Neuroscience illuminating the influence of auditory or phonological intervention on language-related deficits

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INTRODUCTION

Finding the most effective techniques to remediate language-related impairments, such as dyslexia, specific language impairment (SLI), or language-learning impairment (LLI), would be of crucial importance to educators, who try to help children struggling with these learning difficulties. This raises a question, whether understanding the neurobiological underpinnings of language impairments facilitates their efficient treatment. In this review, we discuss how neuroscience illuminates the effects of auditory or phonological intervention on dyslexia, SLI, and LLI. We focus on auditory or phonological interventions, because in many cases dyslexia, SLI, and LLI are all characterized by phonological (or auditory) deficits. Cis (Tallal, 2001; Shaywitz and Shaywitz, 2005; Pennington and Bishop, 2009; Ramus et al., 2013), despite their complex etiology. Whereas detailed brain areas in unexcited by reading interventions can be found in a recent meta-analysis by Barquero et al. (2014), here we address whether neuroscientific research on the remediation of language-related deficits is useful for educators and whether it has something to add over behavioral research from an educational perspective.

In the current review, the selection of publications was based on the following criteria: the research should concern dyslexia, SLI, or LLI, include testing before and after an auditory or phonological intervention or training, involve brain research measures (functional magnetic resonance imaging (fMRI), magnetic source imaging (MSI) or magnetoencephalography (MEG), event-related potentials (ERP), or electroencephalography (EEG)) and compare two or more groups of participants to control for the effects of repeated testing and maturation (McArthur, 2009). Searches from Web of Science and PubMed (keywords dyslexia/SLI/LLI, intervention/remediation/training, fMRI/MEG/ERP) were used in finding literature. Additional publications were found in the reference lists of relevant studies.

IS NEUROSCIENTIFIC RESEARCH USEFUL FOR EDUCATORS?

Research on remedial interventions for learning deficits may have important applicability to education (Tallal, 2012). In this area, collaboration between education and neuroscience could result in mutual benefits (Sigman et al., 2014). However, the value of the neuroscientific approach in such research has been questioned by Bishop (2013) because of methodological and interpretive reasons. She argued that neuroscientific studies often use small subject groups, which may decrease their reliability and result in small statistical power (cf. Button et al., 2013). Furthermore, Bishop (2013) noted that some studies lack an adequate control group, which is important to control for the effects of repeated testing and maturation (see also McArthur, 2009). Indeed, future intervention studies should not only aim at having larger subject groups (Bishop, 2013) and adequate control groups (McArthur, 2009; Bishop, 2013), but also control for placebo effects (Boot et al., 2013).

Bishop (2013) also argued that the critical test of the effectiveness of interventions is the change of behavior rather than that of brain function; changes in the brain should not be considered more important than changes in behavior. However, rather than emphasizing the brain over behavior, neuroscientific intervention studies typically aim to determine the links between brain function and behavior. Importantly, understanding the link or correlation between brain activation and skills as a result of training may help to explain how and why remedial gains take place. Since the combination of neuroscientific and behavioral measures has been
shown to be a better predictor of reading skills than behavioral measures alone (Hoef et al., 2007; Maurer et al., 2009), this combination has potential to outperform mere behavioral measures in the study of remedial gains. Cognitive neuroscience has, in our opinion, also some advantages over behavioral research that were not mentioned by Bishop (2013). Especially when working with children whose motivation and skills can affect their performance considerably, a possibility to study the effects of intervention without subject’s active effort or attention is a clear advantage. This is possible, for example, by recording mismatch negativity (MMN) brain response (Naatanen et al., 2007; Kujala and Naatanen, 2010).

From educators perspective, neuroscientific research is seldom directly applicable in the assessment of remedial interventions. Importantly, however, educators may benefit from neuroscientific research by obtaining a more detailed picture of relevant processes underlying behavior. For example, brain measures may help to disentangle whether behaviorally observed improvement is due to the normalization of the core deficit or some compensatory strategy (e.g., Eden et al., 2004; Shaywitz et al., 2004), which is not evident in behavioral data. If, hypothetically, some intervention resulted in the formation of a compensatory function to solve some task, it may improve behavior to a certain degree but might not compete in effectiveness with the optimal function for solving that task. Still, in a large subject group, this compensatory improvement in behavior may be taken to reflect a successful intervention, if statistically significant improvement is achieved. Thus, neuroscientific research can potentially give some valuable information to educators about the deficits, which may help to target the contents of interventions more accurately.

