Electrophysiological indices of reading intervention response: A systematic review

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Contents

Abstract

Research on reading and reading intervention has benefited from studies that have employed cognitive neuroscience tools. These efforts have established the brain basis of reading disability (RD) and have shown plasticity in the underlying neural systems for reading as children gain proficiency through instruction or intervention. Most of this work has utilized magnetic resonance imaging (MRI) to reveal differences in functional activation (regional blood flow) during reading between typically developing (TD) and RD readers and/or to look at pre-post intervention change in this activation. While this work has revealed which regions of the brain are involved in reading and how regional activation changes in response to intervention, it is limited in its ability to reveal differences or changes in the temporal dynamics of neural function. Electroencephalography (EEG) and event-related potentials (ERPs), which can measure these temporal dynamics, have also been used to explore individual differences in reading as well as reading intervention-associated changes, albeit to a more limited extent. These studies have also revealed differences in the neurobiology of RD and TD readers and changes in the neural signal following intervention. In this chapter, we provide a systematic review of studies

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that have utilized EEG or ERPs to investigate reading intervention associated changes in neural function. While studies differ in their interventions and ERP components of interest, they reveal a general pattern of reading improvement and ERP component change from pre to post-intervention suggesting plasticity in the neural systems that support reading.

Keywords: Dyslexia, EEG, ERP, Intervention response, Reading

1. Introduction

Reading is a complex dynamic behavior that requires the recruitment and coordination of multiple neural systems (e.g., vision, speech) (Schlaggar & McCandliss, 2007). This complex skill must be explicitly taught to most children, and many struggle to become fluent readers even with high-quality instruction. Indeed, reading disability (RD) is one of the most common neurodevelopmental disorders, affecting approximately 9 percent of children (Peterson & Pennington, 2015). Children with RD have significant difficulty with word reading and spelling, despite typical cognitive ability (DSM-5 (Diagnostic & Statistical Manual of Mental Disorders, n.d.). Although RD can be treated—evidence-based multicomponent interventions often lead to significant improvements—there is substantial variability in intervention response (e.g., Torgesen, 2000). To identify drivers of this variability, studies have tried to identify correlates or predictors of intervention response. Findings from these studies reveal that children with better oral language skills, including phonological awareness and vocabulary, and those with faster processing speed, measured via rapid autonomized naming (RAN), tend to make larger intervention gains (for reviews see: Al Otaiba & Fuchs, 2002; Lam & McMaster, 2014; Nelson et al., 2003; Wanzek et al., 2016). While these behavioral predictor-focused studies can tell us about who is more likely to benefit from reading interventions and what skills are likely to support reading acquisition, they cannot inform us on the mechanisms by which interventions improve reading or about plasticity in the underlying systems that support reading.

To address questions of mechanism and plasticity, researchers have used cognitive neuroscience methods to provide a more direct look at how reading shapes the brain. These efforts have established the brain basis of RD over development at the structural and functional levels (for reviews see: Norton et al., 2015; Pugh et al., 2000; Richlan et al., 2009). This research most commonly employs functional magnetic resonance imaging (fMRI), a method in which a powerful magnet takes advantage of hemoglobin changes in the blood to image regional blood flow in the brain. In this way, fMRI can reveal regions (or networks of regions) in the brain with greater blood flow during activities such as reading. This research has shown that RD is associated with reduced activation (relative to typically developing readers) during reading across a network of predominantly left hemisphere regions that have been independently associated with reading and language subprocesses (e.g., Landi et al., 2010; McCrory et al., 2005; Pugh et al., 2000, 2001; Turkeltaub et al., 2003). These regions of the left hemisphere (LH) include an occipitotemporal (OT) region, including the visual word form area (VWFA) which is involved in recognizing letter strings as words, a temporal-parietal (TP) region, including the supramarginal gyrus (SMG) and angular gyrus (AG), which are involved in translating printed words into sound and meaning, the superior temporal gyrus (STG) which is involved in speech sound processing, and the inferior frontal gyrus (IFG) which is involved in overt and covert articulation. The hypoactivation observed in these regions for RD readers during reading is generally though to indicate less utilization of regions that are optimized for these processes, in favor of more diffuse, and/or less reliable regional utilization. These functional findings are mirrored by differences in structure, typically observed as reduced cortical volume in many of the same LH regions for individuals with RD relative to those with TD (for a review see: Richlan et al., 2013). Some studies have also shown reduced and or otherwise atypical connectivity (temporally correlated activity) among these regions and increased trial-by-trial variability in some of these regions for those with RD relative to those with TD (e.g., Malins et al., 2018; Siegelman et al., 2021). Thus further suggesting differences between RD and TD readers in utilization of this reading related neural circuitry during reading.

With respect to intervention response, a number of studies have revealed plasticity in the underlying neural systems for reading as children gain proficiency through instruction or intervention (for reviews see: Barquero et al., 2014; Perdue et al., 2022). In terms of mechanism, some studies have observed patterns of normalization, where RD children's brain activation following intervention looks more like that of TD children (e.g., Shaywitz et al., 2004). This is most commonly observed as increased activation in the LH reading related regions discussed above from pre to post intervention. Other studies have shown patterns that could be interpreted as compensatory, with RD children showing pre to post intervention increases in right hemisphere and/or frontal regions outside of the typically observed reading network (e.g., Aylward et al., 2003). Still other studies find a mixed pattern, with activation changes both inside and outside of the typical reading network (e.g., Eden et al., 2004; Temple et al., 2003). Indeed, a recent meta-analysis found no common pattern of pre-to-post change across the eight studies that were available for meta-analysis (Perdue et al., 2022); however, the authors note that this is unsurprising given differences across studies in fMRI tasks, interventions, and child-level factors such as age and skill level.

