The Role of Executive Functions in the Reading Process

Tzipi Horowitz-Kraus

Abstract “Executive functions” (EF) is an umbrella term for a set of cognitive abilities that are thought to be controlled by the frontal lobe of the brain. The development of these abilities relies on the use of different language skills, including reading. Dyslexia is a specific case of reading impairment that is primarily a result of phonological deficit. In this chapter, the involvement of EF during reading and the possible contribution of executive dysfunction to dyslexia are described. The effect of an executive-based (speed of processing, working memory and visual attention) reading intervention that can improve reading ability in both children and adults with dyslexia by re-wiring brain regions important for both reading and executive functioning is also reviewed. The role of EF in reading may have future implications for diagnosing dyslexia and improving intervention therapy for individuals with reading disabilities.

Keywords Dyslexia • Executive functions • Error detection • Fluency • Training

1 Executive Functions

What Are Executive Functions?

Executive functions (EF) are mental processes that are thought to originate from the prefrontal cortex (PFC) and are used in planning, organizing, learning, etc. (Horowitz-Kraus, Holland & Freund, 2016). These abilities are used to manage attention, emotion, and behavior in relation to determination to reach goals (Horowitz-Kraus, Holland et al., 2016). More specifically, some key EF are

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T. Horowitz-Kraus (✉)
The Educational Neuroimaging Center, The Faculty of Education in Sciences and Technology, Technion, Haifa, Israel

Pediatric Neuroimaging Research Consortium, Cincinnati Children’s Hospital Medical Center, Cincinnati, OH, USA

Reading and Literacy Discovery Center, Cincinnati Children’s Hospital Medical Center, Cincinnati, OH, USA
e-mail: tzipi.horowitz-kraus@cchmc.org

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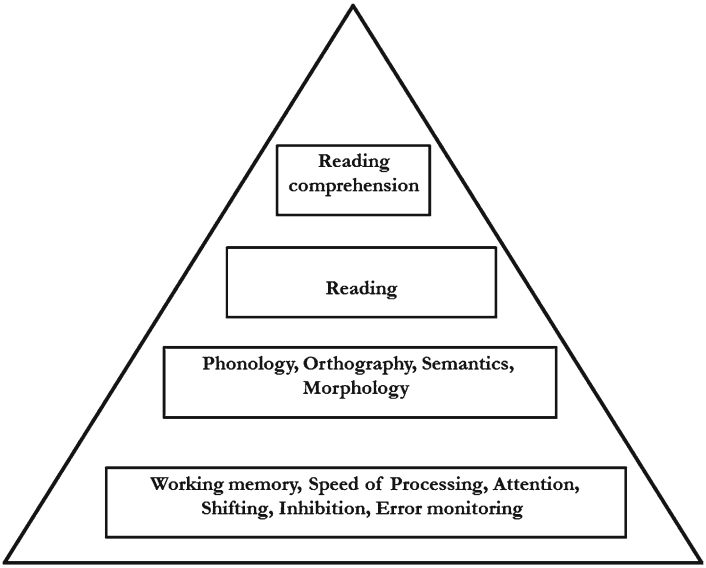

Fig. 1 The reliance of reading and reading comprehension on executive functions

planning, *initiation*, *working memory*, *self-control* (*inhibition and monitoring of performance*), *speed of processing*, *attention*, and *task switching* (Zelazo, 2010) (see also Fig. 1). *Planning* involves goal-directed management techniques that are crucial for task performance; what is the goal, how am I going to pursue it, do I have the right tools and if not, what do I have to do in order to get them? (Zelaso et al., 2003). When there is a plan in place, then the individual can initiate it. *Initiation* is the ability to start a task in a timely manner, while keeping in memory the necessary details for task performance using working memory. *Working memory* is defined as the ability to hold and manipulate several items in memory (Booth, Boyle, & Kelly, 2014). *Self-control/monitoring* is the ability to monitor performance and learn from mistakes, which is done by comparing the desired with the actual response (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000). *Self-control/inhibition* is preventing the execution of a particular, non-relevant behavior (Booth et al., 2014). *Speed of processing* is the time elapsed between when a subject perceives a stimulus until the moment the response is executed (Miller & Vernon, 1997). *Attention* is orienting to stimuli in the visual/auditory space (Posner, Snyder, & Davidson, 1980) and *switching* is the ability to change attention focus from one activity/modality to another (Kieffer, Vukovic, & Berry, 2013). All of these functions are necessary for learning, and individuals who have impaired EF are neither capable of self-regulating their behavior nor retaining knowledge as well as those with functional EF (Booth et al., 2014).