**OVERVIEW OF STUDIES ON NEUROBIOLOGICAL CHANGES FOLLOWING PHONOLOGICAL OR AURAL INTERVENTIONS**

As shown by and the majority of studies on phonological or auditory interventions focused on dyslexia or related problems in reading, writing, or spelling. Furthermore, the majority of studies have focused on children. Older age groups should not be neglected in remediation and its research, however: as noted by Eden et al. (2004), most dyslexics are adults, who may suffer from the socio-economic consequences of their reading deficit. There seem to be no constraints with respect to brain plasticity that would hinder remediation in adults or older children (Simos et al., 2002; Eden et al., 2004). Nevertheless, the earlier the interventions are conducted, the more beneficial to individuals is gained, because learning is cumulative. The early gains may help to prevent difficulties not only in academic but also socio-emotional domain. The optimal timing of intervention is, however, determined by maturity and acquired skills. For example, if a new skill is scaffolded by previous skills, it cannot be adapted before they are mastered (cf. Jolles and Crone, 2012).

The studies listed and suggest that in addition to behavior, the remedial gains of phonological or auditory interventions are consistently reflected in different aspects of brain functioning. These include increased or normalized brain activation as a result of training in previously hypoactive areas as measured with fMRI (Ayward et al., 2003; Temple et al., 2003; Eden et al., 2004; Shaywitz et al., 2004; Gaab et al., 2007; Meyer et al., 2008; Heim et al., 2014) and MEG (Simos et al., 2002; Pihko et al., 2007) during different cognitive tasks. MRI-based proton MR spectroscopy has shown normalized metabolism in certain brain areas after interventions (Richards et al., 2000, 2002). Training-induced changes in strength and timing of neural responses to stimulation have been demonstrated with ERPs (Kujala et al., 2001; Hayes et al., 2003; Stevens et al., 2008, 2013; Jucla et al., 2010; Lovio et al., 2012; Hasko et al., 2014). Also the time-frequency analysis of EEG has revealed amplitude increases in the oscillatory brain activity after training (Häm et al., 2013). In addition to brain function, interventions have been found to change brain anatomy, such as white matter integrity (Keller and Just, 2009), and also show that remedial gains, if any, consistently manifest in both behavioral and brain measures: in 16 out of 17 studies of remedial gains were found in both brain activation and skills targeted by intervention (note that Jucla et al., 2010, failed to find different behavioral improvement and similar brain response patterns between their treatment group and controls). The strong coupling of training gains in behavior and brain activation suggests that most likely the observed changes in the brain drive the changes in the behavior. As neuroscientific research may reveal the neural dynamics of processes related to behavioral performance and allows localize the deficient brain functions, it may enable to specify the neural mechanisms underlying language-related impairments and to determine brain functions and areas altered by interventions, which surface in behavior as improved skills. However, it is noteworthy that lists published studies, whereas studies failing to find changes in behavior or brain activation may remain unpublished. This may cause bias toward systematically finding the coupling between neural and behavioral gains.

A recent meta-analysis of neuroscientific research exploring reading networks in the brain has suggested that dyslexia is characterized by the dysfunction of left occipito-temporal cortex, left inferior frontal gyrus, and the inferior parietal lobe (Richlan, 2012; see also Richlan et al., 2011). These brain areas are involved in phonological encoding, phonological representations, and attention, respectively (Richlan, 2012). Barquero et al. (2014) meta-analysis of the neuroimaging of reading interventions, in turn, suggests intervention-induced functional changes in the left thalamus, left middle occipital gyri, bilateral inferior frontal gyri, right insula, and right posterior cingulate gyrus. Thus, both Richlan’s (2012) and Barquero et al.’s (2014) findings point toward the central role of inferior frontal and occipito-temporal/occipital dysfunction in dyslexia. Correspondingly, the neuroscientific dyslexia studies included in involving auditory or phonological intervention, have shown normalized brain activation, metabolism, or anatomy as a result of interventions in the occipito-temporal (Ayward et al., 2003; Heim et al., 2014) and inferior frontal (Richards et al., 2000, 2002; Ayward et al., 2003; Shaywitz et al., 2004; Heim et al., 2014) areas. In addition, normalized activation following interventions has been repeatedly observed in inferior parietal (Temple et al., 2003; Eden et al., 2004; Meyer et al., 2008, see also Richlan, 2012), superior parietal (Ayward et al., 2003; Eden et al., 2004; Meyer et al., 2008), and temporal (Simos et al., 2002; Ayward et al., 2003; Temple et al., 2003; Shaywitz et al., 2004) areas. Although inferior frontal and...
Table 1 | Publications including neuroscientific research on phonological or auditory remediation of dyslexia (or its risk).

