Working Memory and Dyslexia

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Abstract

Working memory deficits can account for the decoding and comprehension difficulties experienced by readers with dyslexia. A weakness in the short-term storage of phonological information disrupts decoding by making it difficult to remember a sequence of phonemes until they are blended, and adequate short-term storage of visual-spatial information is necessary for the retention of graphemes. Deficits in executive working memory contribute to reading comprehension challenges because the reader has difficulty inhibiting, updating, switching, and error monitoring. Also, too much cognitive load reduces the working memory capacity that is available for reading comprehension. Practicing and applying evidence-based strategies such as rehearsal can strengthen and support working memory, leading to improved decoding and comprehension. Dyslexic readers can be directly supported during the decoding process by repeating phonemes just prior to blending, and comprehension can be facilitated by minimizing cognitive load.

Working memory ability is highly associated with all aspects of academic learning and performance (Gathercole & Alloway, 2004). The relationship is so strong that working memory is widely recognized as one of the best predictors of academic achievement (Alloway & Alloway, 2010). Learning to read, write, and calculate all depend heavily on adequate working memory capacity (for a review, see Dehn, 2008). Skills such as reading decoding, reading comprehension, math problem solving, and expressing ideas in writing rely on working memory. Academic performance, such as assignment completion, is also correlated with the learner's level of working memory. Consequently, individuals with working memory deficits or impairments are at-risk for learning problems and disabilities. For instance, Gathercole, Brown, and Pickering (2003) found that children with a working memory score at the 10th percentile or lower had an 80% chance of having a significant learning problem or disability.

The relationship between working memory deficiencies and dyslexia is well established in research (Pickering, 2006). Working memory deficits are now viewed as one of the major defining characteristics of dyslexia (Fischbach, Konen, Rietz, & Hasselhorn, 2014; Smith-Spark & Fish, 2007). After phonological processing, working memory is the most important cognitive process required for proficient reading. All aspects of working memory—phonological, visual-spatial, and executive—play essential roles during reading. It is therefore extremely important that teachers, reading specialists, psychologists, and speech –language pathologists understand specifically how working memory processes are involved with reading processes. The purpose of this article is to help these professionals acquire more expertise on this subject so that they can better understand, diagnose, and treat readers with dyslexia.

What is Working Memory?

Working memory is the limited cognitive capacity to retain information while simultaneously processing the same or other information. In daily life, frequent demands are placed on working memory. For example, remembering what one was going to say during a conversation depends on working memory. In the typical classroom, high demands on working memory are unrelenting, and even learners with typical working memory capacity often lose information from working memory before they can complete a thought or commit new information to long-term memory. For instance, expressing ideas in writing places high demands on working memory.

What is referred to as *short-term memory* is part of working memory. Short-term memory is the brief storage of information within working memory. According to Baddeley's theory (1986, 2006), there is a phonologically based storage component and a visual-spatial storage component. These storage components are managed by a higher-level component known as *executive working memory*. Short-term storage can function in an unconscious and automatic manner without direct, conscious manipulation from the executive aspect of working memory, but the short-term stores do no actively process information. Processing the information held in brief storage is the responsibility of executive working memory. The key functions of executive working memory include shifting, updating, and inhibition, as well as allocating available attentional resources and applying strategies.

The basic equation is that short-term storage *plus* information processing *equals* working memory. The classic digit span test illustrates the distinction: digits forward requires mainly short-term memory, whereas digits backward requires working memory because one must hold and manipulate the digits in order to reverse the sequence.

Working memory capacity is limited in all individuals, not just in those individuals with working memory deficits. The typical adult individual can maintain only a few items for a few seconds. Consequently, even normal working memory capacity is easily overwhelmed in daily functioning, especially in a learning environment or while reading. For example, nearly everyone finds it challenging to take notes while listening to a presentation. Due to normal working memory limitations, the note-taker may not hear everything the presenter was saying or not remember what he or she was going to write down. If individuals with a normal working memory capacity are frequently struggling to cope with information-processing demands, then it is understandable why children with below average ability in working memory have nearly constant difficulties simultaneously retaining and processing information, such as trying to comprehend what they are reading.