While MRI is useful for localization of function, its temporal resolution is quite poor and thus it reveals little about the temporal dynamics of neural function during reading. Other methods such as electroencephalography (EEG), and event related potentials (ERPs), do have good temporal resolution and can be utilized to reveal typical and atypical patterns of neural firing during reading. These methods use electrodes to measure voltage changes at the scalp, which reflect the underlying firing patterns of large populations of neurons in the cortex. ERPs represent event-related and time-locked averages of the EEG signal in response to externally presented stimuli, such as words or phonemes. ERPs have been used to reveal the temporal dynamics of reading and closely linked language skills, revealing both early (i.e., by 300 ms during reading) components associated with orthographic and phonological processing, and later (i.e., after 300 ms during reading) components associated with semantic and syntactic processing of word and sentence reading. These components are observed as negative and positive deflections in the time locked and averaged waveform that are consistently observed across groups of people doing similar tasks. These components are most often labelled for their deflection (positive [P] or negative [N]) and the time at which they peak (typically between 100 and 600 ms). While ERPs do not provide good spatial resolution in terms of the brain regions they originate from, components do show substantial consistency in terms of where they are observed on the scalp. Thus, careful consideration of scalp location along with timing and waveform morphology affords consistency in component identification across studies. Note also that some components are observed across multiple stimulus contexts. For example, we may observe a positive deflection at 300 ms (a P300) when participants are detecting an infrequent speech sound *and* when participants are detecting an infrequent image. This suggests that the P300 is a domain general response to an unexpected or salient stimulus, rather than to specific stimulus contrast per se. More of these nuances are discussed below with study details (for more on ERPs please also see: Luck, 2014).

When comparing RD and TD readers during reading or speech processing, studies have found differences across many of these components, and most commonly in those that reflect phonological and orthographic processing—e.g., the N170, P200, and P300 (for reviews see: Basma et al., 2024; Lyytinen et al., 2005; Premeti et al., 2022; Volkmer & Schulte-Körne, 2018). And finally, some studies have examined longer segments of continuous EEG, separated via Fourier transform into its component frequencies (synchronous firing rates of populations of neurons), to look for RD associated differences in the underlying firing patterns of neurons. These too have revealed differences—mostly in the theta and alpha frequencies—between RD and TD individuals, both in response to linguistic stimuli and at rest (no stimulus) (for a review see: Cainelli et al., 2023) though somewhat more inconsistently than studies utilizing ERPs.

As with MRI, a small body of research has sought to use ERP and/or EEG to examine reading intervention response at the neurobiological level. This work is motivated by the idea that intervention-associated changes should be observable in the temporal dynamics of neural firing during reading. Moreover, such methods may be more sensitive than fMRI, as changes in reading fluency or automaticity may result in faster processing but not necessarily greater activation or differential regional involvement. As of this writing, we do not know of any papers that have attempted to summarize and synthesize this work. The goal of this chapter is to provide a systematic review and synthesis of studies that have used EEG or ERP to look at pre-to-post-reading intervention changes in the neurobiological signal. We begin with our systematic review methods, followed by the review itself. The review is sectioned by intervention type, and includes: details on the interventions employed; an overview the relevant ERP/EEG measures, including a description of how the EEG/ERP signals are elicited and quantified; and any statistically significant findings. We also provide a summary table (Table 1) of findings. Finally, we discuss the take-aways from this literature.

2. Systematic review methods

2.1 Eligibility criteria

To be included in the systematic review, articles had to: (1) be primary research studies presented in peer-reviewed, published journal articles, in press articles, in preparation articles, conference proceedings, conference presentations, or dissertations; (2) have their full text available in English; (3) include participants with or at-risk for developmental reading disability (i.e., dyslexia); (4) include a behavioral intervention targeting reading or a related

Table 1 Summary of articles included in systematic review.

Author and year	Intervention type	Intervention duration	Number of RD participants	RD participant ages	ERP component(s)	Intervention effects: reading/related skills	Intervention effects: ERP
Alvarenga et al. (2013)	Phonology, reading, writing	18 h over 12 weeks	20	8–14 years	CHEP, P300, P200	Improvement in phonological skills	Reduced P300 latency
Horowitz-Kraus and Breznitz (2014)	Speeded reading	6 h over 8 weeks	29	12 years	ERN, CRN	Improvement in reading accuracy and speed (isolated words and words in text); Improvement on general cognitive measures; improvement in reading comp for RD only	Increased ERN amplitude
Horowitz-Kraus (2016)	Speeded reading	6 h over 8 weeks	29	24 years	ERN, CRN	Improvement in reading accuracy and speed	Increased ERN amplitude