| Reference          | Age of participants (years; mean or range) | Participant ... | Impairment or problem | Content of training                                                                 | Duration of training | Brain research method | Task in testing | Behavioral improvement (pre-test vs. post-test) | Normalization of brain activation |
|--------------------|--------------------------------------------|-----------------|-----------------------|-------------------------------------------------------------------------------------|----------------------|------------------------|-----------------|------------------------------------------------|-------------------------------|
| Aylward et al.     | 11                                         | 10; 11          | Dyslexia              | Linguistic awareness, alphabetic principle, fluency, reading comprehension          | 2 weeks (28 h)       | fMRI                   | Yes             | Yes                                                          |                               |
| Eden et al.        | 41–44                                      | 19; 19          | Dyslexia              | Sound awareness, establishment of the rules for letter-sound organization, sensory stimulation, articulatory feedback | 8 weeks (112 h)     | fMRI                   | Repeating words, sound deletion | Yes                                                      | Yes                                                          |
| Gaab et al.        | 10                                         | 22; 23          | Dyslexia              | FastForWord*                                                                      | 8 weeks (about 67 h) | fMRI                   | Pitch discrimination | Yes                                                      | Yes                                                          |
| Hasko et al.       | 8                                          | 28 (11 improvers, 17 non-improvers); 25 | Dyslexia              | Phonomeme discrimination and orthographic knowledge; phonics training              | 6 months (30 h)      | ERP                    | Phonological lexical decision | Yes (improvers); no (non-improvers)                      | Yes (improvers); no (non-improvers) |
| Heim et al.        | 8                                          | 35 (12 training phonology, 7 training attention; 14 training reading); 10 | Dyslexia              | Phonomological (W rzburger Trainingsprogramm, Kieler Leseaufbau), attentional (CogniPlus, Celeco), reading (Blitzschnelle Worterkennung) | 4 weeks (30 h)       | fMRI                   | Reading | Yes                                                          |                               |
| Jucla et al.       | 9                                          | 24; 10          | Dyslexia              | Phonomological training; visual and orthographic training                          | 2 months (about 16 h) | ERP                    | Visual lexical decision  | Yes (but also in controls)                             | Mixed (treatment group showed a different pattern than controls) |

(Continued)
| Reference            | Age of participants (years; mean or range) | Participant ... (treatment; control) | Impairment or problem | Content of training | Duration of training | Brain research method | Task in testing | Behavioral improvement (pre-test vs. post-test) | Normalization of brain activation |
|----------------------|-------------------------------------------|--------------------------------------|-----------------------|---------------------|---------------------|----------------------|------------------|------------------------------------------------|-------------------------------|
| Keller and Just (2009) | 8–10                                      | 35 treated poor readers; 12 non-treated poor readers; 25 non-treated good readers | Poor reading | Corrective Reading, Wilson Reading, Spell Read Phonological Auditory Training, Failure Free Reading | 6 months (100 h) | DTI | Yes | Yes |
| Kujala et al. (2001)  | 7                                         | 24; 24                               | Dyslexia              | Non-linguistic audiovisual matching | 7 weeks (about 3 h) | ERP | Yes | Yes |
| Lovio et al. (2012)   | 6–7                                       | 10; 10                              | Difficulties in reading-related skills | GraphoGame: letter sound correspondences (vs. number knowledge game for controls) | 3 weeks (3 h) | ERP | Yes | Yes |
| Meyler et al. (2008)  | 10                                        | 23; 12                              | Poor reading          | Corrective Reading, Wilson Reading, Spell Read Phonological Auditory Training, Failure Free Reading | 6 months (100 h) | fMRI | Sentence comprehension | Yes | Yes |
| Richards et al. (2000) | 10–13                                     | 8; 7                                 | Dyslexia              | Phonological and morphological reading instruction | 3 weeks (30 h) | Proton MR spectroscopy | Phonological and lexical access and a non-linguistic tone task | Yes | Yes |