The development of EF is essential for intact personal relationships, as well as for academic success (Zelazo et al., 2003). A developing child uses these abilities to learn how to communicate by focusing the auditory attention to words, matching them to a semantic meaning, and holding them in working memory (Booth et al., 2014) to then be able to comprehend narratives (Horowitz-Kraus, Vannest, & Holland, 2013). Learning a new cognitive task or activity and applying it rely on processing visual or auditory stimuli and repeating them in a fast processing manner while inhibiting unnecessary stimuli, until the behavior becomes automatic and effortless (Kraus & Horowitz-Kraus, 2015). These abilities are supported by the maturation of the prefrontal lobes and specifically of the PFC (Horowitz-Kraus, Holland et al., 2016).

Developing in infancy, the maturation of the PFC peaks at around 25 years of age (Giedd, et al., 2009). Corresponding to frontal lobe maturation, initially EF develop rapidly in childhood and then gradually slow during early adulthood (Kieffer et al., 2013). It is therefore not surprising that different cognitive tasks that rely on EF are challenging for children, especially when entering school at the age of 6 (Horowitz-Kraus, Holland et al., 2016). A specific example of a higher-order ability that relies on EF that a young child needs to cope with is reading.

Reading and Executive Functions

Reading is defined as the ability to translate written graphemes into corresponding sounds in a fluent and efficient manner (Breznitz, 2006) and relies on several basic linguistic abilities, such as phonology, semantics and orthography. Phonological ability involves the relationship between abstract graphemes and their corresponding sounds. Semantics represents the meaning of a particular word, which directly affects reading comprehension (Horowitz-Kraus, Grainger, DiFrancesco, & Holland, 2014). In addition to these basic linguistic abilities, reading involves an orthographic component that enables the recognition of words and word-parts in a holistic manner. A well-defined model of reading called the Parallel-processing model, describes the synchronization between these three key components in reading ability (Seidenberg & McClelland, 1989). This model demonstrates how word reading requires decoding that involves perception of the word in the visual modality and recoding of its sounds in the auditory phonological system, followed by evoking the semantic representation of the word from the mental lexicon (Breznitz, 2006; Seidenberg & McClelland, 1989). During the reading acquisition period, the young reader relies more heavily on the ability to translate the letters into corresponding sounds and to a lesser extent relies on the orthographic route to derive a meaningful representation of a given word. With time, the young reader starts developing a wider mental lexicon with a “bank” of words that can be read holistically using the orthographic processor, and reliance on phonology becomes of limited use only for unfamiliar or long words. Given the description of this process, which involves focused attention, retrieval, fast speed of processing to enable the semantic integration, and also working memory to manipulate the sounds within a word, it seems reasonable that the reading process relies heavily on EF

(Horowitz-Kraus, Holland et al., 2016) (see Fig. 1 for the different EF involved in the reading process).