Capacity is usually measured by span, the number of items that can be recalled in sequence. Immediate sequential recall of items such as numbers, letters, or words is known as *simple span*, and is considered a fairly direct measure of phonological short-term memory. The typical simple span in adults is seven items. Tasks that require processing while retaining information measure working memory, and the amount retained is known as *complex span*. Processing information reduces the amount of information that can be retained. Thus, complex span in typical adults is shorter than simple span. Cowan's research (2001) documents that the typical adult can retain four pieces of information during working memory processing. The simple verbal span of children at an age when they are learning to read is usually about 2-4 items and their complex span ranges from 1-3 items. Visual-spatial span limitations are similar to phonological spans; however, not all visual-spatial information needs to be remembered in sequence.

Information is retained in working memory for only a few seconds. The only way to extend the interval is to repeat the information over and over, a process known as *rehearsal*. After a few seconds without repetition, the information has either been encoded into long-term memory (LTM) or has been forgotten.

Phonological Short-Term Memory

Phonological short-term memory, also referred to as the *phonological loop*, is a speech-based store of auditory and verbal information. Phonological short-term memory continually receives information from auditory and phonological processing and then automatically activates or associates related sounds held in long-term memory. It is named phonological because it is mainly processing phonological codes and recognizing the words they create. According to Baddeley (1986), phonological short-term memory also includes an automatic, subvocal rehearsal process that serves to extend the brief storage interval. When individuals are prevented from rehearsing, their span is reduced significantly (Henry, 2001). However, rehearsal has its limitations. Regardless of age, one's simple span is limited to the number of sounds or words one can articulate within two seconds (Hulme & Mackenzie, 1992). Thus, speech rate partly determines the amount of information than can be rehearsed and retained in short-term memory. Unfortunately, children with dyslexia often are slower in both overt and covert articulation speed (Pickering, 2006), thereby reducing their effectiveness of rehearsal and the amount of information they can retain in phonological short-term memory.

Phonological short-term memory is intricately linked with phonological processing and phonetic decoding of words (Hulme & Mackenzie, 1992). Studies (Wagner & Muse, 2006) have found measures of phonological awareness and phonological short-term memory span to be highly correlated (as high as .88) with each other. Adequate phonological short-term memory is necessary for proficient phonological processing; conversely, phonological processing affects short-term memory span. When both are weak, the reader is facing a serious challenge.

Consequently, professionals who evaluate children for reading disorders should closely examine the child's phonological short-term memory whenever phonological processing is a concern. Tasks that involve immediate sequential recall of letters, sounds, digits, words, and non-words are all appropriate measures of phonological short-term memory (Dehn, 2014a). Difficulties with nonword recall are especially predictive of language impairments and word reading difficulties (Wagner & Muse, 2006).

Visual-Spatial Short-Term Memory

Visual-spatial short-term memory, also known as the *visuospatial sketchpad*, briefly stores information for objects and their locations. Visual-spatial information can be either *static* or *dynamic*. Static information does not need to manipulated, such as simply recalling the color or shape of items. Dynamic information consists of stimuli that are in motion or stimuli that the individual must manipulate, such as imagining how puzzles pieces will fit together. Measures of visual-spatial short-term memory, especially for static materials are abundant in cognitive tests. There is continual updating of information held in visual-spatial short-term memory. Rehearsal of visual-spatial information is accomplished by re-imaging.

Until recently, the role of visual-spatial short-term memory in reading has been downplayed, but it obviously plays an essential role by retaining the graphemes (printed letters) that represent sounds long enough for phonetic decoding to take place. Also, visual-spatial short-term memory is linked with its phonological counterpart because visual stimuli, patterns, and images are typically recoded verbally when they are named.

Executive Working Memory

Executive working memory, also referred to as the *central executive*, is the processing dimension of working memory. As its name implies, executive working memory takes on many executive processes, making it as much an executive or metacognitive function as it is a cognitive function (Dehn, 2014d). Strategic management of limited working memory capacity is one of its key functions. Conscious, effortful retrieval from long-term memory is another responsibility of executive working memory. Executive working memory processes both phonological/auditory/verbal information and visual-spatial information, often integrating the two. What is referred to as *verbal working memory* occurs when executive working memory is processing verbal information, and the same is true for *visual-spatial working memory*.

The most essential executive working memory functions are inhibition, switching, and updating (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Without these operations, an individual would not be able to manage or make sense of the constant flow of information, such as when reading. Inhibition involves suppressing information which is no longer pertinent to the immediate task or thought. An example of inhibition would be suppressing an earlier comment in a conversation so as to focus on constructing a response to the current comment. Switching involves switching between two processing tasks. A common type of switching involves going back and forth between the process at hand and rehearsing the necessary information which is being held in short-term storage. Updating is the constant process of revision whereby newer, more pertinent information replaces, no longer relevant information.