(Continued)
Table 1 | Continued

| Reference          | Age of participants (years; mean or range) | Participant .. (treatment; control) | Impairment or problem | Content of training                                                                 | Duration of training | Brain research method | Task in testing | Behavioral improvement (pre-test vs. post-test) | Normalization of brain activation |
|--------------------|--------------------------------------------|------------------------------------|-----------------------|--------------------------------------------------------------------------------------|---------------------|-----------------------|------------------|------------------------------------------------|--------------------------------|
| Richards et al. (2002) | 9–12                                       | 10; 8                              | Dyslexia             | Phonological vs. morphological reading instruction                                    | 3 weeks (30 h)      | Proton MR spectroscopy | Phonological and lexical tasks, passive listening | Yes                             | Yes                                           |
| Shaywitz et al. (2004) | 6–9                                        | 37 (experimental intervention); 12 (community intervention); 28 (control) | Reading disability | Phonological intervention: sound symbol associations, phoneme analysis, timed reading, oral story reading, dictation (vs. community intervention in school) | 8 months (50 min/day) | fMRI                  | Cross-modal letter identification | Yes (experimental group); no (community intervention) | Yes (experimental group); no (community intervention) |
| Simos et al. (2002)    | 7–17                                       | 8; 8                               | Dyslexia             | Phono-Graphix (phonological processing and decoding), Lindamood Phonemic Sequencing    | 2 months (80 h)     | MSI                   | Pseudoword rhyme-matching          | Yes                             | Yes                                           |
| Stevens et al. (2013)  | 5–6                                        | 8; 6                               | Risk for reading disability | Early Reading Intervention (phonemic awareness, alphabetic understanding, letter writing, word reading, spelling, sentence reading) | 8 weeks (20 h)      | ERP                   | Selective auditory attention         | Yes                             | Yes                                           |
| Temple et al. (2003)   | 8–12                                       | 20; 12                             | Dyslexia             | FastForWord*                                                                        | 8 weeks (about 47 h) | fMRI                  | Rhyme letters, match letters, match lines       | Yes                             | Yes                                           |

DTI, diffusion tensor imaging; ERP, event-related potential; fMRI, functional magnetic resonance imaging; MR, magnetic resonance; MSI, magnetic source imaging. *FastForWord includes auditory discrimination, phoneme discrimination, phoneme identification, phonic match, phonic word, understanding instructions, grammatical structures and rules.
| Reference        | Age | Participant (treatment; control) | Impairment or problem                                      | Content of training                                                                 | Duration of training | Brain research method | Task in testing                                      | Behavioral improvement (pre-test vs. post-test) | Normalization of brain activation |
|------------------|-----|----------------------------------|-----------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------|-----------------------|----------------------------------------------------|------------------------------------------|----------------------------------|
| Hayes et al.     | 8–12| 27 treated; 15 non-treated; 7 non-treated controls | Learning problems, auditory perceptual deficit           | Earobics: phonological awareness, auditory processing, language processing          | 8 weeks             | ABR, ERP              | Passive listening, attention directed elsewhere    | Yes                                       | ERP yes; ABR no                   |
| Heim et al.      | 6–9 | 21; 12                           | LLI                                                      | FastForWord*                                                                         | 1 month             | EEG oscillations      | Passive listening and active target detection      | Yes                                       | Yes (but not all aspects)          |
| Pihko et al.     | 6–7 | 9 (phonological intervention); 9 (physical exercise) | SLI                                                      | Speech and articulation, phoneme discrimination, phonological and linguistic awareness, rapid processing | 8 weeks             | MEG                   | Passive listening, attention directed elsewhere    | Yes                                       | Yes                              |
| Stevens et al.   | 6–8 | 8 treated SLI; 12 treated controls; 13 non-treated controls | SLI                                                      | FastForWord*                                                                         | 6 weeks             | ERP                   | Auditory selective attention                       | Yes                                       | Yes                              |

ABR, auditory brainstem response; EEG, electroencephalography; ERP, event-related potential; MEG, magnetoencephalography. *FastForWord includes auditory discrimination, phoneme discrimination, phoneme identification, phonetic match, phonetic word, understanding instructions, grammatical structures and rules.
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dynamics of neural responses. Studies on dyslexia (Heim et al., 2014) seem to be the robustest effects in dyslexia, the effects in different brain areas that are linked with phonological dysfunctions, and auditory P1-N2 ERP responses have been shown to shorten in response to treatment. This is in line with models of dyslexia proposing that children at risk for reading difficulty show atypical brain representations and processes (Richlan et al., 2011; Richlan, 2012).

From educators' perspective, it would be important to conduct intervention on behavioral performance and brain activation in reading fluency and diffusion of the inferior parietal lobule, which has been implicated in the dysfunction of the inferior parietal lobule, whereas no such gains were found in brain areas that are linked with phonological dysfunctions.

Besides showing a correspondence between improvements in pre-attentive auditory processing that is modified by phonetic discrimination, and selective attention in children with SLI, as a result of interventions, training has been shown to reduce auditory P1-N2 ERP responses reflecting selective attention, which can be remediated by remedial reading (see Shaywitz et al., 2004, for details). As a result of interventions, improvements in reading fluency and increased activation of left-hemisphere brain regions, whereas no such gains were observed in other areas.