The primary EF that reading relies on are *inhibition*, *working memory*, *speed of processing*, *attention switching* and *self-control* (Booth et al., 2014). Working memory is required both at the letter level (for unfamiliar letter-by-letter decoded words) as well as at the sentence level (remembering what was read earlier) (Kieffer et al., 2013). The role of working memory in technical reading is to hold sound representations during the decoding phase, until merging all the sounds for a coherent word and then matching for meaning. Inhibition also plays an important role in reading. For example, the ability to inhibit the eye-gaze from moving to the next word before the earlier word was fully decided or alternatively, to inhibit moving to the next line before complete reading of the current one (Booth et al., 2014). Visual attention is necessary for the performance of every reading task, since the eyes should follow the graphemes and the lines in order (Vogel, Petersen, & Schlaggar, 2014). The involvement of switching in the reading process is by the demand of smooth shifting between one line to the other or even by means of switching between decoding and holistic word recognition at the word level. Reading requires a fast speed of processing to quickly synchronize the auditory (sounds) and the visual (words/letters) in the text (Breznitz & Misra, 2003). If the speed is too slow, then the load on working memory and the attempt to keep track via synchronizing is too heavy, which may impair semantic and comprehension processes (Breznitz & Misra, 2003). Other evidence for the reliance of reading on speed of processing and automatic and fast retrieval of information has been demonstrated by a recent neuroimaging study that used the verb-generation task (Horowitz-Kraus et al., 2013). The researchers determined that proficient word reading by 17-year-old adolescents was correlated with EF-related brain regions [Brodmann areas (BA) 10, 9] as well as with a reading-related region (BA 37) while performing an oral verb-generation task (i.e., a fluency task). This study demonstrated that better reading performance was correlated with a gradual increase in left-lateralized activation of reading and EF regions from the ages of 6–11 to 17, which connects reading to a fast and automatic retrieval of verbs. The commander of all of these processes is *self-control* (performance monitoring), mainly through the error-monitoring process. The error-monitoring system is a cognitive mechanism that is thought to emerge from the anterior cingulate cortex (ACC; BA 24) in the anterior portion of the frontal lobe, which shares strong anatomical and functional connections to the PFC by sending and receiving neural transmissions to the PFC (Scheffers & Coles, 2000). This cognitive process underlies the learning mechanism in general and is a basis for reading in particular (Horowitz-Kraus & Breznitz, 2008). The main role of error monitoring in the reading process is the recognition of reading errors and prevention of error repetition (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991). When a reader makes a reading error, the error-monitoring system regulates comparison of the actual and desired responses (i.e., the actual word that was read is compared with the stored mental representation of that word in the mental lexicon). In case of an erroneous response, a mismatch occurs and a negative event-related potential (ERP) called error-related negativity (ERN) is evoked within approximately 100 ms of execution of the erroneous response and can be distributed to frontal-lobe electrodes (Falkenstein et al., 1991). Interestingly, another negative potential called correct-related negativity (CRN) also is evoked in the same time frame and in the same scalp distribution as ERN and represents a correct response, resulted from conflict and uncertainty (Pailing & Segalowitz, 2004). In healthy individuals, CRN is smaller in size than ERN (Pailing & Segalowitz, 2004).

Dyslexia and Executive Functioning

Dyslexia is a specific impairment in reading that cannot be attributed to other neurological deficits and is defined by slow and/or inaccurate reading that continues into adulthood despite remedial intervention and repeated exposure to the written language (IDA, 2011). There is cumulative data suggesting that both children and adults with dyslexia also share a deficit in executive functioning.

Previous studies have identified deficits in a sub-domain of executive functioning in both children and adults with dyslexia (Altemeier, Abbott, & Berninger, 2008; Brosnan, Demetre, Hamill, Robson Shepherd et al., 2002; Helland & Asbjornsen, 2000; Horowitz-Kraus, 2014; Gooch, Snowling, & Hulme, 2011; Kraus & Horowitz-Kraus, 2015; Menghini, Carlesimo, Marotta, Finzi, & Vicari, 2010, Reiter, Tucha, & Lange, 2005; Tiffin-Richards, Hasselhorn, Woerner, Rothenberger, & Banaschewski, 2008). One of the only ERP studies to examine the impairment of EF in individuals with dyslexia (Horowitz-Kraus, 2014) used the Wisconsin card-sorting task, which is a task that encompasses several EF domains. For this task, participants are presented with 64 cards with a different combination of shapes (triangles, circles, and squares), colors (red, blue, green, and yellow) and numbers (1–4). One key card is presented, and participants are asked to match this card with one of four presented cards. Following each response, the participant is provided with an auditory feedback as to whether the response was correct (and therefore the participant should continue choosing this response) or erroneous (and therefore the participant has to choose another rule to match the target card with another of the other four presented cards). This test often is used to determine executive functioning abilities since it involves both switching and working memory (Nyhus & Barcelo, 2009). Twelve-year old children with dyslexia demonstrated smaller ERP components when processing the cards presented and when required to change the rules, compared to age-matched typical readers (Horowitz-Kraus, 2014). Since these components represent early attention abilities (i.e., N100) and speed of processing (i.e., P300), it was postulated that the difficulties in EF impaired the children's ability to reach the same accuracy scores in the Wisconsin task as age-matched typical readers. It also was suggested that impaired working memory prevents children with reading difficulties to reach the accuracy scores of typical readers in the Wisconsin task, as this task involves the maintenance of the correct rule in memory. This working memory deficit may be linked to an impairment in phonological processing that directly impairs reading (Horowitz-Kraus, 2014), which is compatible with a theory previously postulated for the relationship between working memory and phonological processing (Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986). Difficulty in working memory may also result in impairment of the ability to comprehend written materials, resulting from an attempt to decode words that overloads the working memory processor since all the sounds are needed to be installed until a meaningful word is reached. This may create a bottle-neck that impairs the ability to comprehend longer sentences (Breznitz & Share, 1992; Horowitz-Kraus & Breznitz, 2011).

