errors on a "go/no-go" task (a response inhibition task) correlated with left supplementary motor complex gray matter volume in all children with ADHD. Only among girls with ADHD did variability of reaction time (on the go/no go task) correlate with smaller volumes of left lateral premotor cortex.

With respect to anatomical connections in the brains of children with ADHD, an unexpected finding emerged from application of the technique of diffusion tensor imaging (DTI), which measures fractional anisotropy (FA; an index of diffusion direction of water within axons that form fiber tracts). Maturation of the child's brain is generally accompanied by increased FA, and some previous studies using FA in children with ADHD have reported decreased FA in some regions relevant to ADHD, indicative of "immature" or "lagging" development of connectivity. Peterson and colleagues (2011) found in 16 children with ADHD, relative to 16 controls without ADHD, FA *increases* in right superior frontal gyrus, posterior thalamic radiation, sagittal stratum, left dorsal posterior cingulate gyrus, lingual gyrus, and parahippocampal gyrus. Comparison with the other studies of children with ADHD revealed much comorbidity along with the ADHD diagnoses and a reliance on region-of-interest FA measurement. In any event, in CSRD data, there appear to be paradoxical pathological *increases* in FA, anomalies that may be due to reduced branching of fiber connections or reduced populations of crossing small fibers normally perpendicular to the dominant big fibers, such as the sagittal stratum. In conclusion, anomalies of gray and white matter, measured by delineating functionally relevant anatomic volumes and by the DTI/FA analysis (showing possibly "too simple" connections), reinforce the concept that ADHD represents a neurodevelopmental disorder that even if carefully separated from comorbid conditions, especially basic word-level LD, may confer cognitive and hence learning impairments that underlie late-emerging underachievement.

Summary

Taken together, all of the studies undertaken over the past 6 years addressing the issue of children with ADHD who, despite good basic reading skills, have reading comprehension weaknesses, suggests that their brains are not developed to the same extent to deal with overlapping tasks, speeded performance, and handling simultaneous tasks, all of which could adversely affect a variety of academic functions. They achieve equal results to those of peers but become more fatigued or even exhausted dealing with increased cognitive load, using more brain resources than do their peers, even when they are inhibiting movement. This last point has great implications for moving away from the "commonsense" notion that "sitting still" is a prerequisite for "paying attention" because it might be that for children with ADHD or perhaps very young children in general, the amount of brain resources required to inhibit movement might actually compete with brain resources more "gainfully employed" in academic learning and skills processing effects.

Extension to Reading

The preceding section focused primarily on ADHD-related deficits and revealed linkages between basic elements of processing speed, working memory, reading fluency, and comprehension, even in the absence of basic word-level LD and oral language weaknesses. However, EF deficits themselves exist even in the absence of ADHD, and this more expansive view of EF has also been a major focus of the CSRD and related projects. This additional component of the CSRD (Project 1; Laurie E. Cutting, Principal Investigator) and affiliated research grants (R01s; Laurie E. Cutting, Principal Investigator)specifically focused on the relationship between different types of EF and reading comprehension, including various measures and genres of text.

Overview

Clearly the prerequisite of identifying letters and decoding words must be met to comprehend and gain meaning from text; thus, it follows that a deficit in decoding can hinder reading comprehension through what is referred to as the "bottleneck theory" (LaBerge & Samuels, 1974; Perfetti, 1985; Perfetti & Hogaboam, 1975; Perfetti & Lesgold, 1977; Perfetti, Marron, & Foltz, 1996). A poor decoder's increased effort to decode leaves him or her with fewer cognitive resources for reading comprehension. Decoding the text, however, is only the first battle; comprehending the text is for some students an even greater challenge. According to the simple view of reading, the combination of the two aspects just described—word identification and linguistic or reading comprehension—combine to approximate reading comprehension (Gough & Tunmer, 1986; Hoover & Gough, 1990). Though word identification and reading comprehension are inherently correlated through reading, they depend on different cognitive and linguistic skills and can be separated (Oakhill, Cain, & Bryant, 2003; Storch & Whitehurst, 2002). As such, poor readers can be characterized as having reading difficulties due to (1) word recognition difficulty, (2) comprehension deficits, or (3) both word reading and comprehension difficulty.