Cognitive Load

The processing aspect of working memory is referred to as *cognitive load* (Van Merrienboer, Kirschner, & Kester, 2003). Effortful cognitive processing and storage of information both draw from the same limited working memory capacity. Effective sharing of this limited resource requires rapid, back-and-forth switching between processing and rehearsing, which maintains the necessary information in short-term storage. Memory items are lost when the processing requirements are such that the switching cannot occur or cannot occur in time to prevent loss of information. Therefore, as cognitive load increases, the amount of information that can be retained is diminished. This relationship is bi-directional. Focusing on maintaining information can impede processing, slowing it down or causing processing errors.

In the classroom, high cognitive load is caused by numerous variables arising from the environment, the nature of the materials, instructional variables, and the learner's own internal processing (Dehn, 2014c). Overly high cognitive load not only impairs performance but reduces learning. For example, an overloaded working memory may not have enough capacity to retain new pieces of information long enough to comprehend them and associate them with prior knowledge. Consequently, the new information is not comprehended, is not encoded into long-term memory, and is not learned (Dehn, 2010).

The level of cognitive load during reading determines the extent of comprehension. Reading decoding is a process that contributes to cognitive load. The less automated reading decoding is, the more cognitive load it creates. When there is too much cognitive load dedicated to reading decoding, there is not enough working memory capacity left for reading comprehension. Thus, the acquisition of reading fluency (automaticity) frees up more processing capacity for reading comprehension.

Language Development and Working Memory

The connection between language development and literacy is well established (Goff, Pratt, & Ong, 2005). Language delays often precede and are associated with developmental dyslexia. What is less known is that a deficit in working memory may be the common underlying cognitive weakness that accounts for both types of disorders (Baddeley, 2003). Thus, it is important to understand working memory's role in language development.

Several studies have reported that individuals with language impairments perform poorly on verbal working memory tasks, especially tasks involving phonological processing (Masoura, 2006). For example, Gutierrez-Clellen, Calderon, and Weismer (2004) found that children with a specific language impairment have a verbal (phonological) span two standard deviations below the mean for their age.

In particular, poor language development seems to be directly connected with impaired functioning of phonological short-term memory (Baddeley, 1996). Children with delayed language development often have a deficit in the ability to retain unfamiliar words. If young children are unable to retain the phonological sequence that makes up a new word, they will require more exposures to the word before they acquire its phonetic and semantic representation (Leonard et al., 2007). Accordingly, vocabulary learning has been directly linked with phonological short-term memory capacity (Gathercole & Baddeley, 1990).

Oral expression places high demands on working memory, especially during the conceptualizing and sentence formulation stages. Not only must the speaker retrieve words that convey the intended meaning, but he or she also must plan for correct syntax. For example, accurate production of subject-verb agreement depends on verbal working memory processes. Even in normal speakers, sentence planning is hindered when speakers have insufficient verbal working memory capacity (Hartsuiker & Barkuysen, 2006), such as when there is a secondary processing task.

Working memory also plays a crucial role in listening comprehension by constructing and integrating ideas from a stream of successive words (Just & Carpenter, 1992). To understand the meaning of a sentence, an individual must be able to remember previous words in order to relate them to later-occurring words. Difficulties in processing individual sentences have been related to deficient working memory capacity (Moser, Fridriksson, & Healy, 2007). In addition to adequate executive working memory, adequate phonological storage is also important for oral language comprehension because it stores word sequences long enough for the individual to decode them into their constituent meaning (Baddeley, 1990).

Working Memory and Reading

Numerous studies (Smith-Spark & Fisk, 2007; Swanson & Jerman, 2007) have reported strong relations between working memory capacity and reading skills. Each type of reading skill draws from short-term and working memory processes somewhat differently. Reading decoding and fluency are primarily related to phonological and visual-spatial short-term memory, whereas reading comprehension is primarily related to executive working memory (Swanson, Howard, & Saez, 2006).

Reading Decoding

To convert graphemes (printed letters) into phonemes, reading decoding first depends on visual-spatial processing and visual-spatial short-term memory capacity. Readers must recode visual stimuli by matching the graphemes with the phonemes they represent. Graphemes need to be retained long enough for the recoding to occur. Next, phonological short-term memory retains the accumulating sequence of phonemes until the last letter is converted and the full sequence of sounds is blended into a complete word (Palmer, 2000). If the reader has normal phonological short-term memory capacity but is still struggling to decode, it may be that he or she is not using phonological short-term memory effectively; for example, the reader may not be subvocally rehearsing (repeating) the sequence of phonemes. Finally, executive working memory becomes involved, especially during the blending stage. Efficient recoding and blending also require adequate phonological processing ability (National Reading Panel, 2000).