Huotilainen et al. (2011)	Auditory processing	1.5 h over 5 weeks	39 (very low birth-weight children at risk for RD)	6 years	MMN	Improvement on phoneme omission	Increased MMN amplitude
Jucla et al. (2009)	Phonemic awareness, orthography	16 h over 2 months	24	9–11 years	P300, N170	More accurate lexical decision performance	Reduced N170 amplitude and latency; reduced P300 amplitude
Kujala et al. (2001)	Audiovisual matching	2.3 h over 7 weeks	48	7 years	MMN	Improvement in word reading accuracy and speed	Increased MMN amplitude
Lovio et al. (2012)	Phonological (letter sound, syllable)	3 h over 1 session	31 (pre-readers at risk for RD)	6–7 years	MMN, P3	Improvement in all reading and related skills (e.g., letter knowledge, phonological processing, writing)	Increased P3 amplitude; reduced MMN latency;
Mayseless (2011)	Fluency, general cognition	6–8 h over 8 weeks	20	25 years	P1	Not reported	Longer P1 latencies

Continued

Table 1 Summary of articles included in systematic review.—cont'd

Author and year	Intervention type	Intervention duration	Number of RD participants	RD participant ages	ERP component(s)	Intervention effects: reading/related skills	Intervention effects: ERP
Santos et al. (2007)	Phonology, audiovisual	14 h over 6 weeks	10	9–12 years	P300	Improvement in phonological awareness, spelling, and reading	Increased P300 amplitude
Stevens et al. (2013)	Phonological awareness, alphabetic skills, handwriting, spelling	20 h over 8 weeks	8	5–6 years	Early attention	Improvement in measures of letter naming, nonsense word fluency, and phonemic segmentation	Difference in their ERP attentional component no longer present at post test
González et al. (2016)	Sound-letter mapping	25 h over 22 weeks	18	9 years	N170	Improvement in reading fluency and spelling accuracy for some RD readers (broken into improvers and non- improvers)	Decreased N170 amplitude for words

skill (e.g., phonics, reading fluency, letter-sound matching, phonological awareness, or other speech sound training); (5) include pre- and post-intervention neuroimaging acquired using EEG or ERPs. Articles that presented case studies or had participants with acquired forms of reading disability were excluded. Articles that featured interventions focused on training general skills (e.g., memory) or using biofeedback or TMS were excluded.

2.2 Retrieval of records

We conducted a literature search using databases related to psychology, education, and neuroimaging: PsychInfo, ERIC, Academic Search Ultimate, MedLine, EBSCOhost eBook Collection, PubMed). We identified additional articles by screening the references of published reviews of reading intervention studies that used neuroimaging methods e.g., (Goswami, 2009; van der Molen et al., 2024). After determining which articles from the initial database search and review references met the criteria for our review (see below for more details on screening procedures), we used the "search within citing articles" function in Google Scholar to identify articles that cited them. Search terms for both the database search and the reverse citations search are available in supplementary materials.

2.3 Screening

The initial database search yielded 122 total records. After removing 35 duplicates, we screened the titles and abstracts of 88 records to determine if they met the eligibility criteria listed above. BL completed this initial screening using Rayyan (Ouzzani et al., 2016). Thirty-eight articles appeared to meet the inclusionary criteria and were sought for retrieval. Two of these records were not available in English. NL used the full text to assess the eligibility of the remaining 36 articles. Articles were excluded for various reasons at this stage: two were outdated, one was a duplicate that had not been previously detected, seven did not have a reading intervention, eight had no intervention at all, five did not report enough EEG to be assessed, two were reviews rather than research articles, and one studied a different population. In total, the database search yielded 10 articles to be included in the review.

Three relevant articles were identified from the references of previously published reviews. One of these articles was removed as a duplicate, one was screened but contained no EEG data, and one was deemed eligible for inclusion. Thus, references from prior reviews yielded one additional article to be included in our review. We then used Google Scholar to search the citations of the 11 articles already determined to be eligible. Nine hundred and seven articles were identified in this process. The full text for 13 of these articles was retrieved for screening, but none met the criteria to be included in our review. Ultimately, a total of 11 articles were included in the review. See Fig. 1 for a PRISMA flow diagram (Page et al., 2021) documenting the screening process.

2.4 Coding and validity

The authors (NL & BL) divided the 11 eligible full-text articles between them and coded for several types variables: bibliographic information; participant information (e.g., age, sample size); intervention information (e.g., name, duration, intensity); and EEG/ERP information (e.g., task, components, bands, analyses), and intervention effects (changes pre-to-post intervention, correlation with reading skills). Table 1 lists these studies and their component or frequency band of interest.

3. Systematic review

3.1 Interventions targeting phonics

Perhaps unsurprisingly, the largest set of studies we reviewed ($n = 5$) utilized interventions or training protocols that targeted phonics (learning the connections between letters/letter combinations and speech sounds) and related reading precursor skills like phonological awareness. Such interventions have the most empirical support (Foorman et al., 1997; Gersten et al., 2020; Hall et al., 2023; Torgesen et al., 1997). The first four studies in this section targeted elementary school students or prereaders and used an ERP measure of speech sound processing before and after the intervention. These tasks involved listening to speech sounds (often synthetic speech sounds) that contrast in some meaningful way (i.e., in initial consonant [/ba/ vs. /da/]). They also employed an oddball task, in which one type of stimulus is presented more frequently than another (often counterbalanced across blocks), and participants either listen passively or are asked to press a different button for each stimulus type or just to the less frequently occurring stimulus. In the first study (Lovio et al., 2012), the authors examined the mismatch negativity response (MMN), which is a greater negative deflection peaking around 250 ms to the less frequently occurring

