Literacy Studies: Perspectives from Cognitive Neurosciences, Linguistics, Psychology and Education

Zvia Breznitz
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Reading, Writing, Mathematics and the Developing Brain: Listening to Many Voices

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LITERACY STUDIES

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While language defines humanity, literacy defines civilization. Understandably, illiteracy or difficulties in acquiring literacy skills have become a major concern of our technological society. A conservative estimate of the prevalence of literacy problems would put the figure at more than a billion people in the world. Because of the seriousness of the problem, research in literacy acquisition and its breakdown is pursued with enormous vigor and persistence by experts from diverse backgrounds such as cognitive psychology, neuroscience, linguistics and education. This, of course, has resulted in a plethora of data, and consequently it has become difficult to integrate this abundance of information into a coherent body because of the artificial barriers that exist among different professional specialties. The purpose of the proposed series is to bring together the available research studies into a coherent body of knowledge. Publications in this series are intended for use by educators, clinicians and research scientists in the above-mentioned specialties. Some of the titles suitable for the Series are: fMRI, brain imaging techniques and reading skills, orthography and literacy; and research based techniques for improving decoding, vocabulary, spelling, and comprehension skills.

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This book is dedicated to the Edmond J. Safra Brain Research Center for the Study of Learning Disabilities that was established by the Edmond J. Safra Foundation at the Faculty of Education at the University of Haifa with the idea that every child deserves equal educational opportunities. The goal of the Safra Brain Research Center is to encourage and support the research efforts of the next generation of young researchers to make equal learning opportunities possible.

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Introduction to Reading and Writing Sections

Victoria J. Molfese, Ph.D. and Zvia Breznitz, Ph.D.

Reading and writing skills are important for effective communication in a literate society. The human brain was created about 60,000 years ago and the alphabetic code only about 5,000 years ago. No brain system was created specifically for reading or writing skills and both skills needed to use and rely on a variety of brain systems. Despite this, about 75% of the literate population can read properly while about 25% have reading difficulties and impairments. The first section of this book contains nine chapters focusing on brain and behavior studies of literacy and language skills; seven chapters on reading and two chapters on writing and motor skills. These chapters include reviews of theories and research on reading and language development in typical, learning disabled and dual language samples, as well as reviews of neuroanatomical and neurophysiological methods, traditional and innovative interventions applied to selected samples of child and adult participants, and data analysis approaches. Collectively, these chapters provide a comprehensive introduction to many of the topics of interest to researchers, practitioners and students seeking to understand how the behaviors well known to characterize children and adults with reading, writing or spelling disabilities are reflected in measures of brain processing and behaviors and influenced by interventions. Further, these chapters provide information on how the results of different techniques of brain imaging and behavior remediation are interpreted to further of our knowledge of the effects of developmental and intervention on behavior change.

Chapter by Molfese, Molfese, Garrod and Molfese, entitled "Evidence of Dynamic Changes in Brain Processing from Imaging Techniques: Implications for Interventions for Developmental Disabilities," reviews the critical cognitive skills

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known to underlie the development of reading, and in particular, studies showing how the development of speech perception and phonological processing skills are related to the development of language and reading skills. The chapter then focuses on studies of brain processing differences in typically developing infants and children as well as in those at risk or evidencing language and reading disabilities using event-related potential (ERP) techniques. A dynamic neurocognitive model is described that connects findings from behavioral studies of language and reading skills to findings from brain imaging studies of brain structure and function changes arising from maturation and experience.

Chapter by Rezaie, Simos, Fletcher, Denton and Papanicolaou, entitled "Magnetic Source Imaging: A Suitable Tool of Exploring the Neurophysiology of Typical and Impaired Reading Ability," provides background in Magnetoencephalography (MEG) techniques and the application of magnetic source-imaging measures to studies of brain structure and function. The use of this technique in clinical studies of reading disabilities is described as are findings from studies of children and adults involved in interventions. The use of magnetic source-imaging techniques in understanding changes in brain structure and function due to development and experience can inform both basic and applied research.

Chapter by Molfese, entitled "Imaging Studies of Reading Disabilities in Children," provides a comprehensive review the ERP technique and its uses in studies of children with and without reading disabilities. The heart of the chapter targets studies using different brain imaging techniques (ERP, MEG and functional magnetic resonance imaging [fMRI]) with children with reading disabilities who are responding to reading intervention compared to those who are not responding. Molfese reports findings from an ERP study showing evidence of normalization of brain processing in children with reading disabilities who are responding to a reading intervention and activation profiles that more closely resemble those of typically developing children.

Chapter by Shaul entitled "A Model of Brain Activity of Young as Compared to Adult Dyslexic Readers, and Outcomes After Intervention," targets the understanding of similarities and differences in the brain processing related to reading and several reading-related tasks in samples of children and adults with dyslexia. Cognitive profiles of adults with and without dyslexia, and 4th grade children with and without dyslexia are described. The differences and similarities in the cognitive profiles as related to the participants' responses to the Reading Acceleration Program provide evidence of intervention effectiveness for both children and adults with dyslexia and suggests opportunities for further studies seeking evidence of the effects of intervention on longer-term changes in brain processing.

Chapter by Chuntonov and Breznitz, entitled "Optimizing Reading Enhancement: Evidence from Brain Research," targets cross-linguistic studies in a review of how measures of brain and behavior responses are involved in the development of reading and reading-related skills. The review of brain imaging techniques and neuroscience leads to a review of intervention studies linking brain measures with reading behaviors. Findings from intervention studies using the Reading Acceleration Program with children and adults are described and support the view that existing and new circuits can be activated through training in both children and adults.

Chapter by Horowitz-Kraus, entitled "The Error Detection Mechanism Among Dyslexic and Skilled Readers: Characterization and Plasticity," describes the use of the ERP technique to study brain activation related to error detection (ERN) and correct-related negativities (CRN). The chapter provides an overview of studies investigating errors on cognitive tasks, and studies to localize ERN and CRN in brain regions. Behavioral and brain studies of children and adults with dyslexia are described, as are the results of studies on the effects of intervention or training reflected in ERN and CRN.

Chapter by Prior, entitled "Reading in More than One Language: Behavior and Brain Perspectives," reviews cross-linguistic models of brain and cognitive systems and reports findings emphasizing both similarities and differences in first and second language reading in bilingual samples. Issues related to reading in different orthographies and differences related to the properties of writing systems are described with supporting research evidence.

Chapter by Schulte-Körne, entitled "Spelling Disability – Neurophysiologic Correlates and Intervention," reviews reading and writing studies of German children with dyslexia to examine orthographic influences. In these studies, ERP techniques are used with methods to elicit mismatched negativity (MMN) that reflect discrimination skills. Studies of spelling and/or word reading deficits are examined for the influence of genetic and familial risk on phonological awareness skills and for the effects of intervention strategies targeting phonological awareness in samples of typically developing and children with spelling disabilities

Chapter by Sela, entitled "The Relationships Between Motor Learning, the Visual System and Dyslexia," provides an overview of theories of developmental dyslexia including theories that include neurological or anatomical components. The chapter provides an in depth review of research linking motor learning and the visual system to dyslexia. The results of a study investigating the relation between learning novel motor skills and the visual system in adults with and without dyslexia is described as providing evidence of the role of visual deficits in dyslexia.

Evidence of Dynamic Changes in Brain Processing from Imaging Techniques: Implications for Interventions for Developmental Disabilities

Dennis L. Molfese, Ph.D., Victoria J. Molfese, Ph.D., Krista Garrod, and David L. Molfese, Ph.D.

It has been anticipated from three decades of studies that early identification of children at-risk for reading disabilities based on assessments of cognitive skills would facilitate early intervention. While published studies provide a wealth of information useful for identifying critical early cognitive abilities that predict later reading outcomes, few studies of young children have included both early identification and early intervention components. More research clearly is needed to investigate whether intervention targeting key cognitive skills known to underlie emerging reading abilities is effective in improving targeted cognitive skills as well as impacting subsequent reading performance (Shadish et al. 2002). In addition, more research is needed to expand the growing number of studies seeking evidence of brain processing changes related to intervention. This chapter reviews research on the critical cognitive skills that underlie the development of early reading skills, and links between brain processing of speech cues in infants, children and adults to language and reading skills. The chapter concludes with a dynamic model of brain activity as it relates to the acquisition of reading-related skills and to the impact of educational interventions.

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1 Cognitive Skills

A recently published meta-analysis of studies published through 2003 provides information on the predictive relations between emergent skills in preschool children and skills at school age (kindergarten and beyond) in word decoding, reading comprehension, and spelling (National Early Literacy Panel 2008). This meta-analysis shows medium to large correlations (average $r = .26$–$.50$ across studies) for several cognitive skills: *alphabetic knowledge* (letter sounds and letter names), *phonological processing* (skills in blending, deletion, segmenting, and rhyming at the word and phoneme level), *phonological memory* (digit span and phonological short-term memory), and *naming speed* (automaticity in naming objects, colors, numbers and letters). It is the development of these skills that were found to be particularly critical for the development of reading.

1.1 Alphabetic Knowledge

Skills in identifying letters by sound and name reflect alphabetic knowledge. Denton and colleagues (West et al. 2000; Denton and West 2002) report findings from a general sample of over 22,000 children from kindergarten through fifth grade. Children proficient in identifying letters (naming upper and/or lower case letters) at entry into kindergarten showed stronger skills at the end of kindergarten and in first grade on measures of phonological processing (identification of beginning and ending sounds) and word reading compared to children who were not proficient. Reports from smaller studies also show that alphabetic skills in preschool are robust markers for skills leading to the successful development of reading skills, with accuracy and fluency in alphabetic skills specifically linked with later reading skills (Adams 1990; Badian 1995; Blatchford et al. 1987). Acquisition of alphabetic skills have also been shown to correlate with skills in segmenting and blending syllables, rhyme detection, and Get Ready To Read (Whitehurst and Lonigan 2001), a screener for phonological skills and print knowledge (Molfese et al. 2004). Preschool children who make greater grains in learning letter names across the pre-kindergarten year had stronger literacy-related skills compared to children making few or no grains in letter identification, Snow et al. (1998) report that alphabetic skills are as effective as tests of ‘reading readiness’ in predicting later reading in English language children, although they note the need to add other measures to increase accuracy in identifying children at-risk for poor reading skills. Alphabetic skills also are strong predictors of reading skills in non-English language children (Muter and Diethelm 2001; Lyytinen et al. 2004a). Despite differences across published studies in how alphabetic knowledge is measured (e.g., identification of letters by sounds or name, identification of 26 or fewer letters, and identification of upper and/or lower case letters), the link with later reading skills and other reading-related skills is consistent despite method differences.

The critical aspect of alphabetic knowledge that seems to influence reading development involves the child's understanding that individual sounds of the language correspond to letters or letter combinations (Ehri 1983). Alphabetic knowledge tasks that link individual sounds and names in the language with visual symbols strongly correlate with later phonological processing, word reading, reading fluency and comprehension. McGuinness (2004) argues that if children learn to listen to the phonemes in language, and learn to look at and write phonemes encoded as visual symbols (letters and letter combinations), it will be easier for them to learn the reverse process of decoding the meaning of the visual symbols by reading. Researchers report positive impacts on word decoding, spelling and reading comprehension from teaching phoneme-grapheme (sound-letter) skills to children beginning as early are pre-kindergarten (Brown and Felton 1990; McGuinness et al. 1995; Torgesen et al. 1999).

1.2 Phonological Processing

Abilities to perceive and understand the speech sounds that make up syllables and words are subsumed under the label "phonological processing". This broad term is sometimes separated into phonological awareness (the ability to hear separate words in a sentence, hear syllables in words, manipulate sounds in words), and phoneme awareness (the ability to hear and manipulate sounds within syllables and words). Manipulations of sounds in phonological processing include segmenting, blending, deletion of sounds and rhyming.

Our research shows that both language and reading abilities are grounded in phonological abilities (Molfese et al. 2007a). As a result of genetic and intrauterine factors, humans develop a set of perceptual abilities responsive to speech sound variations. For most people, these perceptual abilities are similar and readily enable them to discriminate speech sounds in similar ways. For others, their perceptual skills do not process sound elements in standard ways. Such fundamental differences in perceptual skills set the stage for early detection of potential reading problems. Research has shown that speech discrimination abilities of children predict language and reading development in different language environments (Burhanpurkar and Barron 2001; Lyytinen et al. 2004a; McBride-Chang 1996). In our work, brain responses (Event Related Potentials, ERPs) recorded at birth, as well as at later ages in infancy and childhood, to speech sound contrasts (for example, /ba/ versus /da/, /ga/ versus /ka/) are highly predictive of the children's subsequent language and reading performance in preschool and older ages. Indeed, classification accuracy exceeds 80% using newborn ERPs to classify word-reading skills at 8 years (Molfese 1995, 1998, 2000; Molfese and Molfese 2000; Andrews-Espy et al. 2004). Similar results are reported from longitudinal studies of Finnish infants in which newborn speech discrimination is linked to later language and reading skills (Guttorm et al. 2005; Lyytinen et al. 2003, 2005). Preschool children who differ in letter knowledge as well as those who differ in performance on Get Ready To Read have been found to show ERP differences in responses to speech sounds (Molfese and Molfese 2001). This link between ERP measures of speech sound processing and emergent reading skills is also found in 9–12 year olds where group (average, below average and above average) differences in reading skills and brain measures to speech sounds were found (Molfese et al. 2007a). Together these findings reflect a continuum between advanced and clinical levels of poor reading skills identifiable by behavior and brain techniques rooted in speech discrimination.