Adults with dyslexia have also been reported to have difficulty when performing the Sternberg task (Horowitz-Kraus & Breznitz, 2009). In this task, participants are requested to look at and memorize a list of digits. Then a probe digit is presented and the participant has to decide whether or not that item was actually in the list (Sternberg, 1966). Difficulty performing this task was associated with the participants' reading impairment (lower number of words per minute was positively correlated with lower scores in the memory task) as well as with smaller ERP components related to error monitoring (i.e., ERN). The impairment in working memory, in particular slower speed of processing and error-monitoring deficit, may result in lower outcomes in this task (Horowitz-Kraus & Breznitz, 2009).

Individuals with dyslexia have impaired inhibition skills, and it has been suggested that their difficulties in mapping graphemes to phonemes is related, among others tasks, to difficulties in inhibition (Booth, Boyle et al. 2014). Speed of processing is essential for fast and automatic reading, since the time that elapses between perceiving the orthographic representation (letter or word) and matching its phonological representation (sounding it out) should be fast and the process should be effortless (i.e. automatic) (Breznitz & Misra, 2003). If the speed of matching these components is slow, then the overload on working memory becomes greater, which results in inefficient and slower reading that in turn, can lead to deficits in comprehension (Breznitz & Misra 2003; Breznitz & Share, 1992). It has been documented that both children and adults with dyslexia demonstrate a slow speed of processing (Breznitz, 2006; Breznitz & Misra, 2003; Horowitz-Kraus & Breznitz, 2011). Recently, it has been shown that a slow speed of processing, measured using the nonverbal (from the WAIS (Wechsler, 1999) and verbal speed of processing (Rapid Automatized Naming, after (Denckla & Rudel, 1976) tests, results in slower reading speed in adults with dyslexia when reading both individual words and sentences (Horowitz-Kraus & Breznitz, 2011). It also has been suggested that a slow speed of processing is related to additional cognitive impairment found among dyslexic readers, which is an impaired error-monitoring ability (Horowitz-Kraus & Breznitz, 2008).

Dyslexia and Error Monitoring

Both children and adults with dyslexia have impaired error monitoring during the reading process that is manifested by smaller ERN than typical readers during reading errors (Horowitz-Kraus & Breznitz, 2008, 2011, 2013). These differences in error monitoring may be explained based on the 'self-teaching' theory. The self-teaching theory was introduced in the mid 1990s by Share who suggested that a word template becomes part of beginning readers' mental lexicon, after several successful exposures to that word template (Share, 1995). However, this may not be the case for dyslexic readers who make different errors for the same word each time they encounter it. Since there is not a constant error pattern for reading mistakes and the templates are not being installed, the construction of a stable mental lexicon is prevented (Horowitz-Kraus & Breznitz, 2008). Therefore, the smaller ERN in individuals with dyslexia may be the result of this impaired mental lexicon in that if there is no stored "correct" representation of the written word, then a comparison of the actual erroneous word and the unstable stored one results in a smaller ERN (Horowitz-Kraus & Breznitz, 2008).