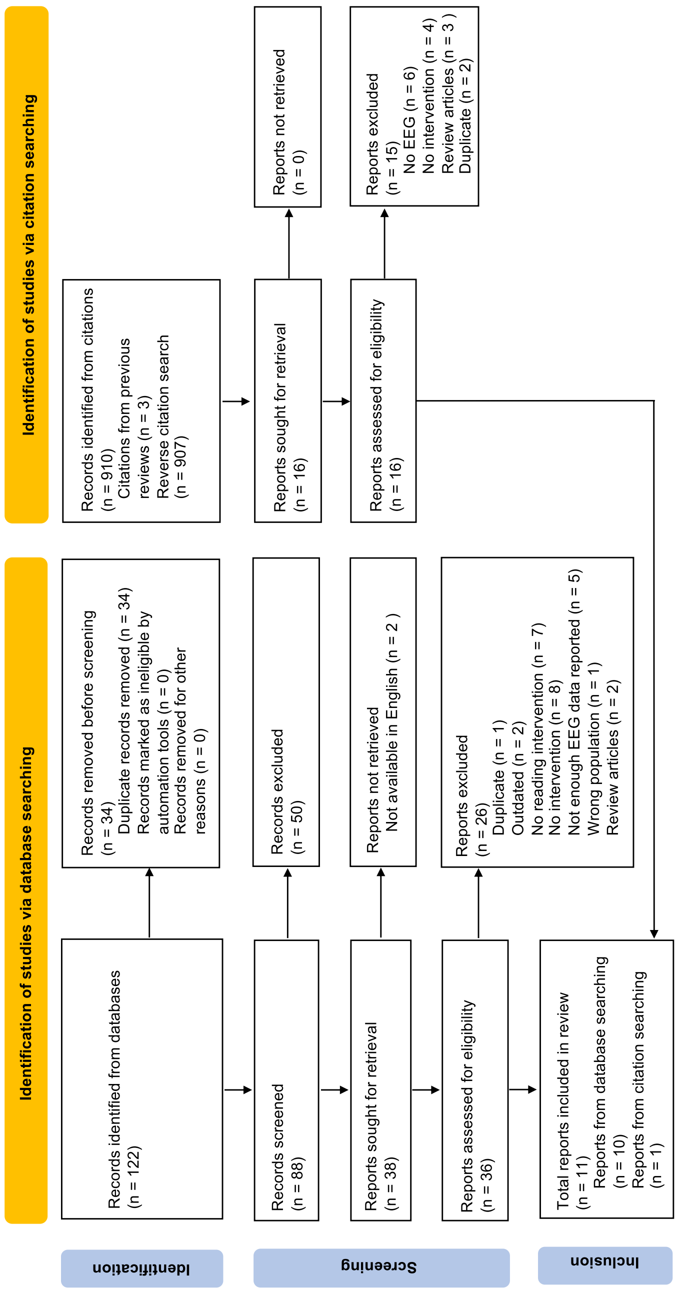
Identification of studies via database searching
Identification of studies via citation searching
Identification
Screening
Inclusion
Records identified from databases (n = 122)
Records removed before screening (n = 34)
Duplicate records removed (n = 34)
Records marked as ineligible by automation tools (n = 0)
Records removed for other reasons (n = 0)
Records screened (n = 88)
Records excluded (n = 50)
Reports sought for retrieval (n = 38)
Reports not retrieved
Not available in English (n = 2)
Reports assessed for eligibility (n = 36)
Reports excluded (n = 26)
Duplicate (n = 1)
Outdated (n = 2)
No reading intervention (n = 7)
No intervention (n = 8)
Not enough EEG data reported (n = 5)
Wrong population (n = 1)
Review articles (n = 2)
Total reports included in review (n = 11)
Reports from database searching (n = 10)
Reports from citation searching (n = 1)
Records identified from citations (n = 910)
Citations from previous reviews (n = 3)
Reverse citation search (n = 907)
Reports sought for retrieval (n = 16)
Reports not retrieved (n = 0)
Reports assessed for eligibility (n = 16)
Reports excluded (n = 15)
No EEG (n = 6)
No intervention (n = 4)
Review articles (n = 3)
Duplicate (n = 2)

Fig. 1

stimulus in a passive design. In the second study (Alvarenga et al., 2013), the authors examined the P300 response, which is a positive deflection peaking around 300 ms to the less frequently occurring stimulus in an active design. Both of these ERP components have been associated with reading disability (Kujala & Näätänen, 2001; Neuhoff et al., 2012; Papagiannopoulou & Lagopoulos, 2017; Schulte-Körne et al., 2001), typically with a smaller amplitude deflection or longer latency (time to peak) for those with RD relative to those with TD. Longitudinal studies have also observed smaller or otherwise atypical MMN response to speech in infants and preschoolers who go on to have reading difficulties (Guttorm et al., 2010; Molfese, 2000). Notably, these components, the P300 in particular, can be elicited to many types of oddball, incongruous, or unexpected stimuli, which makes them very useful. Spoken syllables or words are used most often in investigations of reading and dyslexia because speech and spoken language processing is tightly linked to reading and reading skill (Liberman & Shankweiler, 1985).