Basic skills of speech sound discrimination are evidence of phonological processing at the receptive level and are present at or near birth. Building from these speech perception skills are the phonological skills identified as the core ability underlying reading (Fletcher et al. 1999). The application of phonological skills in reading involves active encoding and decoding of words in spoken or written form. Studies of preschool and kindergarten children report strong correlations of phonological skills with reading skills. Most of these studies link phonological skills (e.g., deletion, segmentation, rhyming, blending of phonemes and syllables) with reading real words and pseudowords (Badian 1995; Bowey 1995; Brady et al. 1994; Bryant et al. 1990; Catts 1991; Lonigan et al. 1998). Dufva et al. (2001) and Puolakanaho et al. (2004) report similar findings in Finnish preschool children, as does Muter and Diethelm (2001) who studied a mixed sample of English-learning preschoolers. Based on the existing evidence it is difficult to identify the distinct roles of component phonological skills to reading acquisition (Castles and Coltheart 2004; Muter 1994; Tunmer and Chapman 1998). Yet, there is compelling evidence that assessments of phonological skills should include different levels of phonological skills (phonemes and syllables), and evidence of a progression in phonological awareness skills from larger (word and syllable) to smaller (phoneme) units (Carroll et al. 2003; Lonigan et al. 1998; Puolakanaho et al. 2003). Training preschoolers in phoneme identification and sequencing (segmenting and blending sounds) has consistently and positively impacted reading skills at school age (Bryne and Fielding-Barnsley 1989; Schneider et al. 2000; McGuinness 2004).

There is also some evidence that alphabetic knowledge and expertise in using phonological processing skills interact in facilitating reading acquisition. Two recent studies from the Jyväskylä Longitudinal Study of Dyslexia examined the effects of training to provide extra experience in hearing and using phonological skills on phonological and reading skills. In the first study (Lyytinen et al. 2007), 12 non-readers (6 to 7-year-old) were divided into matched groups based on pretests. One group started with a computer-based game involving grapheme-phoneme correspondences and the other group started with a math game (control). After several sessions (totaling 57–122 min) an intermediate test was administered to assess blending skills. Then, the two groups switched games. The length of the second playing period was similar to the first and both groups were exposed to both games for the same amount of time. Both groups improved their blending performance after playing the grapheme-phoneme computer game, but no improvement seen after playing the math game. The second study (Lyytinen et al. 2007) involved 1st grade children ($N = 124$). Half of the non-readers ($N = 41$), participated in the grapheme-phoneme computer game intervention while the remainder served as controls. Children who played grapheme-phoneme computer game for 1–3 h performed better on reading skills assessments compared to those who only received the normal support offered by the school. Initial alphabetic knowledge skills were significant predictors of gains in letter-sound learning but grapheme-phoneme computer experience had a highly significant additional contribution. Together these studies point to the critical role of phonological processing skills to the acquisition of reading skills.

1.3 Phonological Memory

Memory processes are involved in linking phonological and orthographic information. The phonological information (e.g., a phoneme or a string of phonemes) that is stored in memory must be linked to the symbol that represents that sound and is used to recognize the symbol in print (reading) or recalled to produce the symbol (writing). Children use phonological memory skills in learning and applying phoneme-grapheme (sound-letter) knowledge in writing and reading and move from slow and effortful processing toward fluency with more rapid recognition or recall of words. Gradually, the use of effortful processing and time-intensive application of phonemic skills to sound out letters is reserved for writing/spelling and decoding less familiar or unfamiliar words. For children with reading disabilities, the majority of which show poor phonological processing skills, the transition from effortful to more automatic skills is difficult. Part of the difficulty appears to be accounted by poor phonological short-term memory. Studies of preschool children focus on relations between phonological memory (typically assessed via word and non-word span measures) and vocabulary development. Strong positive correlations are reported (Bowey 2001; Gathercole and Baddeley 1989). Studies with English-speaking children using phonological memory span (sentence memory, digit span) measures (Catts 1991; Dufva et al. 2001; Wagner et al. 1994) report that phonological memory is correlated with word identification and word attack skills in kindergarten or first grade. Other researchers (DeJong and van der Leij 1999) combine word span with non-word repetition to create a verbal working memory index that along with phonological awareness correlates with reading skills in the first year of reading instruction in Dutch children. Vellutino et al. (1996) reported that kindergarten children with low scores on phonological awareness, verbal memory and naming speed had poor reading scores at 1st grade and were more resistant to improvements in reading skills through intervention. Developmentally, short-term, working and long-term memory skills are needed for the phonological skills involved in encoding, storing and retrieving sound and symbol relations.

1.4 Naming Speed

Phonological processes are also assumed to be involved in skills needed for rapid and accurate recognition and recall of visually presented symbols (e.g., letter strings). Tests of naming speed use graphemic (letters and digits) and non-graphemic (objects and colors) items to assess how orthographic representations are accessed and interpreted. Reading research has focused on naming speed (using lexical access/rapid automatized naming tasks; Ackerman and Dykman 1993; Badian 1995; McBride-Chang and Manis 1996; Wimmer 1993), with differences of opinion as to the underlying processes indexed by measures of naming speed. Some emphasize a phonological basis (Torgesen et al. 1997; Whitehurst and Lonigan 1998) and others emphasize a visual-linguistic basis (Wolf and Bowers 1999). In young children, different measures of naming speed were found to predict early literacy skills. The National Early Literacy Panel's (2008) meta-analysis found that measures of naming speed involving objects and colors in the preschool period were predictive of decoding, reading comprehension and spelling at school age, while measures of naming speed involving digits and letters were predictive of decoding and reading comprehension. No studies linking naming speed using digits and letters and spelling were found. In the Wagner et al. (1997) longitudinal study of children from kindergarten age through 4th grade, however, early differences in naming speed were not found to be related to later word reading. Findings of early versus later influence are consistent with reports by other investigators (Felton and Brown 1990; Kirby et al. 2003; Wolf et al. 1986). Researchers (Adams 1990; Badian 1995) report that preschool naming speed and letter knowledge are strongly related and that letter knowledge could be a proxy for naming speed. Recent analyses of data from the Jyväskylä Longitudinal Study of Dyslexia (Lyytinen et al. 2004a, 2004b) show that naming dysfluency at preschool age accounted for severe reading difficulties in grades 1 and 2 in approximately 1/3 of at-risk children studied.

2 The Role of Phonological-Based Processing Skills in At-Risk Young Children

In the past 10 years, increasing attention has focused on identifying the characteristics of children that place them at-risk for poor reading outcomes. In addition to the risks that arise due to the presence of weaknesses in the cognitive skills needed for development of reading skills, risk for poor reading can arise from other sources, such as experiential deficits and/or poor reading instruction (Clay 1987; McGuinness 2004), and from causes that may arise from genetic or biological sources, as shown by the increased occurrence of reading disabilities among children who are at familial risk for dyslexia (Lyytinen et al. 2003), and the highly elevated occurrence of dyslexia among monozygotic compared to dizygotic twins (Grigorenko 2001).

There is a large body of research on children at-risk due to family history of dyslexia that provide evidence of the importance of phonological skills for the development of reading skills. Seven longitudinal studies cover ages ranging from preschool/kindergarten through 2nd, 4th or 6th grade, include measures of cognitive skills as well as later reading skills, and include a comparison or control group. Children participating in these studies (Elbro et al. 1998; Pennington and Lefly 2001;

DeJong and van der Leij 2003; Lyytinen et al. 2001, 2004a; Scarborough 1990; Snowling et al. 2003; Wagner et al. 1997) are from populations of risk and control families who are English- and non-English-speaking/reading (Dutch, Danish and Finnish). Despite the diversity, these studies report early differences in alphabetic knowledge, specific phonological skills (e.g., rhyming, short-term memory), naming speed, and some language skills (e.g., vocabulary and grammar) as markers of group differences at preschool age or kindergarten. If children are English-speaking/reading, only phonological processing measures continue to differentiate risk and control children at older ages (Pennington and Lefly 2001; Snowling et al. 2003). For non-English-speaking/reading children, group differences in phonological skills are seen at early measurement points but not later (depending on task demands); differences on naming measures show persistent groups differences at the older ages in Dutch, Finnish and German children (DeJong and van der Leij 2003; Holopainen et al. 2000, 2001; Wimmer 1993). These studies emphasize the role of phonological-based skills in development of reading skills and the continuing role of phonological skills across developmental ages in influencing reading.

In addition to studies of children at familial risk for reading disabilities, there is also accumulating evidence from students who already experience reading difficulties using behavioral and brain measures. Improved brain response recording and analysis techniques have provided new information reflecting brain organization and processing. Evidence shows that Event Related Potential (ERP) data reliably reflect phonological discrimination skills and these data are useful for predicting language and reading skills. ERP recordings can also be used to reflect how and when connections between phonemes and graphemes occur and can be used to reflect the effects of training designed to strengthen phonological skills.

3 Electrophysiological Measures of Reading Performance in Infants and Children

ERPs are sensitive to a number of linguistically-relevant variations in speech sounds (Kraus et al. 1993; Molfese 1978a, b, 2000; Molfese and Molfese 1979a, b, 1980, 1985, 1988). Our lab was the first to investigate changes in electrical brain responses to two major speech cues–voice onset time (VOT) and place of articulation (POA)—in infancy and childhood (Molfese and Molfese 1979a, b; Molfese and Hess 1978). Changes in ERP wave shapes as well as scalp topography (the distribution of ERP amplitudes across the scalp) occur from birth into adolescence. In a longitudinal study of speech perception with 47 children at each age from birth to 8 years, a steady decrease is seen in the amplitude of the first positive peak (P1) occurring approximately 100 ms after stimulus onset, as well as an increase in the amplitude of the second negative peak (N2) with increasing age. Table 1 and Fig. 1 reveal a linear decrease of approximately 10 ms per year in the latency of the first large negative peak (N1) from stimulus onset. Not all peak latencies change in a

Table 1 Mean ERP peak latencies (standard deviations) of ERP components recorded in response to stop consonant-vowel syllables

Age (years)	N1 latency	P2 latency	N2 latency
4	227.62 (20.98)	373.01 (33.02)	518.15 (50.25)
5	211.61 (19.71)	365.42 (30.50)	508.87 (46.80)
6	188.73 (20.94)	337.17 (33.22)	493.08 (43.23)
7	186.19 (22.26)	335.14 (28.91)	490.32 (49.58)
8	172.24 (22.05)	312.01 (28.76)	471.45 (41.28)

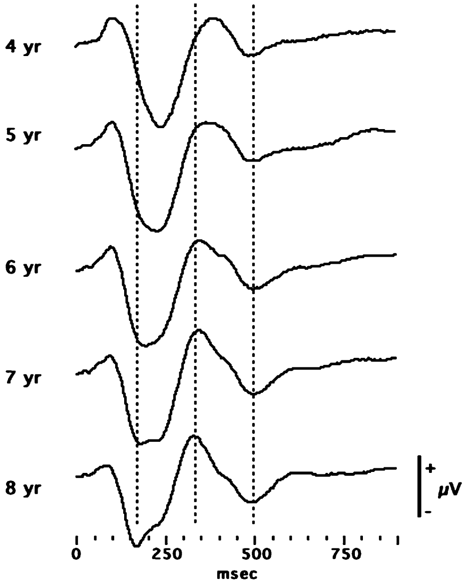

Fig. 1 Grand average ERPs elicited in response to series of stop consonant-vowel syllables from 47 children tested longitudinally from 4 through 8-years of age

similar fashion as indicated for P2 latency (Fig. 2) which decreases in a curvilinear fashion, from 373 ms at age 4 years to 312 ms by 8 years.

Early research on identification and prediction of reading skills set the stage for brain-behavior studies of interventions to determine impacts on the trajectory of skill development. The reasoning for this is based on studies of learning in young children. ERP changes are identified as a function of learning even after brief periods of training with infants (Molfese et al. 1990), children (Molfese and Molfese 1997b) and adults (Fonaryova et al. 2005; Key et al. 2006). For example, Molfese et al. (1990) investigated early word learning in infants. Fourteen-month olds were trained by their parents to form associations between specific CVCV nonsense syllables and novel objects differing in shape and color. Training lasted 10 min/day for 5 days. Before training, infants were pre-tested on a Match-Mismatch task to establish a baseline of behavioral and ERP responses. At a post-training ERP recording session, infants were tested on a Match-Mismatch task in which an object was paired with its CVCV label (Match condition) on half of the trials and with a different CVCV token on the remaining trials (Mismatch condition). Analyses revealed differences between Match and Mismatch trials in two portions of the ERP (Fig. 3). The first occurred between 30 and 120 ms as increased negativity for the Mismatch condition over

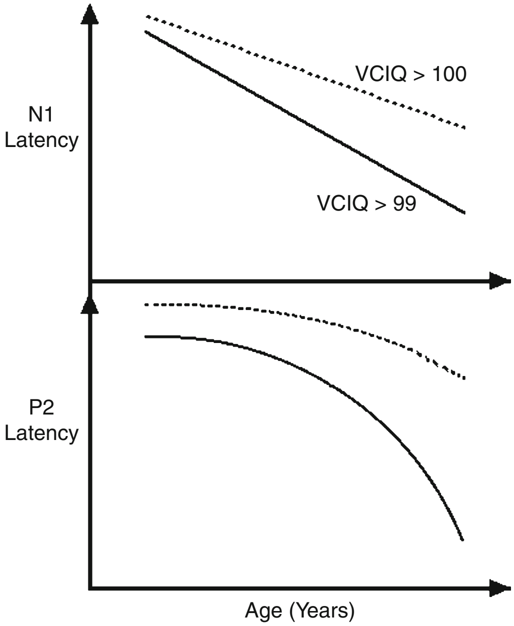

Fig. 2 Growth curves reflecting changes from 1 through 8 years of age in N1 and P2 latency of ERPs elicited in response to a series of stop consonant-vowel syllables