Dyslexics have smaller gaps between ERN and CRN amplitudes when reading, which results in a similar brain response to both correct and erroneous reading compared to typical readers (ERN/CRN gap equals ~5 μV for typical readers and ~1.5 μV for dyslexic readers; see Horowitz-Kraus & Breznitz, 2008). A larger ERN/CRN gap represents a greater distinction between correct reading and erroneous reading that should be modified in the future. Both children and adults with dyslexia have smaller ERN/CRN gaps during reading due to having a relatively smaller ERN for reading errors (based on not having "correct representation" of the word) and a relatively larger CRN as a result of a conflict and uncertainty during reading (Horowitz-Kraus & Breznitz, 2011). In other words, it seems that with respect to error monitoring, erroneous and correct reading patterns are perceived the same by dyslexics, which may provide a physiological explanation for the repetitive erroneous reading behavior in dyslexic reading. Due to the consistency of these results across ages [children: (Horowitz-Kraus & Breznitz, 2013); adults: (Horowitz-Kraus & Breznitz, 2008)] and orthographies [Hebrew: (Horowitz-Kraus & Breznitz, 2008, 2011, 2013); English: (Horowitz-Kraus & Breznitz, 2013; Horowitz-Kraus, Cicchino, Amiel, Holland & Breznitz, 2014), and the correlation of the ERN amplitude with numerous reading and cognitive difficulties in the dyslexic population, the ERN has been suggested as a possible biomarker for dyslexia. If we assume that the ERN is truly a biomarker that reflects the individual's reading impairment, can we suggest that a reading improvement following training will result in changes in the ERN?

2 Plasticity of Error Monitoring in Dyslexia and the Reading Acceleration Program

The Reading Acceleration Program (RAP) is a computerized reading intervention program that focuses on reading fluency (Breznitz, Shaul, Horowitz-Kraus, Sela Nevat et al., 2013). The program manipulates letter presentation rate, requiring the participants to read at their self-paced rate, while monitoring reading comprehension. Following several continuous successful trials, the program speeds the disappearance of letters from the screen, in an accelerated manner, tailored to the individual's reading pace [for more technical information see (Breznitz et al., 2013)]. The RAP has been shown to improve reading speed, and in some cases also accuracy, and comprehension in both children and adults with or without reading disabilities in several orthographies, including Hebrew (Horowitz-Kraus & Breznitz, 2011; Breznitz et al.., 2013; Horowitz-Kraus & Breznitz, 2013, Horowitz- Kraus, 2015; Horowitz-Kraus, Cicchino et al., 2014), English (Breznitz et al., 2013.; Niedo, Lee, Breznitz, & Berninger, 2014; Horowitz-Kraus, 2015; Horowitz-Kraus, Cicchino et al., 2014) German (Korinth, Dimigen, Sommer, & Breznitz, 2009), and Dutch (Snellings, van der Leij, de Jong, & Blok, 2009). The benefit of the RAP training is presumed to arise from a working-memory mechanism (Breznitz & Share, 1992; Niedo et al., 2014) as well as error-monitoring and attention abilities (Horowitz-Kraus & Breznitz, 2014; Horowitz-Kraus, Cicchino et al., 2014). During the reading process, units of data are integrated into the working-memory system at an increased rate and in more meaningful units for storage in the mental lexicon (Breznitz & Share, 1992; Horowitz-Kraus & Breznitz, 2014; Niedo et al., 2014.). A direct comparison of the effect of the RAP in either Hebrew or English revealed a greater effect on Hebrew-speaking children, which may be attributed to differences between Hebrew and English writing systems, given that the Hebrew-speaking children were trained on a shallow form of the Hebrew orthography as opposed to the deep English orthography (Horowitz-Kraus, Cicchino et al., 2014).