In the first study in this section, Lovio and colleagues (Lovio et al., 2012), tested 31 monolingual Finnish speaking pre-readers, half of whom were at risk for reading difficulties, and divided them into reading intervention and control groups. The reading intervention group played a tablet-based letter-speech sound training (GraphoLearn), and the control group played a number knowledge game. The training took place over 3 weeks, and each session lasted 5 to 20 min (~ 180 min total). Pre- and post-intervention EEG were collected using a speech oddball task with both vowel and consonant contrasts. The intervention group improved in all reading related skills and performed significantly better than the control group on phonological processing, writing words, and writing nonwords. There was a marginally significant interaction between group and test time for the MMN response, with those in the intervention group having a larger MMN for the vowel change contrast relative to the control group. These findings suggest that even a short-term intervention can lead to improvement in reading related skills in early/prereaders and that these effects are also observable at the neurobiological level, here in terms of greater neural response to a contrasting speech sound.

In a second study, Alvarenga and colleagues (Alvarenga et al., 2013), 20, eight to 14 year old Brazilian children with dyslexia were divided into control and treatment groups (10 and 10). The treatment group received a phonics-based reading intervention with 24, 45-minute sessions for 12 weeks (1000+ minutes), and the control group received no intervention during this period. Participants also participated in pre- and post-intervention EEG using an active speech (consonant contrast) oddball paradigm, in which participants were asked to detect the deviant (less frequently occurring) stimulus. Students in the intervention group improved in their phonological processing relative to the control group, and the latency of their P300 response decreased. These findings suggest that intervention-associated change in reading is observable over a relatively short period (though longer than the first study approach) in older children as well. The effects observed in the neurobiological response (here faster P300 response to a consonant contrast) mirrored those observed in behavior.

The other three papers in this section use phonics intervention but take a different approach with their ERP tasks. One (Jucla et al., 2010) examines both the P300, and the N170, which is an early visual processing component (positive deflection that peaks around 170 ms) that is thought to reflect expertise or familiarity in processing visual stimuli such as words and faces, and has been linked to reading skill and dyslexia (Dujardin et al., 2011; Schlaggar & McCandliss, 2007). Another (Santos et al., 2007) examines the P300 response but in a more unusual paradigm that indexes prosodic congruency, with a larger deflection expected for prosodically incongruent spoken words. And a third (Stevens et al., 2013) examines an orienting component that is sensitive to attention. This last example is similar to a P300 response (positive deflection peaking around/after 200 ms) and seems to be sensitive to attended vs unattended stimuli.

In the first study, Jucla et al. (2010)[1] enrolled 24 9 to 11-year-old dyslexic children and 11 age matched TD children in a study that investigated the effectiveness of a remediation program, which involved phonological and visual attention training for six days a week, 20 min per day, for 2 months (900+ total minutes). EEG and behavioral measures of accuracy on a visual lexical decision task with words, pseudowords, nonwords, and pseudohomophones were measured before and after the regimen was completed. Dyslexic and control children improved in their accuracy on the visual lexical decision task from session one to session two (indicated by an overall session effect). As to ERP effects, for the N170, dyslexic children had shorter latencies to pseudowords (pronounceable nonwords that do not have a common pronunciation with a real word) after completing the program and smaller amplitudes for pseudo homophones and pseudowords (pronounceable nonwords that sound like a real word) after completing the program. For the P300, there were no latency changes for the dyslexic

[1] Note that statistics were not reported for all pairwise comparisons in this paper.

children from session one to session two, but there was an amplitude decrease for words and nonwords (non-pronounceable letter strings). These findings suggest that this program had an effect on both the speed (i.e., N170 latency) and accuracy of processing for pseudohomophones and pseudowords, though interestingly not for words, and on neural synchrony (P300 amplitude) for words and nonwords. This partially contrasts with Alvarenga et al. (2013) findings, which were in the latency of the P300 and not amplitude; however, the stimuli and tasks used across the two studies were distinct (a deviant detection task with CVs vs. lexical descision with words/nonwords).

Santos and colleagues (Santos et al., 2007), also examined the P300 response but took a unique approach by using a prosodic congruency task. Prosodic processing (perception and production) has been linked to both foundational reading skills and reading comprehension (Breen et al., 2024; Wade-Woolley et al., 2022). In this study, 10 nine to11 year old children with dyslexia participated in a phonological training program and a supplementary audio visual training program with daily exercises for six weeks (Habib et al., 2002) while 10 TD controls participated in an art training. Both groups participated in a pre-post sentence listening ERP study in which they had to judge whether a sentence-final word was normal or strange. This final word was either normal (prosodically congruous) or had its pitch manipulated to be strongly or weakly prosodically incongruous. The authors expected that words with incongruous prosody would produce a larger P300-like deflection if students detected the incongruence.

Performance on measures of phonological awareness, spelling, and reading all improved from pre to post test for the dyslexic group. Performance in the ERP prosody congruency task improved from pre to post test for all children, and the dyslexic children no longer differed from controls for the strongly incongruous condition. The main training relevant ERP finding was that the dyslexics and the controls no longer differed in their P300 response to the strongly incongruous words following training. Both groups had large P300 responses to strongly incongruous words after training; however, only controls showed this pattern before training. These findings suggest that phonological training improved reading and prosodic perception for dyslexic children, which could be detected at the behavioral and neurobiological levels.