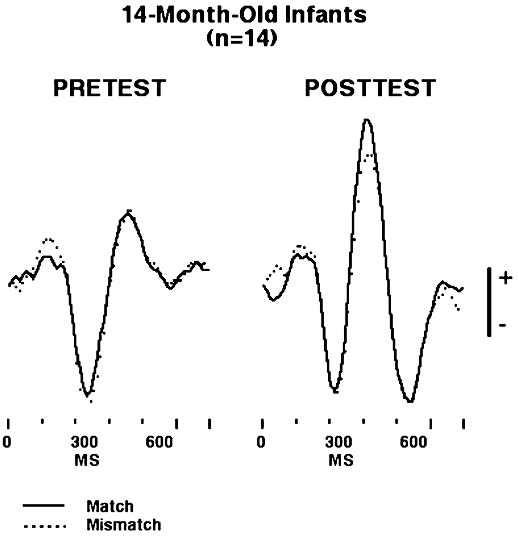

Fig. 3 Group ERPs averaged across frontal, temporal, and parietal scalp regions of both hemispheres in response to auditory CVCVs from 14 infants. ERPs were recorded before (pretest) and after (posttest) word training sessions. Note large significant amplitude increase at 370 ms post-training. Stimulus onset began at 0 ms. Positivity is up. The calibration marker is 5 uV. Split-half comparisons and pooled analyses indicated two ERP regions discriminated Match from Mismatch bilaterally over frontal regions between 30 and 120 ms post stimulus onset and over LH electrode sites from 520 to 600 ms. Result are significant ($p < .01$)

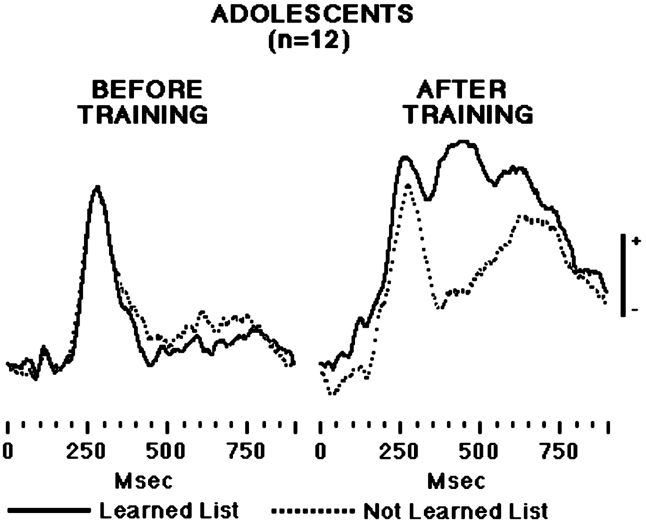

Fig. 4 Group ERPs averaged across frontal, temporal, and parietal scalp regions of both hemispheres in response to auditory CVCVCs from 12 children. ERPs were recorded before (pretest) and after (posttest) word training sessions. For "AFTER TRAINING", note large amplitude increase for LEARNED LIST after 300 ms. Stimulus onset began at 0 ms. Positivity is up

frontal regions of both hemispheres. The second response was found between 520 and 600 ms after stimulus onset. Since no such Match or Mismatch effects were noted in the pre-training ERP session, it is clear that the ERPs detected changes due to training. Moreover, the use of the matching paradigm eliminated possible confounding effects due only to repeated presentations since the match and mismatch conditions occurred with equal regularity before and after training. In a related study, adolescents were trained to associate CVCVC nonsense words with randomly generated shapes (Molfese and Molfese 1997a). Half of the words and shapes were consistently paired during training while half were not. As illustrated in Fig. 4, at the pretest amplitude and latency of visual ERPs did not distinguish between the stimuli. However, after 15 min of training, both significant ERP and behavioral changes occurred for only the learned pairings but not for random pairings. Finally, Fonaryova et al. (2005) conducted a training study in adults that included a pre-training test to establish baseline parameters and a series of different training and test scenarios that included training a subset of stimuli whose features were dictated by a set of rules, a retest of those stimuli as well as novel stimuli, half of which were consistent with those rules and half not. Significant behavioral and ERP differences occurred between the trained vs. non-trained stimuli also presented during the pretest period. Differences also occurred between the trained vs. the non-rule related stimuli but no differences were noted between the trained and novel rule-related stimuli.

The three studies described above that investigated learning in infants, children and adults all noted that both behavior and ERPs differentiate pre-training from post-training responses while various control conditions did not. Such studies indicate that ERPs in a standard match/mismatch task can track the effectiveness of training and that they discriminate between trained and untrained stimuli. But ERPs can also be used to track phonological learning that is the basis of the training paradigm. While the field appears to be moving increasingly towards using such techniques to both identify children at risk for language and learning-related disorders, major questions remain concerning the bases for why some children with risk factors develop normally while others do not and why other children without obvious risk factors fail to develop adequate reading skills or learn to master the learning of material at a rate that meets age- or grade-level expectations. Below we present a broad outline of one theory that characterizes the emergence of cognitive abilities within the context of the brain's early stages of development.

4 A Neurodevelopmental Model for Normal and Abnormal Development of Cognitive Skills

Based on the research reviewed earlier in this paper as well as research by other investigators, we propose a theory that characterizes the emerging link between neural and cognitive development (Molfese et al. 2008). This view builds in part on the work of Hebb (1949) who proposed what is now a widely regarded view of emerging neural networks. These networks are shaped during successive exposures to a stimulus to the point where processing of the entire stimulus event becomes virtually automatic, and perception no longer requires exposure to the entire stimulus or event. Parallel and distributed processing approaches reinforced this view (Anderson 1983; Hinton et al. 2006; Rumelhart and McClelland 1986). However, a number of modifications need to be added to this model to characterize and emphasize the importance of the dynamic reorganization of spatial and temporal distributions of the brain's neural networks that occur during learning at all stages of development. This dynamic process in young children is shaped in part by new and immature brain structures that come on-line as they are drafted into the processing of information and begin forming initially immature and unstable links with other neural structures that are at different levels of neural development.

In the earliest stages of neural development, neurons differentiate according to their relative locations within the neural tube, and continue to do so as the brain develops (Borello and Pierani 2010). Chemical signals within the neural tube create a type of coordinate system with high expression of one chemical signal at one end of the tube and different chemical signals at the other end of tube with gradations of still other signals at intermediate distances and regulating neural crossing from left to right. The growth cones on the leading edges of new, migrating neurons are attracted to (or repelled by) these chemical signals. Through the interplay of multiple chemical signals pushing and pulling, individual neurons—sensitive to particular combinations of these chemical signals—are guided towards the distant brain regions to which they will become wired (Marín et al. 2010). Next, synaptic pruning occurs and un-reinforced connections between neurons are eliminated. This pruning may take two forms: (1) entire neurons may be eliminated or (2) individual synapses may be eliminated while other synapses on the same neuron either remain unaffected or are strengthened (Goodman 1996). The elimination of a particular neuron or synapse and the concurrent reinforcement of other neurons and synapses are activity dependent, as Hebb originally suggested. Every time a pre-synaptic neuron acts on a post-synaptic neuron, that synapse is straightened, weakened, or remains unchanged (Reichert 2009). Synapses that do not receive frequent inputs are pruned while those that receive repeated synaptic activations are enhanced. The strength of a given synapse is determined by the composition of synaptic proteins, including those that form ion channels and neurotransmitter receptors. Once a synapse is activated, protein-signaling cascades are initiated that transmit information about that synaptic activation to the cell nucleus. Furthermore, there is a yet-to-be-understood mechanism by which activation of specific synapses is linked to the particular synapse of origin. Thus, when the cell body responds to synaptic activations by building new proteins or otherwise altering cellular activity, new synaptic proteins are trafficked from the cell body to the activated synapse but not to all synapses (Low and Cheng 2006). The initial wiring of these synaptic connections is determined by the developmental signals organizing the brain along a chemical-coordinate grid. The subsequent state of each synapse will be the product of all prior activations of that specific synapse.

It is clear from the literature that different brain structures come on-line to engage in the processing of information at different points in development, depending upon the physical and functional maturation of those brain structures. There is sufficient data now to indicate that such structures may be functional and already engaged in processing early in life. For example, areas within the hippocampus in neonates differ in terms of their structural differentiation, as well as their rates and stages of gray matter development (neurogenesis) from those of a 1- and 2-year old infant. Yet even immature hippocampal neurons already play a role in processing and impact more mature neurons (Cameron and Christie 2007; Cuppini et al. 2006). Furthermore, the manner in which one area within the hippocampus interacts with other hippocampal areas and with cortical areas in other brain regions also differs depending on age (Shors et al. 2002).

To complicate matters further, the development of gray matter (neurons) and white matter (tissue that connects different brain regions) progresses at different rates at different ages, with rates of change increasing or decreasing relative to each other at different points throughout development. Following an accelerating rate of neurogenesis during the first 2 years of life (Huttenlocher 1997), decreases in gray matter volume at varying rates across different areas of the cortex. Gray matter loss by 5 years of age is most marked in the occipital and central regions posterior to the Rolandic fissure that separates the frontal from the parietal lobes. With further development, this loss begins to extend towards the posterior regions of the brain, through the parietal region and then in an anterior direction into the medial frontal regions, finally moving forward and laterally to encompass the remaining of the frontal lobes (Gogtay et al. 2004). This process continues through adolescence and likely well into adulthood. Casey et al. (2000) noted a significant decrease in cortical gray matter after 12 years of age. Synaptic density also changes throughout this developmental period, adding yet another factor that must be considered in understanding the structural and functional development of the brain (Huttenlocher 1997).

For white matter development, myelination progresses at different rates and at different times across the brain, advancing up through the brainstem, into midbrain structures, stretching out laterally into the temporal lobes and posterior towards the parietal and occipital pathways, and finally extending into the frontal lobes sometime near 25 years of age. Since neural transmission speed increase markedly with myelination (e.g., up to four times), one would expect the speed and integration of communication between brain areas to occur at different rates at different developmental stages as fiber tracts myelinate within different brain regions. Casey et al. (2000) found that cerebral white matter increases throughout childhood and young adulthood. This change is not trivial. Courchesne et al. (2000) noted a 74% increase in white matter volume from early childhood to adolescence followed by a slower rate of increase with a plateau reached by the fourth decade of life. Such neural changes extend well into and throughout the lifespan.

There also are age and region-specific changes occurring in the brain during development. This includes converging evidence of prolonged development and organization of the prefrontal cortex throughout childhood, adolescence and adulthood, suggesting important parallels between brain development and cognitive development. Such factors when considered in the context of development suggest that the links between neural and cognitive factors are in a continual, dynamic state of flux, with different neural tissues maturing at different rates in different regions of the brain while their ability to communicate with proximal and distal systems through neural networks also are in a dynamic state of change. With development, more networks come on-line, albeit at different levels of maturity. During this extended time period, processing speed increases and communication between regions expands as a function of brain structure development and experience. Such a scenario stands in marked contrast to a more traditional position that static brain-behavior relations are established early in development that utilize a limited number of specific brain areas that interact in predictable and uniform ways.

It is our contention that against this backdrop of multifactor, dynamic development in the initial stages of skill acquisition, neural activation is widely distributed across multiple brain sites that communicate in initially unstable and inefficient ways (when compared to adult processing or processing after skills are well established). In this phase, the order in which communication between brain areas occurs changes moment-by-moment. As a skill is mastered and neural development proceeds, these temporal relationships begin to stabilize while the number of brain networks engaged in processing information decline. Thus, processing becomes more efficient as more selective neural regions are engaged. Work by Casey et al. (2000) fits with this model. Analyses of fMRI data noted that the magnitude of neural activity was greater and more diffuse in children than in adults. They reported that children engaged more brain tissue to perform the same task than do adults by activating a larger volume of brain tissue in the superior and middle frontal gyri during performance on go no-go task. While more extensive brain tissue is engaged in a cognitive process at earlier stages of development, the amount of cortex involved declines with the transition into adulthood. Even so, although children at earlier stages may engage more cortex to perform a task similar to adults, their longer reaction times and higher error rates suggest that in spite of the larger recruitment of cortex, qualitative differences exist between their brain processing and that of adults.

We believe that the temporal-spatial relationships noted above are critical to the normal learning process and subject to important changes over time. In fact, we believe that these early patterns at some level also establish the pattern of skill acquisition for the mature brain. Initially, acquisition of a skill requires a widely distributed neural network that engages many neural processes and structures. Initial processing is distributed but these initial spatial and temporal relationships are both spatially and temporally unstable, with some connections more functionally efficient and relevant to the task than others. Over time and experience the more efficient and functional areas begin to play a more prominent role in processing information relative to other neural contributions. The less utilized areas subsequently are dropped from the developing network while still others are added as the system seeks ways to process the information more efficiently with the resources available or as information becomes more complex. Yet the temporal relationships between these neural processes also are unstable and, as a result, some areas may be moved temporally forward in the processing sequence while others are delayed to later stages of processing. Thus, cognitive systems continuously require changes in the ways in which emerging, maturing and established neural areas communicate spatially and temporally with each other in the network. However, more research is needed to explore issues of changes in neuronal activation, how areas of the developing brain becomes pre-disposed to becoming specialized for language and other cognitive functions and into the process by which well-defined functional brain regions such as Broca's and Wernicke's areas or the somatosensory cortex become organized. It is probable that the same chemical signaling mechanisms responsible for initially organizing the brain continue to organize highly-specialized areas of cortex. In the case of learning disabilities, a failure to continue refinement of one or more of these specialized networks may lead to highly specific processing deficits.