Of the executive working memory functions, there is strong evidence that updating of verbal information is the most essential for reading decoding (De Jong, 2006). Some studies have also documented the importance of inhibition. For instance, Palmer (2000) found that good readers were able to better inhibit visual representations (orthographic representations) and focus on the phonological coding. As a reader becomes fluent and basic reading decoding becomes automated, short-term and working memory play a less critical role in reading decoding.

Reading Comprehension

To comprehend text, a reader must hold words and sentences in consciousness until there is enough information to complete an idea (De Beni, Borella, & Carretti, 2007). Most aspects of reading comprehension place a heavy cognitive load on executive-working memory. Studies (Just & Carpenter, 1992) have found that individuals with greater executive-working memory capacity are more successful at integrating information across longer readings. The capacity of the phonological and visual-spatial short-term storage components seems to have little to do with reading comprehension (Swanson & Berninger, 1995). In individual who do not have decoding problems, reading comprehension problems are more highly associated with processing deficits in executive working memory (Goff et al., 2005).

Of the specific executive functions, inhibition is one that has been directly linked with reading comprehension (Savage, Lavers, & Pillay, 2007). Discarding information that is no longer relevant and preventing the entry of unnecessary or irrelevant information affect the ability to engage in processes that are crucial for good comprehension (De Beni & Palladino, 2000). Adults and children with deficient inhibitory processes are more likely to remember irrelevant words and information, resulting in weak reading comprehension (De Beni & Palladino).

Specific Working Memory Weaknesses in Readers with Dyslexia

Readers with dyslexia are deficient in nearly all aspects of working memory. They also commonly have weaknesses in other related memory and cognitive processes (See Table 1).

Phonological Deficits

The most consistent working memory deficit found among readers with dyslexia is in the storage capacity of phonological short-term memory (Smith-Spark & Fish, 2007). Readers with dyslexia simply cannot retain as much sequential, verbal information, such as letters, phonemes, words, and phrases, as normal readers do. The result is a breakdown in the reading process and slow acquisition of reading skills. Examples of how a phonological storage deficit is manifested during reading include: (1) a failure to store phonemes long enough to successfully blend them into a word; (2) forgetting the sequence of the phonemes; (3) forgetting phonemes that were early in the decoding sequence; (4) a failure to store words long enough for comprehension to occur; (5) forgetting words and the phonemes that comprise them before they are encoded into long term memory, and (6) a failure to update during decoding, such as not changing a vowel from a short to a long sound when a silent “e” is encountered at the end of a word.

Visual-Spatial Deficits

There has been conflicting evidence regarding the possibility of a visual-spatial storage deficit in dyslexia. For the most part, visual-spatial storage capacity has been found to be normal in children with literacy disorders. However, recent investigations have uncovered a weakness in this working memory component, at least in one aspect of visual-spatial processing. Fischbach et al. (2014) report that children with dyslexia have a significant weakness in the processing and storage of dynamic visual-spatial information, such as when they need to reverse the sequence of movement. At the same time, subjects in the study had normal ability for storage of static visual-spatial information. In contrast, another recent study (Menghini, Finzi, Carlesimo, & Vicari, 2011) discovered that developmental dyslexia is related to weaknesses in both aspects of visual-spatial storage.

One explanation for the inconsistences in this avenue of research is that visual-spatial storage capacity by itself may be normal, but information may be lost when concurrent processing takes place. The relationship between storage and cognitive load explains this phenomenon. Some visual-spatial information will be lost during processing because cognitive load reduces the amount that can be retained. Evidence in support of this explanation was provided by Swanson and Sachse-Lee (2001) who found that their dyslexic group's weakness in visual-spatial storage disappeared when executive working memory ability was controlled for.

Executive Deficits

Many working memory researchers (e.g., Pickering, 2006; Swanson & Jerman, 2007) believe that executive working memory is the core deficit in dyslexia. The fact that both domain-specific storage components have been implicated in dyslexia supports this claim because a limited executive working memory that is easily overloaded when processing information will reduce the amount of information that can be maintained in storage. For example, the recently discovered weakness in dynamic visual-spatial storage can be explained by a weak executive component. A lack of a capacity for simultaneous processing and storage will impact nearly all aspects of working memory.