In the last article in this section, Stevens and colleagues (Stevens et al., 2013) took a different approach by focusing on selective attention. Selective attention is one of many domain general skills that has been associated with reading difficulties and dyslexia (Casco et al., 1998; Hokken et al., 2023; Schworm, 1979; Valdois et al., 2004). These authors examined selective attention (using ERPs) in kindergarteners identified as at risk (AR; $n = 8$) and an on-track control group (OT; $n = 6$) in a pre-post design. At-risk (AR) children received early reading intervention (ERI). The ERI consisted of 30 min per day, 5 days per week for eight weeks and focused on phonemic awareness, alphabetic understanding, letter writing, word reading, spelling, and sentence reading. The OT group received only their normal schooling. The ERP task consisted of two simultaneously presented stories in which children were told to attend to one and ignore the other. ERPs were recorded to linguistic (the syllable /ba/) and nonlinguistic (scrambled /ba/) probe stimuli (100 ms duration) embedded in the attended and unattended stories. The authors analyzed an early auditory component with a positive deflection ~200 ms (P300 like) that was larger for the attended than the unattended probes. Following the intervention, the AR group improved on measures of letter naming, nonsense word fluency, and phonemic segmentation (differences from OT participants were no longer significant). Furthermore, while their P300-like ERP response was present but small at pretest, it was larger and similar to that of the OT controls at posttest. These findings suggest that this ERI improved both reading-related behavioral skills and selective auditory attention (measured at the neural level) for at-risk kindergarteners.

Taken together, studies in this section find that phonics-based interventions are effective for improving reading and related skills and that these effects can be observed in both behavioral performance and neurobiologically via changes in early ERP component response. Collectively these studies reveal changes in MMN response to speech (larger following intervention [greater speech sound discrimination]), P300 response to speech (faster latency), P300 amplitude decrease to printed word-like stimuli (increased familiarity), reduced N170 amplitude and latency to printed word-like stimuli (increased familiarity), and P300 increase to prosodically incongruous stimuli and embedded speech probes [better detection/attention to speech sounds]). Most of these effects were in amplitude rather than latency, which suggests changes in overall neural firing and/or synchrony, rather than in speed, though these two measures are not necessarily independent and latency effects can be harder to detect due to ERP processing methods that smooth over peaks. Perhaps unsurprisingly given phonics-based training, many of the observed ERP effects were to speech, suggesting that this training improved aspects of phonological processing. However, there were also two effects observed to print, suggesting that phonics-based training improved decoding/and or word recognition as well.

3.2 Interventions targeting audiovisual processing

A second type of intervention reported involved audio visual (AV) processing or integration ($n = 2$). This type of intervention is motivated by the notion that reading involves integration of letters and sounds and thus training students to link the two modalities (visual and auditory) could strengthen early reading skills. In both studies discussed here (Huotilainen et al., 2011 and Kujala et al., 2001), the trainings involve nonlinguistic stimuli, however others have utilized AV training with linguistic stimuli. ERP tasks in these studies utilized oddball designs to elicit the mismatch negativity response. In both studies, the researchers used a tonal oddball, in which children passively listed to tones that differed in one or more acoustic dimensions (e.g., frequency, duration).

In the first study, Huotilainen and colleagues (Huotilainen et al., 2011), examined very low birthweight (VLBW) Finnish speaking children, who are at risk for reading and other difficulties. Thirty nine eight-year-old VLBW children were randomized into the AV training and control groups. The AV training (Karma, 2002) consisted of a nonlinguistic task in which children learned to associate visual features to sounds. Specifically, they had to learn that rectangles varied in ways that corresponded to sounds, with length corresponding to sound duration, thickness to sound intensity, and vertical position to pitch. Training involved playing for five weeks three times a week for at least 10 min at a time (at least 150 total minutes). A set of tonal oddball tasks were conducted before and after training and MMN responses were examined. Fifteen children in the training group and 13 in the control group completed all tasks. Both groups improved in reading-related skills, and behavioral differences between the groups were negligible, with only one task (initial phoneme omission) showing improvement associated with the training specifically. The primary ERP finding was a difference in MMN response for the treated group, with increased MMN amplitude during tone discrimination in which deviants differed in frequency and duration. Taken together, the authors interpreted these findings as reflecting changes to the auditory system (plasticity) that supports phonemic processing, given that the behavioral improvement was in an aspect of phonemic awareness and that the ERP task involved fast presentation of tones and variation that mimics some aspects of speech.

Similarly, Kujala and colleagues (Kujala et al., 2001) used the same training program (Audilex, described above) to determine whether AV training could improve reading skills in seven-year-old Finnish speaking children with dyslexia. Thirty-nine children were divided into training and control groups. For the training group, there were 14 training sessions, each lasting 10 min, twice a week for seven weeks (140 total minutes). The control group received no training. Again, as in (Huotilainen et al., 2011), students participanted in a tonal oddbal task to elicit the MMN response before and after trainning. Despite similar scores before training, after training children in the training group read significantly more words correctly than those in the control group and their reading speed was faster than those in the control group. Similarly, after training, children in the Audilex training group showed larger MMN response in the tonal oddball task relative to the control group children. Further, there was a significant correlation between MMN amplitude change from pre to post test and change in reading scores. Beyond Huotilainen et al. (2011), which showed changes in phonemic awareness and tonal processing following AV training, findings from this study suggest that even fully non-lingusitic AV training can improve reading performance and tone discrimination in chilren with reading difficulties.