In line with Heim et al.'s (2014) conclusions on shared effects of interventions, phonic match, phonic word, and understanding instructions had different effects on brain activation: phonological and reading fluency gains in the experimental intervention group had achieved significant improvement.

Table 1 shows the remedial gains in brain activation and behavior have, however, been obtained in brain areas involved in, and perhaps necessary for, reading and language skills and changes in neural function, neuroscientific measures of selective attention, which can be remediated by remedial reading.

Table 2 shows the optimal method of remediating language-related deficits can be illuminated by the specific effects of interventions on brain areas and may, in concert with others, participate in different training techniques and experimental tasks in the scanner. Direct comparisons using the same experimental intervention on behavioral performance and brain activation in different training types, very different kinds of intervention tasks allude to the possibility that they tap some common, domain-general process.

Non-linguistic tasks that, at first sight, might seem to have a less obvious link to language-related deficits have also been shown to shorten the latency of auditory P1-N2 ERP responses. Kujala et al. (2001) presented dyslexics with an intervention with non-speech sounds with a sequence of visual shapes. As Pihko et al. (2007) used non-speech stimuli with rapid transitions to remediate MMN brain responses to tone-order reversals, the latency of auditory P1-N2 ERP responses has increased.

Stevens et al. (2013) have also been shown to enhance MMN responses indicating remedial effects on low-level, pre-attentive auditory processing that is modified by phonetic discrimination, and auditory cortical P1-N2 ERP responses have been shown to attenuate event-related brain responses reflecting selective attention that children at risk for reading difficulty show atypical brain representations and processes.

The MMN study by Pihko et al. (2007) involved participants, where participants' attention was directed elsewhere, resulting in a more mature response pattern (Hayes et al., 2000; Valdois et al., 2004; Shaywitz and Shaywitz, 2008). As the MMN study by Pihko et al. (2007) involved participants, the experimental intervention group had achieved significant improvement.
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...and may enable cumulative gains in language-related hypoactive areas had normalized, probably reflecting cumulative continued to increase. Thus, the activation pattern of previously they found that the activation of the parietal areas had continued of these areas immediately after intervention. Interestingly, areas before intervention in poor readers and increased activation... 

...as 1 year after it, suggesting long-lasting remedial effects. Sim- scan 1 year after the intervention. The normalization of activa-

...tion of remedial interventions. However, keeping up-to-date in such research methods are seldom directly applicable to the assessment... 

...cient neural networks, if methodological requirements are met understanding of how and why interventions change the defi-

...Specifically, we argue that the use of both neuroscientific and contribution to the treatment of language-related impairments.

...different training programs. Gains from very different phonological and partly specific patterns of neural activation as a result of dif-

...ment. Neuroimaging studies have also highlighted partly similar in white matter. Especially in the study of dyslexia, neurosci-

...activity after training. T raining effects have been observed also electrophysiological measures have demonstrated the normaliza-

...normalized training-induced brain activation patterns, whereas brain function and brain anatomy. Neuroimaging has revealed... 

...SLI, and LLI. Neuroscientific research has demonstrated that auditory tasks as well as training effects in the parietal cortex... 

...neuroimaging studies have illuminated the location of aberrant brain... 

...effects. Shaywitz et al.'s (2004) experimen-

...changes induced by intervention can be explored with follow-up... 

...that show long-term effects. Shaywitz et al.'s (2004) experimen-

...neuroimaging studies of intervention for language impairment in children:... 

...cases... 

...sufficient to rule out placebo effects.

...problem with placebos in psychology: why active control groups are not... 

...does the brain of children with developmental dyslexia tell us about reading... 

...early gamma oscillations during rapid auditory processing in children with a... 

...language learning: changes in neural mass activity after training. Early gamma oscillations during rapid auditory processing in children with a... 

...plasticity following auditory training in children with learning problems.

...related to rapid auditory processing are disrupted in children with developmental... 

...dyslexia and ameliorated with training: an fMRI study. Early gamma oscillations during rapid auditory processing in children with a... 

...dyslexia that relates of rapid auditory processing are disrupted in children with developmental... 

...this... 

...a causal link between visual spatial attention and reading acquisition.

...relates of rapid auditory processing are disrupted in children with developmental dyslexia and ameliorated with training: an fMRI study. Early gamma oscillations during rapid auditory processing in children with a... 

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