Much of RD research has focused on the first component of the simple view of reading, word-level deficiencies (i.e., decoding and word recognition); students who exhibit these difficulties tend to be identified during the early elementary years (Nation & Snowling, 1997; Shankweiler et al., 1999; Yuill & Oakhill, 1991). However, as children get older, comprehension begins to become more central, and an increase in heterogeneity in terms of the origin of RD occurs. Further complicating the picture is an interesting pattern that has been observed in longitudinal studies. It has been reported that some students who have demonstrated typical reading development in early elementary school develop reading problems later; prevalence estimates for this group range between 27 and 46% of all children with this RD, the so-called "late-emerging" RD (LERD; Badian, 1999; Catts, Compton, Tomblin, & Bridgens, 2012; Compton, Fuchs, Fuchs, Elleman, & Gilbert, 2008; Leach, Scarborough, & Rescorla, 2003; Share & Silva, 1986; Shaywitz, Escobar, Shaywitz, Fletcher, & Makuch, 1992). The early grade profiles of these students are not distinguishably different from typically achieving readers until reading deficiencies appear sometime after third grade, suggesting late-emerging rather than late-identified RD (Compton et al., 2008; Leach et al., 2003; Lipka, Lesaux, & Siegel, 2006). Of these students, approximately two-thirds have problems with comprehension, either in the form of a specific comprehension deficit or in conjunction with word reading difficulties (Catts et al., 2012; Leach et al., 2003; Lipka et al., 2006). Therefore, in older children for whom reading comprehension is a more central skill for academic achievement across all subjects, there is likely a mix of two types: children who always have struggled with reading to some extent but encounter increasing difficulty as the demands for "reading to learn" increase, and those who never had difficulty but now are struggling (LERD). While not all children's LERDs are due to a comprehension deficit, many struggle with reading comprehension in some manner. It is very possible that underlying deficits, such as those in oral language or EF, that are present early on exhibit themselves later, when reading comprehension demands are increased, such as when nearing the middle school grades that either allow an RD to "emerge" or exacerbate an already long-standing RD. Thus, while still acknowledging strong empirical support for word-reading skills, as well as oral language abilities, as significant contributors to comprehension, researchers have sought to explore other factors, including higher level skills, such as those that can be classified as EFs.

In particular, comprehension of text is a complex construct that comprises multiple components, especially for older readers, suggesting that in addition to the obvious role of oral language, EF could be an important element of reading comprehension (Cutting & Scarborough, in press). EF skills are higher order skills needed for goal-oriented, independent behavior, including storing and manipulating information in working memory, planning and sequencing multilevel tasks, and establishing overall themes from an intricate set of details, as well as response inhibition (Locascio, Mahone, Eason, & Cutting, 2010). While EF encompasses the basic response preparation–inhibition (processing speed) and working memory components discussed extensively earlier in the chapter with regard to ADHD, it also comprises other higher order skills, such as planning, organizing, and self-monitoring. These are hypothesized to be connected to comprehension, in that readers struggling with comprehension tend to necessitate extended planning time and produce less structured and organized responses than typically developing peers. Additionally, critical analysis and reasoning, along with cognitive and metacognitive strategies, are more likely to be used by readers with strong comprehension. While deficits in EF are commonly linked to ADHD, more recent research has found that EF deficits may have further implications for LD beyond those related to ADHD. Specifically, an increasing body of literature has begun to link EF deficits to RD, including findings from the CSRD and affiliated grants. Of particular interest in terms of linking EF to reading comprehension is understanding those readers characterized as having a specific reading comprehension deficit (S-RCD); that is, they have difficulty understanding text despite typical achievement in word reading and fluency (Nation, Cocksey, Taylor, & Bishop, 2010).