Furthermore, a dysfunctional executive working memory or one that is easily overloaded may include poor functioning of updating, inhibition, and error monitoring, all of which are crucial for successful reading. Individuals with weak executive working memory also tend to be less strategic, in part because implementing a strategy adds to cognitive load (Swanson, 2000). This is unfortunate because consistent use of effective strategies enhances reading performance.

Long-Term Memory Encoding Differences

The use of different long-term memory encoding and rehearsal strategies is another difference between readers with and without dyslexia that was discovered by Miller and Kupfermann (2009). Graphemes can be encoded and rehearsed phonologically or visually. Normal readers focus on the phonological code of written material and verbally rehearse the phonemes and words in sequence. However, readers with dyslexia are more likely to use visual encoding and rehearsal. The problem is that visual encoding and rehearsal is less efficient and effective. Fewer letters, sounds, and words are remembered or remembered in sequence when the encoding and storage is visual-spatial, resulting is more reading errors. Phonological encoding, storage, and rehearsal are more efficient because they maintain the sequence of the information, whereas visual-spatial encoding is not necessarily sequential. It may be that those with dyslexia prefer the visual-spatial route because they possess weak phonological processing and storage abilities while having normal visual-spatial processing and storage. Another possibility is that a weak executive working memory underlies this inefficient coding and storage. That is, one responsibility of the executive component is to inhibit visual-spatial processing and storage in favor of phonological processing and storage.

Sequential Processing Deficits

A weakness in sequential processing, also known as *successive* or *serial* processing, is also common among individuals who suffer from dyslexia. This particular processing weakness may account for observed weaknesses in working memory storage components (Fischbach et al., 2014). For example, a weakness in sequencing may underlie storage weaknesses in both phonological and dynamic visual-spatial information, because sequences need to be maintained in both domains when the task involves reading. Poor sequencing ability might also explain why readers with a disability seldom use verbal rehearsal as a strategy. Verbal rehearsal is also challenging when an individual has a slow speech rate, another characteristic of readers with dyslexia. Finally, slow naming speed, another marker for dyslexia, may be related to a dysfunctional working memory. Naming speed involves retrieval of common names from long-term memory, and working memory is involved in conscious retrieval.

Table 1 Specific Weaknesses Associated with Dyslexia

- Phonological processing
- Phonemic awareness
- Executive working memory
- Phonological short-term memory
- Visual-spatial short-term memory
- Long-term memory encoding
- Verbal rehearsal
- Speech rate
- Sequencing
- Updating
- Inhibition
- Switching
- Error monitoring
- Strategy use
- Naming speed

Evidence-Based Working Memory Interventions

Over the past two decades numerous empirical investigations have documented the efficacy of working memory training, strategies, and accommodations (see Dehn, 2015 for a comprehensive review). Unfortunately, a review of the research and detailed instructions for implementing these procedures are beyond the purview of this introductory article. A few examples and suggestions and how they will benefit dyslexic readers are provided below.

Rehearsal Training as an Intervention

Children with disabilities often fail to develop or use verbal rehearsal strategies. Some children may know the strategy but be unable to maintain items in sequence during a series of repetitions. Given that individuals with dyslexia do not rehearse as much as normal readers, rehearsal training may be especially beneficial for them. Rehearsal allows more information to be maintained in working memory for a longer period of time (Gathercole, 1999), allowing processing of the information to be completed. In readers with normal working memory ability, rehearsal can be carried out semi-automatically without a very concentrated use of attention or working memory.

Rehearsal, simply repeating information over and over, is the first and most basic memory strategy acquired. It usually develops without any explicit instruction or training. Children may begin using a simple rehearsal strategy as early as 5 or 6 years of age, but rehearsal is not a widespread or consistently used strategy until the ages of 7 to 10 (Gill, Klecan-Aker, Roberts, & Fredenburg, 2003). The development of subvocal rehearsal strategies is as least partially responsible for increased verbal working memory span as children develop (Minear & Shah, 2006). Children as young as 5 years of age can be trained to use rehearsal and this has been found to improve their recall and their academic learning (Henry & Millar, 1993).

Teaching rehearsal strategies to individuals, in small groups, or to an entire classroom of students is relatively easy (Dehn, 2011). Cumulative rehearsal involves training children to name the first item after it is presented, then the first and second items together after the second item is presented, and so on until all items in the series have been presented and rehearsed. For example, the subject (S) is taught to overtly repeat successively longer sequences as each word is spoken by the instructor (I) (e.g., I-foot, S-foot; I-bird, S-foot, bird; I-house, S-foot, bird, house; and so on). An alternative is to present the entire list at once and have the child repeat the entire list a few times. At first, students should be directed to say the words aloud to make sure they are rehearsing correctly, but as the practice progresses they should whisper the words and eventually subvocalize.