Taken together, findings from these two studies suggest that a nonlingusitic training program can improve reading and phonological processing, at least in the short term, as well as MMN response to tones (better tone discrimination). These results are somewhat surprising given that these training programs did not involve training in letters, speech sounds, or reading. Again, as with most studies in the first section, findings were in amplitude rather than latency, suggesting changes in the amount or sycnchrony of firing during tonal processing. Overall, learning to link visual and auditory stimuli appears to transfer to improved linking of letters and letter sounds.

3.3 Interventions targeting reading fluency

The next group of studies ($n = 4$) involved interventions that target reading fluency, which is typically defined as connected-text reading speed. These studies are also concerned with monitoring other aspects of processing that may change in response to a fluency intervention: error monitoring and detection in the first two studies (Horowitz-Kraus, 2016; Horowitz-Kraus & Breznitz, 2014) and visual processing in the second two (González et al., 2016; Mayseless, 2011). Four different ERP components are elicited across these studies. The first two examined the error related negativity (ERN) and correct response negativity (CRN). These components, much like the P300, can be elicited by a variety of different stimulus types and track the subject's initial realization of making an incorrect or correct response. The second two studies measured visual processing components: the N170 (discussed in the prior section) and/or the P1 (or P100), which is an early visual processing component thought to reflect very early extraction of visual features or visual orienting.

In the first study, Horowitz-Kraus and Breznitz (Horowitz-Kraus & Breznitz, 2014) asked whether the reading acceleration program (RAP), could improve reading and general cognitive processing in 29 adolescents with RD. This program removes letters from the screen as participants read sentences and slowly increases the rate at which letters disappear to encourage the participant to read more quickly. The authors of RAP suggest that it frees up space in working memory and thus improves fluency. Pre and post training ERPs were compared to those of 32 typically developing controls. All participants were trained with RAP for eight weeks, three times a week, 15 min per session, for a total of 24 sessions (360 total minutes). For ERP elicitation, participants completed a lexical decision task in which they were asked to decide if visually presented words were lexical items or not. The authors were interested in the error related negativity (ERN) and the correct response negativity (CRN), which measure sensitivity to errors and correct responses as a negative deflection peaking around 300 ms. They predicted that the ERN and the difference between the ERN and CRN would increase after training, reflecting better/faster processing of the visual information and hence greater awareness of correct and incorrect responses.

After training, both groups read isolated words and words in text faster, and their accuracy improved. For adolescents with RD, reading comprehension also improved. Additionally, the ERN–CRN measure was significantly correlated with change in words per minute read, but only for the RD group. Both groups also improved on several general cognitive measures, including visual memory, working memory, and visual scanning. Individuals with RD also improved on processing speed. Both groups improved on lexical decision accuracy. In terms of ERP response, both groups showed greater ERN (relative to CRN) following training, and this difference was greater for the RD participants. Greater ERN amplitude suggests that participants were better able to detect their correct and incorrect responses in the task. The authors suggest that these findings provide evidence for RAP improving general cognitive skills (e.g., memory, processing speed), which in turn improves reading accuracy and fluency. They also suggest that

RAP might improve visual scanning, given that participants must quickly scan/read ahead and process as the letters are removed from the screen.

A second, similar study from the same group (Horowitz-Kraus, 2016) examined adults with dyslexia with a nearly identical paradigm. In this study 29 adults with dyslexia and 36 typical readers also underwent RAP training (identical regimen as above), reading assessment, as well as pre- and post-test ERP measurement using a lexical decision task. Both groups improved in reading accuracy and rate following training. In terms of ERPs, both groups had larger amplitude ERN and CRN, with larger increases in ERN following training. The findings of increased ERN and faster/more accurate reading are consistent with the prior study in children. Thus, these findings further support the idea that RAP can improve some aspect of cognitive processing, such as overall speed or visual scanning, that influences reading rate and accuracy as well as speed/facility of error monitoring during word reading.

In a third study, Mayseless (2011) compared RAP training (as above) to a general cognitive computerized program called CogniFit Personal Coach (CPC), which focused on working memory using visual and auditory stimuli (Kraus & Breznitz, 2009). They tested 10 reading disabled and 10 typically reading university students, divided into evenly mixed groups of 10 for the training program groups. Each of the training programs included 24 training sessions three to four times a week for 15–20 min each (at least 360 total minutes). Reading skills were tested at baseline only to measure group status, thus no pre to post reading performance differences were reported. In terms of ERPs, these authors employed two types of a visual oddball task to determine whether RAP improved visual scan/general visual processing. The first involved two different letters, with participants detecting the less frequent letter with a button press. The second involved rectangles of two different colors, with participants pressing a button for the less frequently occurring color. These authors were interested in the P1 component, a positive deflection that peaks around 100msand reflects automatic visual processes. The authors found that P1 amplitudes decreased after training for both tasks and training types. These results suggest that training in either RAP or a more general cognitive program reduces P1 amplitude, indicative of more automatic visual processing.