EF and S-RCD Studies

As the requirements for reading comprehension seem logically to necessitate the involvement of EF skills, exploration of the role of EF in S-RCD is a focus of CSRD and affiliated projects. While many have examined elements related to S-RCD and EF, fewer studies have directly examined EF skills in a neuropsychological framework. In an initial study, Sesma, Mahone, Levine, Eason, and Cutting (2009) investigated the role of EF, specifically working memory and planning, after controlling for other contributors to reading comprehension (attention, decoding, fluency, and vocabulary). Specifically, they examined reading abilities and EFs in children ages 9–15 with a range of reading abilities. Attention and EFs were measured using the Behavior Assessment System for Children (BASC) Attention Scale, Tower of London, WISC-III Freedom from Distractibility Index (FDI). Reading and language measures included the Woodcock Reading Mastery Test (WRMT) Word Attack subtest, the Gray Oral Reading Test–4 (GORT-4) Fluency subtest, Peabody Picture Vocabulary Test–II (PPVT-III), and the Wechsler Individual Achievement Test–II (WIAT-II) Reading Comprehension and Word Reading subtests. FDI (r = .61) was approximately equivalent to reading fluency and vocabulary in predicting comprehension (r = .61 and r = .63, respectively), and more significant than decoding (r = .47). Sesma and colleagues also found that EF does not contribute to single word reading skills, but it contributes significantly to reading comprehension. Their findings were consistent after they controlled for individual differences in attention, decoding, reading fluency, and vocabulary. Therefore, overall, findings revealed a significant contribution of EF to comprehension, but not to word recognition skills.

In a related study, Cutting, Materek, Cole, Levine, and Mahone (2009) analyzed the effects of fluency, EF, and oral language on reading comprehension. The study compared contrasting hypotheses: (1) All reading comprehension deficits are attributed to processing bottleneck, including those exhibited by students with apparently typical word reading, and (2) higher-level processes in oral language and EF contribute to reading comprehension failure. For EF, they looked specifically at verbal and visual working memory, and the capacity to plan, organize, and monitor information (Cutting, Eason, Young, & Alberstadt, 2009; Daneman & Carpenter, 1980; Just & Carpenter, 1992; Oakhill & Yuill, 1996; Perfetti et al., 1996; Ruffman, 1996; Sesma et al., 2009; Swanson & Alexander, 1997; Swanson & Berninger, 1996; Swanson & Trahan, 1996) through the following measures: the Tower of London, which assesses spatial planning, rule learning, and inhibition of impulsive responding; the Elithorn Perceptual Maze test, which assesses planning, organization, and monitoring abilities; and Digit Span Backwards, which assesses the ability to manipulate orally presented information. Fluency is an indicator of whether bottlenecking limits reading comprehension because belabored yet accurate reading creates demands on working memory. Cutting, Materek, and colleagues (2009) found that there are prominent deficits in EF associated with S-RCD when they compared both students with specific word reading disabilities (WRD) and controls. Notably, while some in the RD groups also had ADHD, ADHD was not more common in students with S-RCD than in those with WRD, suggesting that EF deficits could not be attributed to ADHD.

In another, better-defined sample, Locascio and colleagues (2010) investigated further the effects of EF on children with specific WRD and S-RCD. They found that all children with RD (both WRD and S-RCD) performed poorly on EF measures, but the pattern of EF weaknesses was different. Specifically, the group with WRD performed worse on measures of verbal working memory and response inhibition, which is consistent with previous literature reports that children with dyslexia exhibit deficits in verbal (as well as visual) domains of working memory (Reiter, Tucha, & Lange, 2005). Nevertheless, although children with WRD demonstrated deficits in verbal working memory and response inhibition, Locascio and colleagues found that these deficits were more closely linked to phonological processing deficits: The WRD group showed less distinction after covarying for phonological processing, consistent with Baddeley's model of an executive system regulated by phonological input (Baddeley & Hitch, 1974; Gathercole & Baddeley, 1993). On the other hand, children with S-RCD showed different EF weaknesses; they had weaknesses in strategic planning (both with and without controlling for phonological processing). Locascio and colleagues found that planning and organizing contributed more substantially than other EFs or basic reading components to comprehension. Planning deficits, as measured by move accuracy and error occurrence on the Tower of London task, also distinguished participants with S-RCD from those with WRD, after researchers controlled for socioeconomic status and ADHD diagnosis. Students with S-RCD scored substantially lower on the Tower of London tasks. The implications are that children who suffer planning deficits on measures such as the Tower of London may similarly struggle to navigate and organize information in text.