The RAP and Executive Functions

Several studies have demonstrated that the RAP improves the activation of the error-detection mechanism (Horowitz-Kraus & Breznitz, 2011, 2013); after 8 weeks of the RAP training, both children and adults with dyslexia as well as typical readers showed greater ERN and had a larger ERN/CRN gap during reading than prior to the RAP training. This improvement, which was positively correlated with the level of improvement in word reading scores, and with greater activation in the Anterior cingulate cortex (ACC)- where the ERN is evoked from as well as in the Fusiform gyrus which is considered as the visual word form area in the brain (Horowitz-Kraus, Vannest, Kadis, Cicchino, Wang et al., 2014), was thought to be due to increased storage and retrieval of words from the mental lexicon. This improved lexical processes may specifically be due to better error monitoring or is a general effect on the entire executive system. The effect of the RAP training on EF in children with dyslexia was examined using the Wisconsin task (Horowitz-Kraus, 2015). In this study, 12-year-old children showed an improved performance in the Wisconsin task, as well as smaller N100 amplitudes after training. The smaller N100 may reflect less attention resources needed to perform the task following RAP training, which was accompanied by improvement with other behavioral EF measures (working memory, switching and attention) and highlights the effect of the RAP training specifically on EF.

The Anatomical and Functional Correlates to the Effect of the RAP Training

Given that ERPs are the result of a neuronal activation over the scalp that may result from different brain regions, another interesting question was to examine the effect of the RAP training on regions of interest in reading-related neural circuitry by using a lexical decision task during fMRI. A specific question of interest was the involvement of the frontal lobe, and specifically of the ACC, following intervention. After 4 weeks of the RAP training, 8–12 year-old children with dyslexia showed improvements in reading comprehension that were associated with significant increases in right frontal-lobe activation. These results corresponded with previous findings pointing at positive correlations of white-matter tracts in the right frontal lobe with better reading comprehension scores in proficient readers (Horowitz-Kraus, Wang et al., 2014). Children with dyslexia also demonstrated greater activation in the ACC, which was the anatomical region from which the ERN is evoked after RAP training. This may position the ACC in general and the error detection mechanism in particular as a compensatory pathway for reading improvement (Horowitz-Kraus et al., 2013, Horowitz-Kraus & Breznitz, 2014). A further functional connectivity analysis suggested that the greater activation in frontal regions during reading in children with dyslexia, but the right ACC showed greater functional connectivity with the fusiform gyrus during word reading following reading training (Horowitz-Kraus, 2013). Additional studies demonstrated an increased functional connectivity between these two regions also during a resting-state condition (Horowitz-Kraus, 2015) as well as an overall increased functional connectivity within the cingulo-opercular network (which Is composed of the ACC) during rest in children with dyslexia following RAP training (Horowitz-Kraus, 2015). These results reinforce findings that greater activation of the error-monitoring system (in the ACC) is related to a more-efficient lexical processing (referred to as FG activation). Although a coupled EEG-fMRI study has not yet been performed, the author presumes that the activation of the ACC following the RAP training would be related to better monitoring performance during reading.

3 Closing Remarks

As researchers and clinicians continue to struggle to find underlying causes for dyslexia, in the past few years accumulated studies have indicated that impaired EF contribute to the existence and severity of dyslexia. With the development of neuroimaging tools, there are now more-sophisticated ways to objectively examine the association between different cognitive abilities, like reading and EF, in time and space. In a top-down cognitive control model, the EF system has been demonstrated to be anatomically divided into two different neural networks: the cingulo-opercular network for set-maintenance and the fronto-parietal for information processing (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008). These authors also described how reading relies in part on visual attention components that are located in the information processing network (precuneus). It is possible that individuals with dyslexia have a specific impairment in one of these networks and therefore compensation for one of them may result from a stronger functional connectivity with the other. Future neuroimaging studies should examine this point in depth. Another interesting question for future study is the effect of a specific EF training on neural circuits supporting both reading and EF. Is it possible that a specific training for the networks supporting EF would result in increased functional connectivity between reading and executive-related brain regions, as well as better reading outcomes? Future studies using fMRI would be useful for the investigation of this point. Nevertheless, this review highlights the important relationship between EF and reading, which is particularly relevant in the case of reading difficulties. Clinicians are urged to pay special attention to the EF domains when diagnosing and while tailoring interventions for those who suffer from reading difficulties.

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