In the case of developmental disabilities, we believe that the neural networks have more difficulty in making the transition from engaging numerous spatially and temporally distributed neural sources to a smaller, more efficient functional unit that, at the same time, maintains enough flexibility to learn through some continuing level of instability. For example, in the case of a child with a reading disability, the child is unable to make the transition from processing that is dependent upon multiple areas and pathways to one in which a more restricted set of areas communicate temporally along more predictable pathways. While the normal learner's performance improves in accuracy and speed and perhaps moves towards some level of automaticity, the impaired learner is less able to make or maintain the transition from a spatially and temporally unstable distributed network. Consequently, each contact with their environment places greater demands on the child's neural system than the normal learner. The impaired child addresses each task using a spatially and temporally unstable network that is unable to effectively restructure itself in order to establish more efficient means to process and acquire information. For this child, each moment-by-moment experience is in some real sense a novel one because the neural network that supports their attempts to process and master information is unstable and changes from moment-to-moment, with little progress in establishing the necessary reductions in cortical areas pathways, and time sequencing that is crucial to skill acquisition. Evidence of such learning difficulties reflected in differences in brain processing areas and speed is reported in Molfese et al. (2007b) and Molfese et al. (2008).

In summary, our theory suggests that initially there is an engagement of processing across distal areas of the brain (divergence). With further maturation and integration, the processing increasingly is restricted to fewer brain areas and pathways that act in a more coordinated fashion (convergence). Finally, when convergence reaches some point, a new level of more efficient processing emerges that represents a significant qualitative change in processing and behavior (Teilhard de Chardin 1955). This overall state of dynamic spatial and temporal processing continues throughout the lifespan, with both neurophysiological and cognitive change marking a succession of subsequent periods of divergence, convergence and emergence that push the organism towards more complex and dynamic levels of processing.

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Magnetic Source Imaging: A Suitable Tool of Exploring the Neurophysiology of Typical and Impaired Reading Ability

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1 Introduction

Magnetoencephalography (MEG) is a functional brain mapping technique based on the principle that all electrical currents generate magnetic fields. Measurement of these fields on the scalp surface allows localization of their anatomical origin, a procedure also referred to as Magnetic Source Imaging (MSI). An advantage of MEG over alternative functional brain mapping modalities is that the technique provides temporal resolution in the order of milliseconds, with millimeter spatial resolution, allowing for real-time mapping of cortical activation. The purpose of this chapter is to introduce the technique of MEG (or MSI), and outline its utility as a functional brain imaging tool. First, the principles behind MEG are discussed, including a basic description of the underlying physiology and physics associated with the procedure. Moreover, the fundamentals of data acquisition and analysis, as well as the validity of the technique as a non-invasive tool for localizing brain function, are presented. Finally, the application of MEG to addressing developmental issues is reviewed, with particular emphasis on studies exploring the organization of the cerebral mechanisms underlying typical and impaired reading ability in children.

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1.1 The Type of Activation Imaged with Magnetoencephalography

Signaling among neurons involves electrochemical events that take place at the synapses, in the axon and the dendrites of neurons. With the exception of the phenomena of neurotransmitter release and uptake, which do not directly involve electrical activity, all other events involve the flow of electrically charged particles, or ions, which results in an *electrical current***.** The main source of the extracranial magnetic fields that can be measured with MEG is current flow through the long apical dendrites of cortical pyramidal cells (i.e., *intracellular* current; Okada et al. 1997). Pyramidal neurons comprise a significant proportion of neocortical neurons. A proportion of these cells are oriented with their apical dendrites perpendicular to the cortical surface as shown in Fig. 1. An excitatory synaptic event will induce a dendritic current that propagates toward the cell body. This configuration can be considered an electric dipole. A dipole is a pair of electric charges or magnetic poles of equal magnitude but opposite polarity, separated by a small distance. It is estimated that a minimum of 50,000–150,000 pyramidal neurons must show increased intracellular current flow simultaneously in order to produce magnetic flux detectable at the surface of the head. This estimate corresponds to a minimum cortical area of 0.4–4 mm^2 (Lu and Williamson 1991). Importantly, electrical currents that flow in the extracellular space to close the electrical circuit formed by the dipole (secondary currents) contribute minimally to the magnetic flux recorded using MEG (Haueisen et al. 1995; Kwon et al. 2002). Indeed, it is the flow of these secondary currents that are most readily captured by electroencephalography (EEG), a technique that closely parallels MEG. Therefore, EEG recordings generally illustrate the contribution of radial sources, likely reflecting the summation of neuronal activity arising from the gyral crown. However, intracellular dendritic currents produce circular patterns of magnetic flux (i.e., magnetic flux lines) forming planes that are perpendicular to the long axis of the dendrite. Cells oriented parallel to the surface of the skull will produce maximally detectable extracranial magnetic fields (Murro et al. 1995). These dipolar sources would be located at the banks of sulci, whereas dipolar sources located at the troughs of cortical sulci and at the crests of gyri must be considerably stronger in order to be detected with conventional instruments (Hillebrand and Barnes 2002).

1.2 Recording the Magnetic Flux

The magnetic flux is recorded by means of loops of wire positioned over the head surface. As the flux lines thread through the loop, they create in it a current by *induction*. The strength of the current is proportional to the density of the flux at that point, so that by assessing the magnitude of the induced current, we have a measure of the flux strength at that point. If a sufficient number of magnetic sensors

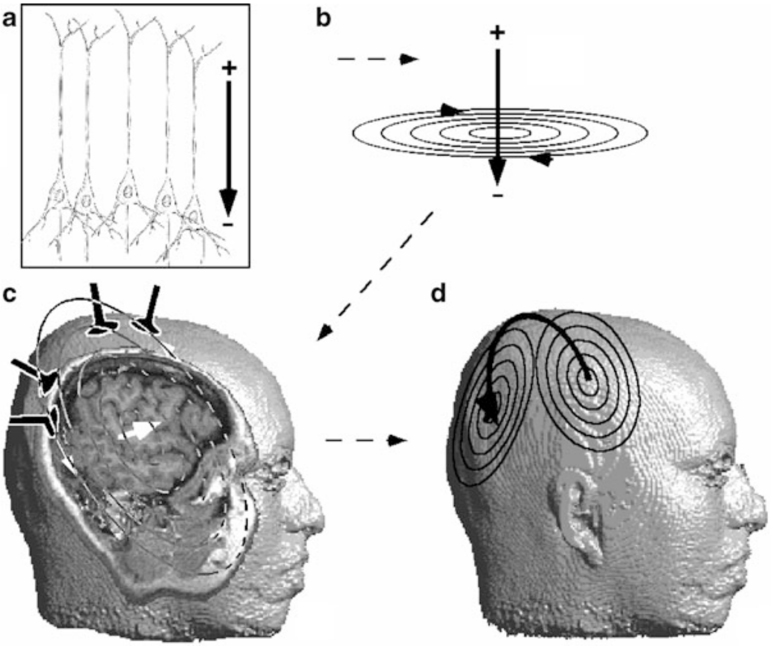

Fig. 1 A schematic rendering of the electromagnetic signals recorded on the head surface echoing the electrical currents inside the brain. (**a**) Intracellular currents developing in the apical dendrites of a population of pyramidal cells can be represented by an electrical dipole (*solid arrow*). The cortical surface is at the top of the inset. (**b**) Magnetic flux lines produced by intracellular currents are shown as concentric circles; magnetic flux direction is indicated by *arrowheads*. (**c**) The location of the electrical dipole is shown by the *white arrow* on a three dimensional rendering of the brain. In this case the dipolar source is located in the temporal lobe. The resulting magnetic flux is recorded by magnetic sensors. Only four magnetic sensors are shown in the figure, although modern neuromagnetometer systems consist of a dense array of 148–250 sensors placed at <2 cm apart. (**d**) The instantaneous configuration of magnetic flux produced at the surface of the scalp by the current dipole is obtained by combining magnetic flux measurements from the entire magnetic sensor array

are placed at regular intervals over the entire head surface, then the shape of the entire distribution created by a brain activity source can be determined. Magnetic sensors are either *magnetometers*, when they consist of a single loop of wire, or *gradiometers*, typically consisting of two loops. Magnetometers are highly sensitive, but cannot discriminate between near and distant sources, so they are strongly affected by environmental magnetic fields. In order to reduce the contribution of remote sources of magnetic artifacts in the recordings, systems utilizing magnetometer sensors must be equipped with special software designed to take into account magnetic flux generated outside of the participant's head (e.g., due to moving vehicles or other metallic objects outside the MEG chamber). As these approaches have not been perfected, their implementation requires considerable skill and their effectiveness depends on the signal-to-noise ratio of each experiment.

Although not quite as sensitive, gradiometer sensors are the most commonly used coil types because they are less affected by background noise. The most commonly used gradiometer configurations are *first-order* gradiometers consisting of two loops separated by a distance called the gradiometer baseline. The two loops are wound in opposite directions so that magnetic flux generated at a considerable distance from the sensor (as in the case of environmental noise) will induce current of similar strength but opposite direction in both loops. The gradiometer output is therefore proportional to the difference in the magnetic field measured by the two wire loops. For equal noise level, magnetometers have the best sensitivity, followed closely by long baseline (5 cm or more) axial gradiometers. With respect to their susceptibility to external magnetic noise (artifacts), gradiometer sensors perform significantly better than magnetometers.

To provide additional protection against external magnetic noise, the MEG instrument is placed in a specially constructed magnetically shielded room. As the magnetic fields are extremely small the magnetic sensors are made superconductive by being housed in a dewar (drum) that is cooled with liquid helium to about 4 K (kelvin). The induced currents are then processed by special low-intrinsic noise amplifiers known as Superconductive Quantum Interference Devices (SQUIDS).

1.3 The Averaging Procedure

The advances in electronics and software described in the previous paragraph made it possible to detect changes in magnetic flux associated with the presentation of a single stimulus as shown in Fig. 2. It is often the case, however, that the increase in the rate of neuronal signaling, due to the cognitive operations involved in the function under investigation, is minute compared to the background signaling that corresponds to all concurrent functions of the brain. In this case, the relative contribution of the “signal” (i.e., the amount of magnetic flux solely related to task-specific neuronal currents) to the magnetic flux recorded by the magnetic sensors can be significantly enhanced through the *averaging* procedure. In principle, the averaging procedure is identical to that which gives rise to the phenomenon of event-related potentials (ERPs), used to define a characteristic, time-dependent response in the EEG record following repeated exposure to an exogenous stimulus. Using MEG, the records of magnetic flux associated with each presentation of the stimulus are initially *digitized* separately for each magnetic sensor. After converting the intensity of the flux at each successive time point into numbers, these single-stimulus records of magnetic flux are summed and divided by the total number to derive an average. The resulting waveform (averaged event-related magnetic field record at each recording site) is a more stable representation of task-specific changes in underlying magnetic activity than the single-stimulus record.

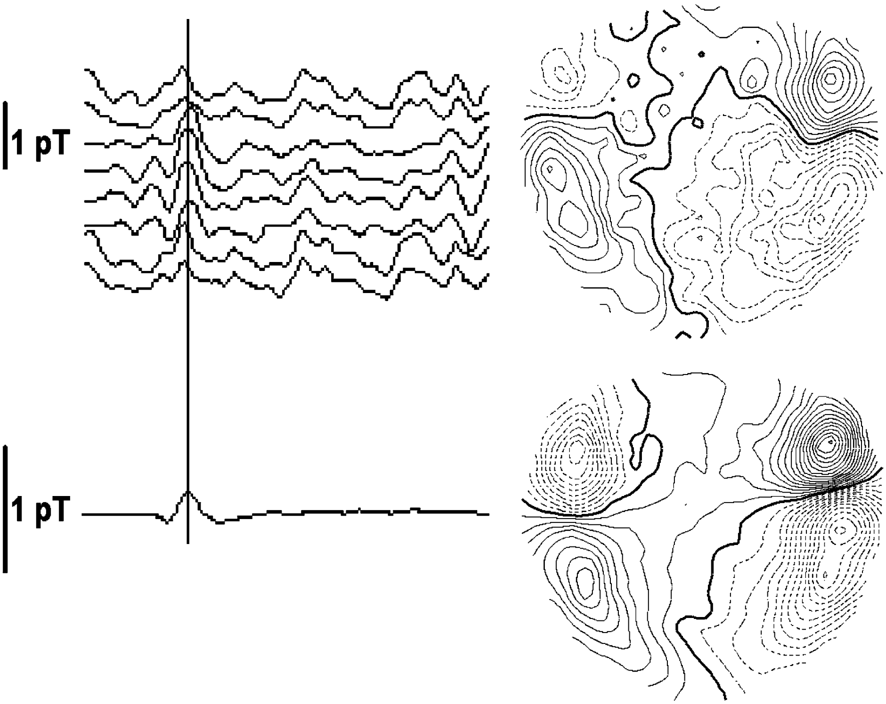

Fig. 2 *Top left:* Single-trial magnetic flux recordings. Each trace represents a record of magnetic flux time-locked to a spoken word stimulus (the onset of which occurs at the beginning of the trace) registered at a single scalp location. Here, the stimulus is repeated eight times. The transient increase in magnetic flux reflecting increased neuronal signaling in primary auditory cortex is apparent in the single-trial data along with other transient changes caused by extraneous sources and ongoing neurophysiological events that are not time-locked to the stimuli. Averaging the individual epochs, point-by-point, reduces the amplitude of task-irrelevant flux and results in the "smoothed" record shown in the *lower left* portion of the figure. Notice that the surface distribution of magnetic flux at the peak of the event-related response (here at 90 ms post-stimulus onset) is very similar in the single-trial data (*upper right*-hand panel) and in the averaged data (*lower right*-hand panel)

2 Source Estimation: Solving the Inverse Problem

2.1 Single Dipolar Methods

As mentioned above, the type of neurophysiological event that can be estimated with magnetoencephalography is intracellular current flow, primarily within the apical dendrites of pyramidal cells. Through a number of steps this set of events produces magnetic flux that crosses the surface of the scalp and can be measured with the magnetic sensors. Several measurements of the magnitude of this flux are obtained simultaneously from the entire surface of the head (anywhere from

148 to 250 sensors for neuromagnetometer systems commercially available). The distribution of magnetic flux measurements taken at the surface of the scalp is then used to determine the characteristics of the underlying dipolar source – strength, direction, orientation, and location.