It is still unclear which specific EF skills a particular text demands, and how to correlate that with the very specific demands of the different EF measures used. It is plausible to hypothesize that as text becomes more complex, increased EF demands are placed on the reader. For instance, texts that are less cohesive may require integrating background information, with the information presented by the text through inferential reasoning to reach conclusions, as well as strategic planning or metacognitive strategies in how to approach the text. In particular, demands in higher-order cognitive skills may be necessary for children in later elementary and middle school to remain successful readers. While previous studies have shown that reading comprehension scores can differ significantly depending on the assessment method used (Cutting & Scarborough, 2006; Keenan, Betjemann, & Olson, 2008), further study has revealed a more specific role for EF as related to genre. More recently, Eason, Goldberg, Young, Geist, and Cutting (in press) explored the relationships among reader characteristics, text types, and question types. Children 10 to 14 years old were given narrative, expository, and functional passages, and the differences between these different text types, as well as children's performance on comprehension questions that assessed their literal or inferential information, were examined. Findings indicated that higher-order cognitive skills, including the ability to make inferences and to plan and organize information, contributed to comprehension of expository, but not narrative, text. These findings were furthermore of interest because the narrative and expository passages were similar in terms of the characteristics one typically thinks of as determining text difficulty (word frequency, syntax, etc.), thus suggesting something more inherent within expository text that additionally draws upon EF skills. Further study, which is currently ongoing, is needed to understand the contribution of EF to comprehension of expository text. Nevertheless, regardless of why exactly, these findings therefore suggest that comprehension of expository text, the type of text often encountered in later elementary and middle school students, relies on EF. The implications are that developing comprehension of expository text early in school may better equip students for comprehending the type of genres (expository) they will encounter in higher grades where they are *reading to learn*.

Reading Comprehension: Neurobiological Findings

It is well known that children and adolescents with RD at the word level have been found to have anomalous patterns of functional brain activity relative to typically achieving children (e.g., Pugh et al., 2000; Shaywitz et al., 2002; Simos et al., 2005). Though more challenging to implement and analyze than studies at the word level, neuroimaging studies of reading comprehension expand on studies that focus only on word recognition (Rimrodt et al., 2009) by exploring reading for meaning. Because reading for meaning requires engagement of higher-level cognitive skills, as well as sustained attention, neuroimaging may further elucidate the relation between EF and reading comprehension, particularly if common areas of the brain are engaged during EF and reading comprehension tasks.

For typically achieving children and adolescents, fMRI studies of EF have shown involvement of bilateral, dorsolateral, prefrontal, and inferior prefrontal cortices, which is in congruence with adult studies (Dove, Pollmann, Schubert, Wiggnes, & Von Cramon, 2000; Houdé, Rossi, Lubin, & Joliot, 2010). Additionally, in children and adolescents, the anterior insular cortex is implicated in EF, consistent with literature that describes the insula and anterior cingulate cortex as areas involved in detection of salient events, working memory, attention, and task shifting (Dove et al., 2000; Menon & Uddin, 2010). Therefore, it is reasonable that these areas could be involved in the higher-level processing and sustained attention needed for reading comprehension.

Indeed, there is some evidence for involvement of EF brain areas in reading comprehension. In an fMRI study of sentence comprehension in unimpaired adult readers, reading ambiguous sentences was accompanied by increased activation in the dorsolateral prefrontal cortex, an area associated with EF (Novais-Santos et al., 2007). The same study reported increased inferior parietal cortex activation, with increased demands on working memory. Controlling for processes involved in reading at the single-word level also provides insight into the neural mechanisms required for comprehension of text. In an fMRI study stemming from research affiliated with the Center, Cutting and colleagues (2006) employed a sentence comprehension paradigm that controlled for word reading and short-term memory for words. Findings indicated that unimpaired adult readers exhibited greater activation in bilateral temporal lobes (left > right), bilateral occipital lobes, and middle frontal gyri, suggesting that these areas are involved in the reading comprehension component that is beyond word reading and short-term memory. Interestingly, these areas are not the areas primarily involved in EF.

In contrast, in another study related to CSRD research, controlling for word reading, Rimrodt and colleagues (2009) found that when performing sentence reading, children and adolescents with WRD activated more than typical readers in areas associated with not only linguistic processing but also attention and response selection. Areas of increased activation linked to attention and response in other studies (Braver, Barch, Gray, Molfese, & Snyder, 2001; Downar, Crawley, Mikulis, & Davis, 2001; Hahn, Ross, & Stein, 2006) included bilateral insula, right cingulate gyrus, right superior frontal gyrus, and right parietal lobe, suggesting additional effort in directing and sustaining attention for the WRD group during reading comprehension.