For children with normal cognitive ability, lists constructed of randomly chosen monosyllable words should be used. Begin with a list of only two or three items. As training progresses, the difficulty level can be adjusted by increasing the number of words to be recalled. Students may benefit from rehearsal training sessions of only 10 minutes per day over a period of 10 days, but daily training over a period of several weeks may produce better long-term change (Dehn 2008).

Dyslexic readers should benefit from rehearsal training because better rehearsal extends the number of phonological items (phonemes, syllables, and words) that can be retained, as well as the duration of the retention interval. Thus, they will be able to retain phonemes and syllables until blending is completed. Also, their reading comprehension will benefit because they will be able to retain decoded words and phrases long enough to make associations and understand the text.

Internet-Based Working Memory Training

Many cognitive and working memory training programs are offered on the internet. Examples include Cogmed®, Jungle Memory, Lumosity, and Brain HQ. These programs and other exercises that challenge working memory usually produce significant gains in working memory performance (Dahlin, Nyberg, Backman, & Neely, 2008). Although there is consistent evidence that performance will improve on untrained measures of working memory, transfer to improved reading and other academic skills is found only periodically. For example, Loosli, Buschkuehl, Perrig, and Jaeggi (2012), reported significantly enhanced reading performance in typically developing children aged 9 to 11 after online working memory training. Similarly, improvements in reading comprehension were reported by Dahlin (2011).

One reason why internet-based training is seldom found to improve reading is that the training primarily involves visual-spatial working memory, whereas, the primary deficits for most readers with dyslexia are phonological and verbal. That's why face-to-face verbal rehearsal practice may be more beneficial that computer-based training. Another explanation for inconsistent transfer is that online training needs to be consistently challenging (adaptive) over an extended period of time (Klingberg, 2009).

Supporting a Reader with Dyslexia

Until reading fluency and decoding automaticity are attained, working memory deficient readers will benefit from direct support with processing and storage. Support is especially needed for recognizing, storing, and blending phonemes. When the reader does not recognize a word and does not attempt to decode the word, saying the first phoneme of the word may serve as a prompt. Especially with longer words, some dyslexic readers have difficulty remembering the sequence of sounded-out phonemes when they are ready to blend them. For these readers, the person assisting the reader can serve as the reader's phonological short-term storage. That is, the assistant should repeat the separated phonemes in sequence, allowing the reader to blend them without having to start over.

Another way to support a working memory impaired reader with dyslexia is to minimize cognitive load during reading (Dehn, 2014e). There are several ways of doing this: (1) a quiet environment with limited distractions is important because noise and distractions add to cognitive load; (2) reading about a familiar subject is also helpful because the novelty and complexity of the material adds to cognitive load; (3) reducing verbalizations by providing non-verbal cues is important because verbalizations from the reading assistant add to cognitive load; and (4) taking frequent breaks while reading is helpful because they reduce cumulative interference and the need to inhibit that interference, which also adds to cognitive load.

Finally, a working memory impaired reader will need more exposures to new words before they become encoded and consolidated in long-term memory. Additional exposure should begin with immediate re-reading of a passage, even when it was read fluently. New sight words should then be reviewed on a systematic basis (Bahrick, 2000). Reviews that occur with longer and longer intervals between them are the most effective (Karpicke & Roediger, 2007). For students with working memory deficits, an ideal review schedule might be: (1) at the end of the lesson; (2) the next day; (3) after a delay of two or three days; (4) after another delay of a week; and (5) after two weeks have passed since the last review.

Summary

In addition to the primary deficit of phonological processing, deficits in one or more aspects of working memory contribute significantly to dyslexia. Adequate short-term storage and simultaneous processing of information in working memory are both required for successful reading. Furthermore, the executive dimensions of working memory---inhibition, switching, and updating---play crucial roles during reading decoding and comprehension. Also, high cognitive load due to such factors as novel material and distractions impairs working memory performance and makes reading more challenging. In dyslexic readers, working memory deficits are typically manifested by difficulties converting graphemes into phonemes, maintaining the sequence of phonemes long enough to blend them, and maintaining the words, phrases, and sentences long enough to finish the thought processes necessary for comprehension. Evidence-based interventions, such as rehearsal, may not only enhance working memory performance but lead to improved reading skills in individuals with dyslexia.

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