The problem of computing the strength, direction, and orientation of magnetic flux at any given point in space around a known dipolar source is easy to accomplish using a simple formula (based on Biot-Savart's law) and has a unique solution (Gençer et al. 2003). Performing the reverse operation, or computing the characteristics of the dipolar source that produces a particular distribution of magnetic flux sampled as several points in space, is less straightforward. This so called *inverse problem* does not have a unique solution: a particular configuration of magnetic flux in space can, in principle, be produced by an infinite number of different combinations of dipolar sources, each with various characteristics. In the case of the aforementioned example used to describe the averaging procedure, the MEG data practically corresponds to the shape of the magnetic flux distribution as measured on the head surface. The solution to the inverse problem requires certain assumptions concerning the nature of the observed configuration of magnetic flux, which are further constrained by known facts regarding the characteristics of the underlying dipolar source (for a thorough discussion of the biophysics of the inverse problem see Wang and Kaufman 2003).

Similar to MEG, the reconstruction of activity sources giving rise to EEG signals is subject to the limits posed by the inverse problem. However, the sensitivity of two methods to the different types of electromagnetic properties associated with neuronal signaling highlight the major difference between MEG and EEG. Specifically, secondary (extracellular) currents take the path of least resistance to reach the scalp surface, traversing various layers of the brain volume (gray matter, white matter, cerebrospinal fluid, meninges and bone), resulting in an irregular voltage distribution at the scalp surface. Accordingly, the correspondence between the estimated brain source and signal recorded at the scalp surface using EEG is often imperfect, reducing the fidelity with which functional brain images are generated. Unlike secondary currents, however, magnetic flux measurements obtained using MEG emerge through various tissue layers with almost zero resistance, resulting in geometrically regular surface distributions that can be used to generate real-time functional brain images of relatively high fidelity.

Iterative computer algorithms developed to solve the inverse problem are based on the assumption that the field pattern generated by a dipole is embedded in a sphere and therefore treat the head as a uniform spherical volume conductor. The iterative process starts with the postulation of a hypothetical dipole with known orientation, strength, and location. The resulting hypothetical magnetic flux distribution is then compared with the actual distribution as measured during the experiment, and the process is repeated, until the "best fit" between the calculated and the measured field is found. This is then assumed to be the dipolar source that best accounts for the observed magnetic flux distribution measured over a particular portion of the head surface (typically one side of the scalp, or just a portion thereof). As explained in more detail below, high-density neuromagnetometer systems permit estimation of several dipolar sources, independently, in the entire brain at each successive time frame of magnetic flux measurement (usually every 1–4 ms long, depending on the desired sampling rate).

A variety of source modeling algorithms have been developed to solve the electromagnetic inverse problem, some of which have the desirable feature of taking into account the complex geometry of the cortical surface (e.g., Haueisen et al. 1997; Mosher et al. 1999). Among the available approaches, the single equivalent current dipole (ECD) model has seen widespread application, particularly for estimating a limited number (usually 1–3) of simultaneous sources of neuronal activity contributing to the late components of event-related magnetic fields during complex cognitive tasks. In addition to its simplicity, one desirable feature of the single ECD method is that the technique has been validated against the more invasive Wada (intracarotid amobarbital procedure) and intraoperative electrical stimulation mapping procedures (Breier et al. 1999a; Simos et al. 1999a; Papanicolaou 2009). However, alternative source models may prove to be useful in identifying multiple sources that contribute to surface magnetic flux variations, otherwise not detectable by the single ECD model, and will therefore also be considered below.

According to the analysis protocol based on the single ECD approach, magnetic source estimation is performed separately for each hemisphere. In particular, source estimation is attempted only when the surface distribution of magnetic flux is locally dipolar, in that it consists of a single region of magnetic outflux and a single region of magnetic influx (like the two sets of concentric circles in Fig. 1d). This kind of surface distribution usually indicates the presence of a single underlying active cortical region that can be modeled as an ECD (henceforth referred to as an “activity source”). Occasionally, two (or more) distinct dipolar distributions can be discerned at a single time point (in one or both hemispheres). In order to determine the anatomical regions where the activity sources are located, source coordinates are overlaid onto high-resolution, magnetic resonance (MR) images obtained from participants and the anatomical location of each source is visually determined using a standard MRI atlas (Damasio 1995).

Regions of interest are not usually established a priori in MEG studies. Modeling of activity sources is performed solely on the basis of the surface distribution of magnetic flux without making hypotheses or placing constraints regarding the anatomical location of the underlying intracranial sources. When activity source locations are co-registered on the participants’ MRI scans, the resulting individual spatiotemporal brain activation profiles are inspected visually (and blindly with respect to experimental condition) to identify brain regions where activity sources are localized consistently across participants. Given variations in individual anatomy, manual quantification of activity sources modeled using the single ECD approach necessarily requires the use of each individual’s three-dimensional MRI images. However, more recent methodological developments have seen the introduction of automated application of the single ECD model for measuring the density of dipolar sources in pre-specified brain regions, correcting for global anatomical differences using normalization procedures which allows for projection of sources into a common stereotactic coordinate space (Papanicolaou et al. 2006; Pazo-Alvarez et al. 2008).

The sum of all acceptable sources localized in each region starting at approximately 100 ms following stimulus onset serves as a metric of the degree of stimulus- and time- locked activation of that area. This measure directly reflects the amount of time that neurophysiological activity can be detected and modeled in a particular brain region as participants process each stimulus. This measure correlates strongly with other more direct estimates of the strength of neurophysiological activity (Valaki et al. 2004), expressed as either the amplitude of the magnetic field recorded at the scalp surface (Root Mean Square of instantaneous magnetic flux), or the estimated strength of the intracellular current producing this field (product moment of the equivalent current dipole). The number of successive sources was preferred in early MEG studies on typical and impaired reading ability as a metric of the degree of regional activation. At the time highly desired features of this metric consisted of: (a) its concurrent validity against invasive brain mapping techniques in clinical populations (Breier et al. 1999a, 2001; Maestu et al. 2002; Papanicolaou et al. 2004; Simos et al. 1999a, b); (b) its sensitivity to regional/hemispheric differences in brain activity, in contrast to measures of magnetic flux or estimated electrical current (Valaki et al. 2004); and (c) its sensitivity to both the degree and temporal course of regional neurophysiological activity. More recently alternative methods to MEG source-level data analysis have been implemented in studies of reading yielding comparable results, as explained in more detail below.

2.2 Minimum Norm Estimates

The simplicity and validity of the single equivalent current dipole model lends itself readily to reconstructing neuronal sources of activation associated with time-varying magnetic flux. However, a potential drawback of this approach is susceptibility to spatial undersampling of scalp field distributions. Specifically, higher order cognitive processes could arise from the co-activation of multiple brain regions for which the associated magnetic activity observed at the surface of the scalp may not necessarily conform to clear single dipole patterns. A means of overcoming this potential problem is the application of distributed source modeling techniques, and in particular the method of minimum norm estimates (MNE) (Hämäläinen and Ilmoniemi 1994; Moran and Tepley 2000). Minimum norm estimates attempt to reconstruct the intracranial sources of activity by identifying the smallest distribution of dipoles (e.g., minimum norm) that can account for the magnetic flux distribution recorded simultaneously over the entire head surface at successive time points. In contrast to the spherical head model employed by single equivalent current dipole approach, the MNE technique affords greater spatial resolution by assuming a continuous distribution of dipolar sources along the cortical surface (Hämäläinen and Sarvas 1987; Lalancette et al. 2011), which are anatomically constrained using a realistic model of the head constructed from each participants' high-resolution MRI. The merit of realistic head models, when contrasting the ECD and distributed source modeling techniques, is highlighted by the need for localization accuracy. For example, using the ECD approach, spherical head models are generally suited for modeling activity sources, with relatively high accuracy, in regions where the skull can be approximated by a sphere (e.g., primary sensorimotor cortex). However, in regions where the skull surface does not assume a spherical curvature (e.g., basal temporal cortex), better localization may be achieved by better demarcation of boundaries between tissues of different conductivity.

Solving the inverse problem using the MNE method (and distributed source models in general) initially requires the construction of a cortical surface model based on individual brain anatomy. Specifically, the surface model is created using automated extraction techniques that generate a detailed geometric description of the gray-white matter boundary of the neocortical mantle. For each of the cerebral hemispheres, a regular tessellation of the cortical surface consisting of approximately 150,000 (depending on the individuals' cortical surface area) equilateral triangles known as vertices is created. Actual estimation of the activity sources is derived by defining a solution source space, using a grid-spacing of several millimeters, to model each vertex (cortical patch) as a potential current dipole perpendicular to the cortical surface. The inverse solution is subsequently reduced to obtaining an estimate of the scalar distribution of dipole strength across activity sources within orientation-specific vertices (Dale and Sereno 1993). Similar to the single equivalent current dipole method, the spatial extent of the activity sources is defined with reference to a Cartesian coordinate system, by coregistering each MEG dataset with its corresponding MRI.

As an alternative to the single equivalent current dipole model, the MNE method offers several advantages for reconstructing sources associated with surface-recorded magnetic flux, including: (1) taking into account the complex cortical geometry; (2) greater spatial resolution and sensitivity to sources generating non-dipolar patterns at the scalp surface; and (3) an automated approach to signal reduction and analysis across participants. In a similar vein, complementary approaches to source analysis of electromagnetic data have also contributed to understanding the neural basis of linguistic processing. For example, the adaptation of beamforming techniques operating in the time-frequency domain have allowed for the visualization of brain networks underlying reading based on quantification of cortical oscillatory dynamics (e.g., Salmelin and Kujala 2006; Kujala et al. 2007). Nevertheless, it should be noted that these alternative methods are still fundamentally prone to the inverse problem, and have yet to be subjected to external validation against the "gold standard" invasive methods. However, a growing trend for adopting such methods has highlighted their utility in basic research, and examples of their application to reading and reading disability are subsequently provided.

3 MEG Studies with Clinical Populations

The MEG data acquisition and analysis protocols for obtaining the outline of the cerebral mechanisms that support simple sensory and motor functions, as well the mechanisms that serve more complex (e.g., linguistic) functions, have largely been developed in parallel with clinical applications. Some of these applications comprise mainly diagnostic procedures, such as the localization of epileptogenic foci in patients with medically intractable forms of epilepsy prior to undergoing resective surgical treatment. These procedures have obvious clinical utility as non-invasive brain imaging procedures (see for instance Pataraia et al. 2004; Mamelak et al. 2002; Knowlton et al. 1997; Bowyer et al. 2003)., Nevertheless, results obtained in the context of these applications contribute to the reliability, validity, and practicality of MEG as a research tool in the field of developmental psychology (for a detailed review of clinical applications Papanicolaou 2009). One of the most prolific field of MEG studies has been the investigation of the brain mechanisms that support reading in typical and struggling readers.

3.1 Applications of MEG to the Study of Reading Difficulties

Function-specific activation patterns have been used to explore possible differences in brain mechanisms of particular functions in groups of individuals that differ with respect to some prominent psychological characteristic, such as reading or math ability. MEG is very suitable for studies with young children because the participant is not constrained into a tube as in fMRI and movement artifacts are minimized by simply rejecting segments of contaminated magnetic activity from further processing. However, the limited availability of MEG in the past has restricted the number of studies addressing developmental issues. Successful attempts to use the method for addressing developmental issues related to reading acquisition are briefly reviewed.

3.2 The Neurobiological Substrate of Reading in Children and Adults

For neuroimaging data to become relevant to reading development, one must establish links between behavioral/cognitive processes and those neural systems that support these processes. It is therefore of utmost importance that neuroimaging research is informed by cognitive-behavioral research from the outset. Behavioral studies have characterized critical cognitive processes necessary to acquire fluent reading, and how these processes are altered in struggling readers. The core difficulty in word level reading disability (RD, the most common kind of reading disorder;

Fletcher et al. 2007), manifests itself as a deficiency within the language system and, in particular, a deficiency at the level of phonological analysis. To learn to read words, a child must first develop an appreciation of the segmental nature of speech and come to realize that spoken words are composed of small segments, or phonemes. This appreciation of the segmental nature of speech is termed *phonemic awareness*. Subsequently, the beginning reader must understand that written words possess an internal phonological structure that can be deciphered based on their understanding of the internal structures of the spoken word. It is phonemic awareness and the understanding that the constituents of a printed word – its letters – bear a relationship to phonemes that allows the reader to connect printed words to the corresponding words in his/her speech lexicon. As many studies have shown, phonemic awareness is deficient in RD children and adults who, as a consequence, have difficulty mapping the alphabetic characters of print onto the spoken word (Brady and Shankweiler 1991; Rieben and Perfetti 1991; Shankweiler et al. 1995; Fletcher et al. 2007). With experience, word reading becomes automatic and decoding occurs without conscious effort as the proficient reader develops representations of words at a neural level.