The findings of Cutting and colleagues (2006) and Rimrodt and colleagues (2009), though somewhat dissimilar, are not necessarily at odds with each other or with extant literature. Rather, each may provide a small piece to a complex puzzle. There are at least two reasons why these discrepancies may exist. First, the Cutting and colleagues (2006) study was conducted with adult skilled readers, whereas the Rimrodt and colleagues (2009) study was conducted with children and adolescents. Despite many similarities, substantial differences exist in the structure and function of the human brain between childhood and adulthood. From early school age to young adulthood, gray matter in the frontal cortex decreases, concurrent with enhancement of myelination and connectivity (Giedd et al., 1999; Sowell et al., 2004). Corresponding changes in cognitive performance suggest increased specialization of the prefrontal circuits and enhanced processing, as evidenced by increased speed of processing, working memory performance, inhibition, and strategy use throughout childhood and adolescence (Amso & Casey, 2006; Gogtay et al., 2004; Liston et al., 2006). Such changes may be accompanied by shifts in location and extent of cortical engagement in higher-level processing. A second, important distinction is that the Cutting and colleagues study included typically developing readers, while the Rimrodt and colleagues study included children with WRD. An interesting paradox in functional activation is that more is not always better, nor is less always better; therefore, interpreting relative amounts of activation must be done with caution. Less activation in a given region may indicate less effortful cognitive processing (Chein & Schneider, 2005; Meyler, Keller, Cherkassky, Gabrieli, & Just, 2008). As such, an expert in a task may have less activation, and a novice may have more activation. Additionally, differing results in these studies versus other functional neuroimaging studies may in part be due to differences in imaging tasks. Studies examining individuals' and controls' manipulations of sentences by semantics and syntax in S-RCD and WRD are ongoing in both the CSRD and related grants, and may yield some clarification of the role of EF in text comprehension in various populations.

Summary

Measures of EF skills have been shown to be predictors of reading comprehension abilities; therefore, it may be appropriate to consider using EF measures, along with oral language measures, as potential screeners for children in order to predict risk of S-RCD. Also, the correlations between specific aspects of EF and reading comprehension suggest the possibility of implementing interventions that specifically address strategies that help strengthen EF skills, or that can help students compensate for EF weaknesses by focusing on planning, organization, and inferential reasoning. These areas of focus appear to be different from those EF deficits found in WRD and/or ADHD, which appear to be linked in part either to phonological processing speed or working memory weaknesses. Further exploration, particularly at the neurobiological level of inquiry, which appears promising but is still under way in terms of analyses, may yield fruitful insights into where the overlap and distinctions are in terms of deficits associated with ADHD, WRD, and S-RCD.

Conclusions

Research projects both within the CSRD and in affiliated research grants have an overarching focus on the systematic study of the interrelationships between the development of EF, language, and academic skills in grades 4 through 8. Findings from our research on ADHD suggest that the processing speed deficits typically seen in ADHD are linked to anterior circuits. Therefore, academic struggles that typically are present in those with ADHD, even if word recognition and oral language abilities are intact, are likely a result of abnormalities in frontal lobe circuitry. Working memory problems, as well as difficulty processing information when two perceptual processing streams overlap, appear to be primary areas of weakness; clearly reading comprehension and general academic functioning would be impacted by deficits in these two areas. Additional research examining EF deficits beyond those simply associated with ADHD suggests a more focal role for the planning, organizing, and monitoring aspects of EF in reading comprehension. Both neurobiologically and neuropsychologically based findings suggest that EF circuitry plays a role in comprehension. Furthermore, more recent research suggests that this is more focally related to comprehension of expository text. Such findings may shed light on both the importance of promoting expository text comprehension in early elementary school, and also may provide insights into why some children's struggle with reading comprehension does not appear until they enter upper elementary school—when expository text becomes more predominant. This suggests that screening for EF deficits earlier on may be fruitful for detecting those at risk later for reading comprehension problems. In summary, further elucidating brain–behavior linkages using neuroimaging and behavioral methods (cognitive testing and experimental paradigms), we hope, will contribute to our understanding of the complex relationships among ADHD, EF, and academic achievement, most centrally reading comprehension. Studies are ongoing and under way in terms of further characterizing these brain–behavior relationships.

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