In a fourth study, González et al. (2016) examined the effects of a sound-letter mapping training on reading fluency. They tested 18 Dutch third graders with dyslexia before and after the training, which included intensive one-to-one tutoring on letter-sound correspondences using a computer-assisted program. On average, the students participated two 45-minute sessions per week, averaging 33.83 total training sessions (1522 min) over 22–23 weeks. Behavioral measures included word reading fluency, text reading fluency, and a battery of reading tasks (rapid automatized naming, letter-sound associations, and a computerized spelling task) as well as IQ and a behavior checklist. For ERPs, participants completed a repetition detection task with short and long words and symbol strings. A control group of 20 typically developing readers also completed the behavioral and ERP tasks at a single timepoint and received no training. Training led to marked improvement in reading fluency and spelling accuracy for some dyslexic children ("improvers") but not others ("nonimprovers"). Prior to training, improvers showed a larger N170 amplitude to words compared to non-improvers but did not show the left-lateralization to words that was seen in typically developing readers. Following training, improvers demonstrated a bilateral decrease in N170 amplitude to words, which was associated with reading fluency gains at left hemisphere sites. This decrease was not observed in non-improvers, but it still differed from left-lateralized N170 responses of the typical readers. These results reveal that N170 amplitude is sensitive to reading fluency gains and may be used as a potential predictor of which children will show improved neural tuning for print in response to audiovisual training.

Together, these studies suggest that fluency-focused intervention can improve students' reading accuracy and rate and modify neural signals associated with error detection and visual processing during reading. The latter suggests that these interventions may have affected aspects of visual scanning, attention, or processing as well as participants' awareness of when they made errors during reading. Again, findings were primarily amplitude changes, suggesting more/differential firing or greater synchrony rather than simply faster firing rates.

4. Discussion

Across the studies presented here, researchers observed improvements in reading and related skills such as phonological processing or visual processing and changes in the neurobiological response to speech, tones, or printed words and word-like stimuli. These ERP findings were most often observed as increased or reduced amplitudes, depending on the stimulus type and experimental setup. Studies in which a change was to be detected in speech or tones (e.g., MMN) saw increased amplitude, implying better detection.

This greater amplitude may reflect more coordinated (synchronous) firing of neurons to these stimuli following training/intervention. Those that indexed familiarity or experience, such as the N170, typically saw a reduction in amplitude following training, suggesting more efficient processing following training or intervention. Few studies saw changes in latencies, which are thought to reflect changes in processing speed; however, as previously stated, amplitude and latency may not cleanly dissociate into amount and rates of firing due to design and processing limitations. Thus, the primary way in which the temporal dynamics of processing are revealed with ERPs is through the components of interest. That is, effects in early components (i.e., prior to 400 ms) suggest an earlier or faster stage of processing than effects in later components (after 400 ms). All the components studied here are considered early components. Later components, such as the N400 and P600 are thought to reflect higher levels of processing and are sensitive to semantic and syntactic information encoded in words and sentences. Overall, the findings summarized here are consistent with findings from MRI studies of intervention response (see Perdue et al., 2022 for a review) and reveal plasticity in the neural systems that undergird learning to read. Because effects were observed in early components and because of the nature of the experimental manipulations, we can infer that the tested interventions affected early stages of speech and print processing such as phonemic processing and initial word recognition.

This general pattern of reading improvement and enhanced or more efficient neural processing was observed across studies that trained students in phonics/phonology, orthography, fluency, and nonlinguistic audiovisual integration, which suggests plasticity in many of the subskills that support learning to read. Moreover, this general pattern was observed across a range of ages, from pre-readers to adults and across a range of spoken languages, including English, Finnish, and Hebrew, revealing remarkable consistency despite variability in the samples and study procedures.

Finally, this collection of studies should be considered in light of several design limitations. First, these studies generally included small samples (ranges for RD or AR samples = 6–39). Further, the control groups and experimental designs varied quite a lot. Most studies included a TD control group that received no or different training, while others had an RD control group that received training at a later date (wait list control). Horowitz-Kraus gave the intervention to both RD and TD groups, and only Lovio and colleagues utilized two groups of RD students with an active control. There are also factors that limit synthesis of findings across studies. For example, the tasks and interventions varied quite a lot. We tried to make direct comparisons when more than one study used the same intervention, like RAP, the Habib et al. training, and Audilex, however we avoided direct comparisons across studies that used different interventions or measured different components. The ages of the students across studies also varied substantially, from prereaders to adolescents, as did the languages spoken (e.g., English, Finnish, Hebrew, Dutch). We also expect that there is some publication bias represented in this sample, given that all but one study found significant behavioral intervention effects and all found significant ERP intervention effects, even with small samples. Finally, although we set out to include both ERP and EEG studies in our review, we identified no EEG studies that met our screening criteria; thus we could not present or discuss EEG studies.

In conclusion, ERP studies of reading intervention response among reading disabled or at-risk participants reveal plasticity in the neural systems that support reading. This plasticity was observed as improvements in reading and reading-related skills following intervention and concomitant changes in ERP component amplitude or latency from pre to post test. Despite variations in intervention type and intensity, ERP task, language, and participant age, there was some consistency in the observed patterns of pre to post change, with more similar interventions and ERP tasks producing more similar findings. Future studies would benefit from larger sample sizes and testing multiple skills and ERP components within a single study for more direct comparison. Continued investigation using both behavioral and neuroimaging measures is vital for leveraging the science of reading towards effective and efficient interventions for children with reading disability.

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