According to a popular theory of the brain mechanisms supporting skilled word recognition, access to word-like representations of printed stimuli relies heavily upon a ventral circuit, consisting primarily of ventral occipito-temporal regions and the middle temporal gyrus, when the stimulus is familiar and task demands are appropriate (Pugh et al. 2000). Notably, activity in ventral association areas takes place early during reading (Breier et al. 1998, 1999b; Simos et al. 2009). Conversely, the mechanism that supports reading relies more heavily upon a dorsal system (consisting of the superior temporal, supramarginal, and angular gyri) and an anterior component (in the inferior frontal gyrus), especially when the stimulus is novel or low frequency (Pugh et al. 2000). This functional differentiation within the brain mechanism for reading corresponds to some extent to the two routes of classical dual route theory (Coltheart et al. 1993). Direct evidence supporting the critical role of the dorsal system, at least for sublexical phonological analysis, comes from an electrocortical stimulation study (Simos et al. 2000a) where it was seen that electrical interference with a small portion of the posterior superior temporal gyrus consistently impaired the patients' ability to decode pseudowords.

MEG has been employed successfully in the area of reading development and reading disability. Regions that consistently show increased levels of activation in typically developing readers (non-impaired readers-NI) during decoding tasks include the following (listed by order of peak latency): the primary visual cortex (initial visual analysis of print), ventral occipito-temporal areas (association visual cortex), inferior parietal (angular and supramarginal gyri) and superior temporal cortex, and the inferior frontal gyrus (Simos et al. 2001, 2011). With the exception of primary visual cortex, where activation is noted bilaterally, activity in all other areas is stronger in the left hemisphere in the majority of fluent readers who have never experienced difficulties in learning to read, regardless of age. During performance of tasks involving word recognition, posing increased demands for retrieval of word forms, increased activation in parts of the middle temporal gyrus and mesial temporal cortex (hippocampus and parahippocampal gyrus) is also noted (Simos et al. 2001; Rezaie et al. 2011).

3.3 Altered Brain Circuits in Reading Disability

There are clear functional differences between readers who never experienced problems in learning to read and individuals who are reading disabled (RD), with regard to several components of the brain mechanism for reading. Based on results obtained using the single equivalent current dipole model, the most prominent finding in RD children is reduced activation of the left superior temporal and inferior parietal cortices, especially in tasks where phonological processing demands are high (Simos et al. 2000b, c, 2002a). The suspected functional deficit in posterior left hemisphere circuits was observed with a high degree of consistency, on a case-by-case basis, as suggested by the review of MEG data from a large series of children with severe reading difficulties (Papanicolaou et al. 2003). Evidence for reduced engagement of additional components of the brain mechanism, which normally supports reading, is also found, albeit less consistently in RD children. These include the angular gyrus and the ventral occipito-temporal region (Simos et al. 2007a).

Reduced activity in left hemisphere circuits for reading is typically accompanied by increased activity in brain areas that are not typically indispensable components of the reading mechanism, namely right temporoparietal regions and the inferior frontal gyrus bilaterally. Although frontal activity is observed in NI readers as well, it can be distinguished from the activity that is typically found in RD readers because it is disproportionate in magnitude to the (already reduced) activation in temporoparietal regions and it occurs much earlier during stimulus processing than in NI readers (Simos et al. 2007a, b). The aberrant profile of brain activation associated with decoding is detectable as early as the end of Kindergarten in children who have not reached important milestones in learning to read (Simos et al. 2005).

Further insight into the organization of the neural circuits underlying reading ability has been gained through more recent MEG studies of NI and RD students, with emphasis on the adoption of distributed source modeling techniques (MNE), adequate sample diversity (in terms of socioeconomic status, general intelligence, AD/HD co-morbidity), and modifications in task demands. For example, a recent study (Rezaie et al. 2011) included a large, representative sample of typical ($n = 40$) and struggling readers ($n = 44$) matched on age, gender, ethnic background and general cognitive ability. A higher density gradiometer MEG system was employed ensuring adequate spatial sampling of surface magnetic gradients. MEG recordings were obtained during a continuous visual word recognition task (involving silent reading), the level of difficulty of which was titrated from our earlier studies cited above (Simos et al. 2000b) to ensure comparable levels of performance across groups. Results partially replicated and extended previous reports (Booth et al. 2007; Pugh et al. 2008; Shaywitz et al. 2002; Simos et al. 2000b) regarding the nature of the functional disruption of the brain mechanism for word reading in RD. Relative to the strong lateralized differences reported in earlier MEG studies, findings from thislarger-scale investigation found that children with RD showed decreased degree of neurophysiological activity in the posterior temporal lobe regions

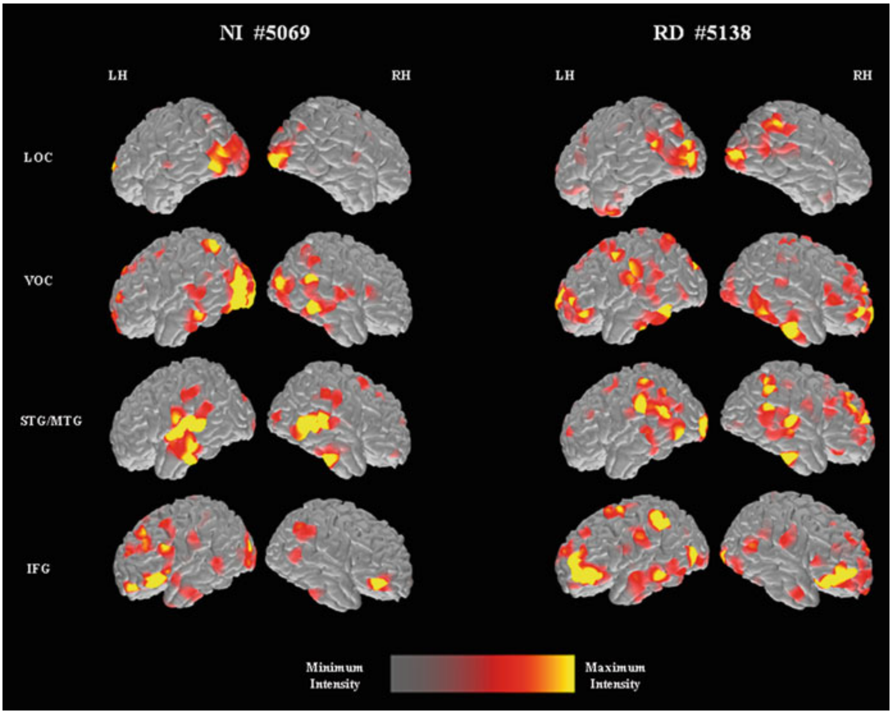

Fig. 3 Successive brain activation snapshots in response to printed words (word recognition task) from two representative participants (a student from the NI group (*left* pair of columns) and a student with reading difficulties (*right* pair of columns)). Each set of *right* and *left* hemisphere images was taken near the peak of activity in one of the following regions: lateral occipitotemporal (LOC), ventral occipitotemporal (VOC), superior/middle temporal (STG/MTG) and inferior frontal (IFG). *LH* and *RH* indicate the left and right hemispheres, respectively (Rezaie et al. 2011)

(superior and middle temporal gyri) bilaterally, during late phases of word reading (see Fig. 3). Moreover, while a previously-reported bilateral increase in activation of the prefrontal cortex was replicated in this larger and more diverse sample, we also detected overactivation of the mesial and ventral occipito-temporal regions in the RD group. Similar to the posited compensatory mechanisms thought to be associated with increased prefrontal activity in struggling readers, overactivation in the mesial temporal regions may reflect additional demands for both encoding and retrieval operations posed by the continuous word recognition task. Increased activation in ventral occipito-temporal cortices could be associated with the need to maintain orthographic representations of target words throughout task performance, reflecting greater reliance on a visual/orthographic strategy for encoding and recognition of the printed word stimuli. An extension of the current knowledge regarding the functional organization of cortical networks for impaired reading is manifest in the pattern of associations between the degree of regional neurophysiological activity and performance on standardized measures of reading/spelling ability (Fig. 4; see also Simos et al.

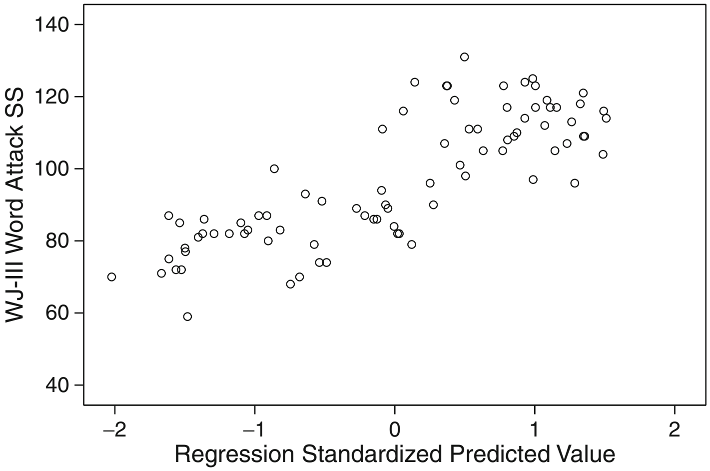

Fig. 4 Linear regression plot of Word Attack scores (WJ-III) scores over a combination of MEG variables representing degree of activity in left posterior and mesial temporal cortices during performance of the visual word recognition task among NI children. Similar associations were found between degree of activity in these regions and standardized measures of word-level reading and spelling ability (Rezaie et al. 2011)

in the same volume). Specifically, whereas the degree of activity in left posterior temporal regions was a significant positive predictor of reading and spelling skill among NI readers, this relation was absent in RD children. Instead, this group displayed a significant negative association between degree of activity in right hemisphere homologous areas and prefrontal regions, and achievement scores.

In light of the aforementioned methodological developments, replicating and extending previous MEG findings of altered brain circuits in RD has generated further evidence regarding the nature of the core deficits in struggling readers, including the impact of attention-deficit/hyperactivity disorder (AD/HD) comorbidity. Findings from a second recent study (Simos et al. 2011) investigating group differences in brain activation profiles of typical (n = 50) and struggling readers (n = 70) on tasks varying on explicit phonological decoding demands (letter-naming and pseudoword reading) concur with our earlier MEG studies in demonstrating that children with RD exhibit a marked reduction in the degree of activity in the left inferior parietal region (supramarginal and angular gyri), relative to the NI readers. These effects were restricted to the more demanding pseudoword reading task and were more prominent during late stages of stimulus processing as shown in the time-plots in Fig. 5. In agreement with previous MEG studies employing phonological decoding tasks (Simos et al. 2000c, 2007a), was the profile of hemispheric laterality for activity in the inferior parietal cortex, where the robust leftward asymmetry exhibited by NI children in this region was contrasted by bilaterally symmetric degree of activity in RD students. Activity-performance correlations shed more light onto the role of regional activity in each group for decoding ability. As demonstrated graphically in the regression plots of Fig. 6,

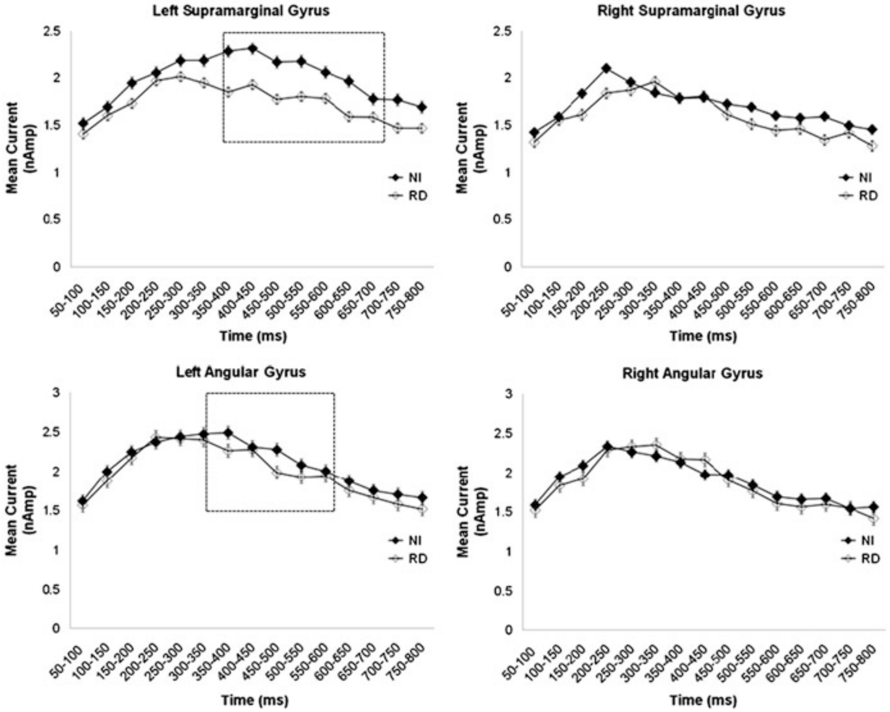

Fig. 5 Time plots of the degree of estimated neurophysiological activity associated with oral pseudoword reading where significant group differences were found between NI and RD children. Stimulus onset is at 0 ms. Time windows of significant group differences are marked by *squares* (Simos et al. 2011)

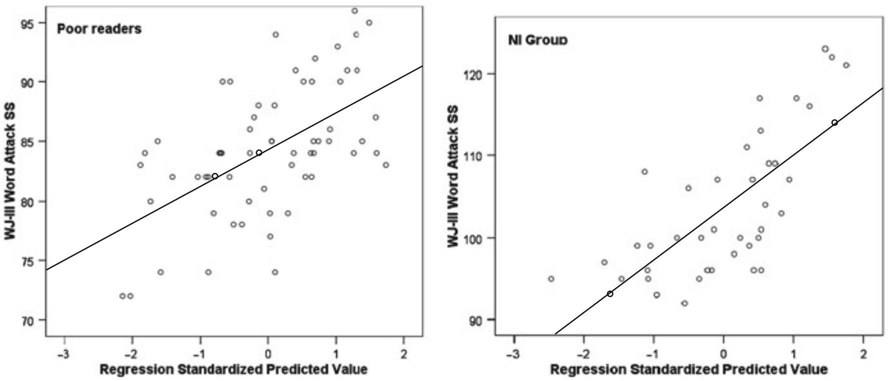

Fig. 6 Regression plots of Word Attack scores (WJ-III) over a linear combination of MEG variables for RD (*left panel*) and NI students (*right panel*). For NI readers (n = 50) significant *positive* predictors of decoding ability included degree of activity in *left* hemisphere regions (inferior parietal cortex, superior temporal, inferior frontal, and fusiform gyri) and peak latency in the left fusiform gyrus. Conversely, increased activity in *right* hemisphere regions (inferior parietal cortex, inferior frontal, *middle* temporal, inferior frontal, and fusiform gyri) was associated with *lower* Word Attack scores among poor readers (n = 70) (Simos et al. 2011)

strong decoding ability was predicted by high levels of neurophysiological activity in *left* hemisphere superior temporal, inferior parietal, inferior frontal, and ventral occipito-temporal regions. In sharp contrast, high levels of activity in *right* hemisphere homologous regions appeared to be detrimental to decoding ability among RD individuals.

As well as evidence of replicability, a significant finding from this study is that the aberrant pattern of regional activity observed among RD students was not found among children with AD/HD and average to above-average reading skills (n = 20). This latter observation is particularly revealing given the substantial comorbidity between RD and AD/HD in the school-age population (Pennington 2008). Indeed, despite variability in their cognitive correlates (Bonafina et al. 2000; Laasonen et al. 2009; Willcutt et al. 2007), it has been acknowledged that there exists a genetic overlap in the heredity of the two disorders (Pennington et al. 2009).

However, current findings suggest that aberrant brain activation patterns are largely dependent upon demands for explicit phonological decoding and independent from commonly encountered comorbidities between RD and AD/HD, consistent with a large number of behavioral studies (Pennington 2008).

3.4 Reading Intervention Studies

If the left temporo-parietal region plays a key role in normal reading acquisition, and atypical engagement of this region accounts, at least in part, for pervasive reading difficulties in the majority of RD cases, one would predict that successful remedial instruction would impact on the timing and/or degree of temporo-parietal activation. This issue has been examined in several MEG studies.

In the earliest study (Simos et al. 2002a), eight children with very severe reading difficulties underwent a brief but intensive remediation program, focusing on the development of phonological awareness and decoding skills. The intervention was performed on a one-to-one basis for 2 months (approximately 80 h of instruction). The most salient change observed on a case-by-case basis was a several-fold increase in the apparent engagement of the left temporoparietal region, accompanied by a moderate reduction in the activation of the right temporoparietal area. Although results confirmed the prediction regarding the critical role of left temporoparietal cortices in acquiring adequate decoding skills in RD, the relatively small surface-spatial sampling capacity of the neuromagnetometer used the study, in conjunction with the limitations of the ECD model of magnetic source localization, precluded a more thorough evaluation of intervention-related changes in additional components of the reading mechanism.

More recently, these initial findings were extended to a larger group of 15 children who showed severe difficulties in reading despite adequate exposure to the alphabetic principle in the regular classroom (Denton et al. 2006; Simos et al. 2007a). In this study, brain activation profiles were obtained with a higher density neuromagnetometer that afforded greater sensitivity for detecting less prominent activity sources (such as those in the angular gyrus and inferior frontal cortex). MEG scans were registered during performance of an oral reading task involving three-letter pseudowords (i.e., KAK), placing explicit demands for phonological decoding. Each participant was assessed three times: (1) baseline, (2) following completion of an 8-week small-group remedial program focusing on the development of phonological awareness and decoding skills (Phono-Graphix administered for 2 h daily; McGuinness et al. 1996), and (3) at the end of a subsequent 8-week program targeting reading fluency (based on the Read Naturally program; Ihnot et al. 2001), administered for 1 h each day of the week.

Baseline scores on standardized reading tests showed group mean performance that was at least 1 standard deviation below average on measures of word and pseudoword reading accuracy and efficiency. At baseline participants showed brain activation profiles typical of RD children, consisting of early activity in occipito-temporal regions, followed by activity in bilateral dorsolateral prefrontal and premotor regions. Activity in temporoparietal regions was noted much later (typically between 500 and 700 ms after stimulus onset) which either lasted longer in the right hemisphere or was bilaterally symmetric in duration (or degree).

The 16-week intervention resulted in significant improvement in word recognition and decoding, fluency, and comprehension for eight children (Adequate Responders), demonstrating a mean improvement on the Basic Reading Composite of 15 ± 3 points (range: 11–19.5 points). The remaining seven students demonstrated smaller gains (4 ± 3 points on average: Inadequate Responders). Brain activation profiles of Inadequate Responders were essentially identical to those obtained at baseline. For Adequate Responders, post-intervention results were consistent with both normalizing and compensatory changes in the brain activation profiles. Normalizing changes consisted of an increase in the degree of activity in left temporoparietal regions, a parallel reduction in the onset latency of activity in the same region, and an increase in the onset latency of activity in inferior frontal regions. Following these latency changes the relative timing of activity in the left temporoparietal area and inferior frontal cortex became similar to that observed in NI readers. Compensatory changes, consisting of smaller-scale increases in right superior temporal and bilateral inferior frontal activity, were observed less consistently across participants (in 30% and 60% of cases, respectively).

Spatiotemporal profiles from the same group of participants during an externally paced word reading task (Simos et al. 2007b) were also obtained at each of the three testing sessions described above. The stimuli were high frequency words of the sort that most students are regularly exposed as sight words. At baseline the spatiotemporal profiles of activity preceding the pronunciation of sight words featured, again, early activation of occipito-temporal regions followed by prominent activity in the right middle temporal gyrus and dorsolateral prefrontal and premotor cortices, bilaterally. Activity was observed last in the superior temporal gyrus bilaterally and in the left middle temporal gyrus. As our word reading task did not make significant demands on phonological decoding, increased relative activation of the middle temporal gyrus, than in the superior temporal and supramarginal gyri, was expected (Damasio and Damasio 1989; Fiebach et al. 2002; Hagoort et al. 1999; Roux et al. 2004; Simos et al. 2002b, 2009; Turkeltaub et al. 2002).

Significant changes in the duration and relative timing of regional activity following intervention consisted of: (1) increased degree (or total duration) of neurophysiological activity in the posterior portion of the middle temporal gyrus bilaterally, (2) decreased onset latency of activity in the left middle temporal gyrus and in the right occipito-temporal region, and (3) increased onset latency of activity in dorsolateral prefrontal and premotor regions. The combined changes in frontal and temporal lobe onset latencies resulted in activation profiles resembling those typically found in average readers. It is of particular interest that systematic individual variability in the duration and onset of activity in brain regions "normally" involved in the circuit for reading was again a positive predictor of reading accuracy measures: the greater the duration of neurophysiological activity in the posterior portion of the middle temporal gyrus in the left hemisphere and the earlier the onset of activity in visual association areas the higher the reading performance following intervention. Conversely, earlier onset of activity in "compensatory" components of the brain circuit for reading (inferior frontal regions) was associated with lower the performance on these measures.

These recent intervention studies corroborate previous MSI and fMRI findings (Eden et al. 2004; Meyler et al. 2008; Shaywitz et al. 2004; Simos et al. 2002a; Temple et al. 2003) in showing that completion of an intensive instruction program focusing on the development of phonological awareness and decoding skills was accompanied by increased neurophysiological activity in temporo-parietal cortices in the left hemisphere. Importantly, results provided additional support to the crucial role of left temporo-parietal regions in reading acquisition by showing that increased activity in this area accompanies successful remediation of RD. Increased activity in other areas following such training are sometimes observed, but don not appear to be sufficient to support the development of an effective brain mechanism capable of supporting skilled reading. Another important conclusion that stems from recent MEG studies on reading and RD is that the precise nature of aberrant features of the activation profile in RD depends to a certain extent upon specific task demands.

4 Conclusions

As a functional brain mapping technique, MEG represents a suitable alternative to neuroimaging methods that rely on hemodynamic correlates of brain activity for the purposes of outlining the spatial and temporal characteristics of cerebral mechanisms that mediate language and other cognitive, motor, and sensory functions. Furthermore, in contrast to other non-invasive brain mapping modalities, the reliability and validity of MEG as a tool for studying the neurophysiology of language has been established against routine clinical invasive procedures, recognized as the "gold standard" techniques for lateralizing and localizing brain activity associated with language function.

MEG is a technique that holds great value for developmental neuroscience. Brain function in children as young as 5 years old can be studied reliably with MEG, yielding results of both theoretical and practical significance. MEG studies of reading development in children have revealed activity in areas of the brain which appear to be critical for the acquisition of reading skills. Researchers have shown with MEG how brain mechanisms for reading differ in children with RD when they attempt to read words and in what ways these mechanisms may be altered following behavioral intervention and remediation. The sensitivity of MEG to these changes highlights its potential to be used, along with cognitive assessments, to determine which children may be at greatest risk for reading impairment later in development, and those who may benefit most from remediation.

However, it should be noted that MEG is not without some practical limitations. For example, high operating costs still prohibit widespread application of this technology, unlike relatively affordable contemporary brain imaging approaches such as EEG and functional MRI. Furthermore, the special recording environment necessary to carry out experimental MEG procedures may be equally challenging for testing pediatric populations. Similarly, the portability of modern EEG systems may facilitate testing, particularly given their increasing use in the school environment, a feature not suited for MEG.

The potential applications of MEG in developmental neuroscience are significant. The research described herein represents just the beginning of the knowledge that can be gained about the developing brain. Not only will MEG research continue to serve the interests of academics in understanding normal and aberrant development of brain function, but it will continue to provide clinical and practical benefits for individual patients.

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Imaging Studies of Reading Disabilities in Children

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1 Imaging Studies of Reading Disabilities

Event-Related Potentials (ERPs) have a long history as a scientific tool in psychology and there has been an explosion of interest in using ERPs to identify differences between children with reading disabilities (RD) and typically developing (TD) children. This chapter covers (1) a brief overview of ERPs; (2) some of the difficulties studying RD; (3) a summary of studies using ERPs to investigate reading disabilities in children; (4) how additional forms of neuroimaging have been used to identify neural correlates of response to intervention (RTI); and (5) future directions for ERP research as demonstrated from a recently submitted study using ERPs to study RTI. Additionally, a more detailed presentation is included of how RD studies have changed over time, and some of the next steps in research of RD using ERPs and other imaging modalities.

In addition to the various methodological differences across studies in the reading and reading-like tasks used to elicit the ERPs, there has been a corresponding progression in the portions of the ERPs used to index group differences in reading. In general, early studies of RD targeted their analyses of ERPs at the beginning of the wave (shorter latencies) but as tasks became more involved, the regions of interest moved towards the end of the waveform (longer latencies). The original work on the use of ERPs to study RD first looked towards exogenous components in search of a sensory deficit or developmental lag as the mechanism underlying deficits in learning to read. Later research shifted to investigating the shape and speed or latency of ERPs generated when children attempted to read, rhyme, or recognize words and pseudowords, as they would when actually reading. This work led to a plethora of work on differences between typically developing children and children with RD and exciting findings.

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2 ERP Background

The ERP is a portion of the ongoing electroencephalograph (EEG), time-locked to the onset of a stimulus. ERPs are usually recorded from electrodes placed on the scalp. Electrodes are used to pickup the small voltages of electrical activity in the brain that crosses the scalp measured in microvolts (μV). These small voltages are then amplified and recorded by a computer.

The ERP is composed of a series of peaks and valleys; each peak is labeled by its polarity (positive or negative) and either the latency (P100; being the positive peak occurring at approximately 100 ms after stimulus onset, N100 being the negative peak occurring at approximately 100 ms after stimulus onset, and so forth) or the number of peaks since stimulus onset (P1; being the first positive peak identified after stimulus onset, N1 being the first negative peak after stimulus onset, and so forth). The ERP is usually divided into endogenous or exogenous components (Fabiani et al. 2000). Figure 1 shows a generic ERP waveform with both naming conventions. Exogenous components occur earlier in the waveform and have been shown to modulate activation based on the characteristics of the stimuli. As such, they are sometimes referred to as "Sensory Components." Endogenous components occur after the exogenous components and are thought to reflect the cognitive processes involved with evaluating and interpreting the incoming stimuli (Picton et al. 2000). For example, the P300 (an endogenous component) is evoked by an "oddball" paradigm in which participants are asked to identify a target stimulus amidst a presentation of distracter stimuli (Sutton et al. 1965). Depending on the study, researchers consider the influences of both endogenous and exogenous components of ERP. For a full review of ERP components and theoretical meanings associated with each ERP component, see Key et al. (2005).

The ERP can be influenced by a number of methodological variables, such as the type, number, and placement of electrodes, amplifier filter settings, and recording equipment (see Picton et al. 2000). First, the choice of electrode sites is often based on theoretical areas of interest. Individuals recording ERPs of language stimuli (such as speech sounds or words) may focus on the temporal lobes where anatomical, behavioral and theoretical papers have located several primary language processing sites, while researchers using visual stimuli might focus on scalp areas over the occipital lobe based on anatomical data in vision. While electrodes placed at these sites may inform research questions about these specific scalp regions (and possibly the underlying brain sources), it is also important that electrodes be arranged in other regions so that information critical to interpreting this and other brain activity is not missed. In an attempt to standardize electrode placement, the 10–10 and 10–20 systems for electrode placement are used across studies (American Electroencephalographic Society 1994; Jasper 1958). Still, these standard "montages" of electrode placements are just guidelines for where electrodes should be placed, and they do not specify the number of electrodes to use for each experiment. Due to the costs of electrodes, amplifiers, and the normal progression of technology, many older studies have relied on only a few electrodes strategically

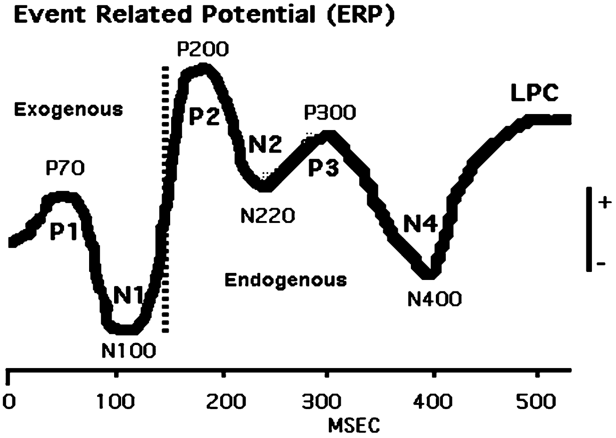

Fig. 1 Exemplar of ERP waveform (Image created by Dr. Dennis Molfese, used with permission)

placed over regions of interest. However, more recent studies may employ larger electrode arrays of 64, 128, or 256 electrodes (see Tucker 1993). This increase in electrodes has allowed researchers to quantify more of the scalp topography, which corresponds to the underlying neural processes. In essence, the added information can be used to more accurately identify and quantify the underlying processes of the brain.

Second, each electrode array, regardless of number, is also “referenced” to another electrode. The amplifier measures the difference between a particular electrode and its reference. The choice of reference site is important and can greatly influence the shape, size, and even polarity of ERPs at sites across the scalp. Many older studies have used linked-ears references or linked-mastoid reference, which was believed to be the best reference location. However, problems have now been recognized and reported with these references (Picton et al. 2000), and it is now recommended that researchers use a single reference electrode or an average reference (Dien 1998).

Finally, the characteristics of the filters used for both recording of ERPs and later data analysis can influence the latency, amplitude, and in some cases the existence of difference peaks and components. There are three common classes of filters: high-pass (also called low cutoff), low-pass (also called high cutoff), and notch filters. High-pass filters allow frequencies above a particular setting to pass through the filter; low-pass filters allow frequencies below the filter setting to pass through the filter; and notch filters are typically set around a single frequency, such as 50 or 60 Hz, to reduce the contribution of artifacts (such as electrical noise in that frequency range) to contaminate the ERP. Some authors use the term “bandpass filter” to show the range of signals allowed to pass through a set of filters, for example a bandpass filter of 0.1–30 Hz allows frequencies between 0.1 and 30 Hz to pass through and be recorded while attenuating or eliminating frequencies outside of the range (for full review of digital signal processing, see Smith 1997; for implications of filters used on ERP data see Nitschke et al. 1998).

Unfortunately, researchers using ERPs to investigate RD (and many other phenomena) have been highly variable in their use of type and number of electrodes, reference sites, and filter settings. Despite these methodological intricacies, ERP research has and continues to show reliable findings in a number of fields of study.

3 Difficulties Studying RD

A major issue concerning research on RD is how to define the disorder. As ERPs have evolved over time to better evaluate research questions, the definition of RD has also been changing. As outlined by Fletcher et al. (2007), there have been several models for identifying learning disabilities: The aptitude-achievement discrepancy, which focuses on differences between IQ and reading ability; Low achievement models, which focus entirely on measures of reading ability; The intra-individual model, which looks at profiles of strengths and weaknesses in cognitive skills; and Response to Intervention (RTI) model, which focuses on identification of children whose response to reading intervention is below an expected level. Each of the studies reviewed in the next sections uses one of these models for identification and classification of children with RD; these RD groups are then compared with groups of typical readers.

One of the weaknesses of the ERP research on RD has been the lack of a clear definition of RD. As described above, there are at least four ways of identifying children with RD. Within each of the studies reviewed below, different researchers have categorized children with RD differently, and sometimes without justification. For example, some studies identify children with RD as dyslexic, without identifying whether the children meet the specific criteria for dyslexia. Dyslexia is a word reading disorder and may be associated with RD, but children with RD do not necessarily meet criteria for a diagnosis of dyslexia. Other studies use definitions based on reading comprehension abilities; still others simply use a clinical diagnosis. This information shown in Table 1 is included for reference as the population of children with RD is heterogeneous and definition used to identify children may vary, which may impact the results of a given study.

4 ERPs and Reading Disabilities

The study of RD using ERPs begins with the examination of the sensory or exogenous components, which are those components occurring earlier in the waveform, and thought to be modulated by stimulus characteristics (Picton et al. 2000). For example, the N1 component can be modulated by the intensity of auditory stimuli, where louder stimuli produce a larger N1 ERP component. The P1 (P100), N1 (N100),

Table 1 Comparison of ERP studies investigating differences between children with dyslexia, reading disabilities, and typically developing children

Author (year)	Paradigm	Age	Number of electrodes	LD/RD discrim	ERP peaks
Ackerman et al. (1994)	Rhyming tasks	7.5–12 years	8	WISC-R and WRAT-R	N450, P500, Negative slow wave
Bergmann et al. (2005)	Letter and word	13–14 years	12	Sentence reading task	N220, P310, N400
Bernal et al. (2000)	Auditory oddball	10–12 years	19	Low achievement academically	P200, N200
Bonte and Blomert (2004)	Rhyming tasks	7.5–9.5 years	29	Assessment at Regional Institute of Dyslexia	N150, N300
Conners (1971)	Visual flashes and patterns	Children and adults	5	GORT or school referral	P140, N200
Dainer et al. (1981)	Letter and word	11.1–15.3	2	Psychoeducational battery, 1.4 years below grade norms on reading or math	Late positive component
Holcomb et al. (1985)	Letter and word	8.0–12 years	5	UAMS Child Study Center evaluation	P300
Lovrich et al. (2003)	Rhyming tasks	11.1–13.6 years	15	WJ word attack or passage comp at least 1 SD below	N270, P450
Molfese et al. (2006)	Letter and Word	9–12 years	128	Word recognition and reading skill	N200, P300
Preston et al. (1974)	Light flashes, word “cat”	9 years	5	PPVT and reading level	N180, P200
Regtvoort et al. (2006)	Black and white patterns	8 years	32	Family history of dyslexia	N1, P300
Robichon et al. (2002)	Sentence tasks	Adults	6	Familial history, WISC, previous diagnosis	N400
Rodriguez et al. (2006)	Sentence tasks	4–6 grade	19	One level below current on accuracy and speed in word reading, grammar, comprehension, rapid naming	N400, P600
Shucard et al. (1984)	Probe paradigm	7 years, 11 months–16 years, 11 months	3	School referral	Auditory evoked responses
Symann-Louett et al. (1977)	Letter and word	Average age 12.3 years	8	Two grade levels below on reading	# peaks between 0 and 200 ms and # of peaks between 200 and 350 ms
Taylor and Keenan (1990)	Auditory oddball	7–12 years	15	1 SD below in reading, assessed by Child Development Clinic	N200, P300
Weber and Omenn (1977)	Light flashes	Families, children 8–17	2	Slingerland screening, academic records, word list reading, parent interviews	N1, P2

P2 (P200) and N2 (N200) all have been identified as exogenous components (Key et al. 2005). Paradigms used to elicit exogenous components in the RD literature have used a series of light flashes or checkerboard pattern presentations.

ERP studies investigating differences between children with RD and normal control children have had mixed success using sensory components. Due to the limited sampling sizes in early studies, differences in defining a sample of children with RD, the restricted number of electrodes and processing routines, it is difficult to come to definitive conclusions about the sensory components as a measure for differentiating typically developing children from children with RD. For example, Conners (1971) and Preston et al. (1974) reported smaller amplitudes in sensory components (P140, N200, P180, N200; see Table 1) were evoked using light flash stimuli for children with RD, while Weber and Omenn (1977) found no differences between the groups using similar stimuli. Conversely, Bernal et al. (2000) and Regtvoort et al. (2006) found amplitude differences between groups, showing that children with RD had larger amplitudes than TD children using black and white pattern flashes. Regtvoot et al. also found some latency differences in the N100 and P300 between groups, indicating that typically developing children showed shorter latencies than children with RD. While there are methodological differences between these studies, the array of differences (or lack of differences) between TD children and children with RD highlights the inconsistent nature of studying the sensory components and question whether the hypothesis that children with RD have a sensory deficit.

While studies which have focused on the sensory components of the ERP have shown mixed results, much of the more recent ERP literature has focused on how typically developing and children with RD read words and how the underlying processes (as reflected in the ERP) differentiate the groups. From this work, several key findings are evident: (a) children with RD may produce more distinct ERP peaks (see Table 1) than typically developing children (Symann-Louett et al. 1977), and the peaks produced are often larger over the left hemisphere than peaks found in typically developing children (Bergmann et al. 2005); (b) some studies report that children with RD show larger amplitudes earlier in the waveform (P200), while TD children show larger amplitudes later in the waveform (N400; Stelmack et al. 1988); (c) children with RD may be processing word stimuli more in the right hemisphere than in the left hemisphere (Shucard et al. 1984); and (d) typically developing children show faster latencies in ERP components and larger P300 responses (Dainer et al. 1981; Holcomb et al. 1985; Taylor and Keenan 1990).

Going beyond simple word reading, recent studies have looked at rhyming of words, by serially presenting one word followed by another word and asking participants to identify whether the two words rhymed or did not rhyme. The rhyming tasks require both decoding and increased phonological processing beyond word recognition. Studies using this paradigm have shown (a) smaller left hemisphere amplitudes (N270, N450, P500; see Table 1) in children with RD (Ackerman et al. 1994; Lovrich et al. 2003; Molfese et al. 2006); (b) stimuli effects detected in later components (e.g. N450 vs. Nslo; Ackerman et al. 1994) for both groups; (c) children with RD did not produce an "alliteration effect" to rhyming words, which would show smaller N100 peaks to rhyming words when compared to non-rhyming words (Bonte and Blomert 2004); (d) shorter latencies and smaller amplitudes for more proficient readers (Molfese et al. 2006). The significance of these studies is greater than just increased processing of presented words. Rather, the paradigms utilized are thought to involve different processing centers in the brain including the temporo-parietal and inferior frontal gyrus for slow processing of words and phonological recoding (Pugh et al. 2001, 2008).

More recent studies of children with and without RD have used even more demanding tasks involving sentences. The N400 component was found to be enhanced after reading sentences that had semantic violations, or unexpected (incongruent) endings (Kutas and Hillyard 1980). Similarly, the P600 was found to reflect syntactic processing (Kutas and Hillyard 1983). Results from studies of sentence processing show some mixed results: (a) children with RD do not show a consistent N400 effect (Rodriguez et al. 2006), though adults with a history of developmental dyslexia do (Robichon et al. 2002); (b) The P600 is present for TD children, but not present for poor readers in response to sentences with syntactic violations (Rodriguez et al. 2006). The lack of N400 or P600 effect in children with RD is evidence of a deficit in deeper processing involved in comprehensive reading.

As briefly reviewed above, there were few consistent differences in ERP studies investigating sensory deficits in children with RD. However, studies that used tasks that involved more reading oriented tasks (e.g. word reading, rhyming, sentence comprehension) elicit ERPs do show consistent differences between TD children and children with RD. The ERP results fit into a four categories (a) under activation (smaller amplitudes) in children with RD; (b) over activation (larger amplitudes) in children with RD; (c) a combination of both of these (such as lateralization differences); and (d) missing ERP components or effects in children with RD (e.g. N400). While the reviewed literature represents a subset of studies of children with RD, there are consistent findings of differences between children with RD and typically developing children as measured by ERPs to reading oriented tasks.

5 Studying RD in Response to Intervention

While all previous work has reported individuals identified by discrepancy or low achievement models of identifying learning disabilities, more recent research has focused on the fourth model: Response to intervention (RTI). Intervention involves placing children who are poor achieving in one area into a research-based intervention program, focusing on areas the child is weak in. Work on RTI has been reviewed elsewhere (Fletcher et al. 2007; Fuchs and Fuchs 2006; Justice 2006). To date, there have been several studies that have looked at reading interventions and the changes that occur in the brain by having participants scanned in a pre-post experiment design. Details on interventions used and criteria to define RD are shown in Table 2.

Table 2 Comparison of intervention studies using fMRI and MEG based on sample size, ages, poor reading (or dyslexia) definition criteria, and intervention length

Author (year)	Sample	Age	Poor reading criteria	Intervention
Aylward et al. (2003)	21	10–12.5	Below 1 standard deviation (85) on Woodcock Johnson Word Attack or Word Identification	28 h
Meyler et al. (2008)	28	5th grade	Below 30th percentile on TOWRE SWE and PWE	Approx. 90 h
Shaywitz et al. (2004)	77	6.1–9.4 years	Below 25th percentile on Woodcok Johnson Word Attack or Word Identification	Experimental intervention: Approx. 105 h
Simos et al. (2002)	16	7–17 years	Below 5th percentile basic reading skills cluster	80 h
Simos et al. (2005)	33	5.6–7.2 years	Below 20th percentile word recognition and comprehension	Approx 90 h
Simos et al. (2006)	15	8.6 years	Below 31st percentile word reading, less than 40 words per minute	40 h in addition to previous intervention
Simos et al. (2007)	15	7–9 years 8 months	At least 1 SD below average on untimed TOWRE SWE	120 h
Temple et al. (2003)	32	8–12 years	WJRMT-R, Word Attack or Word Identification less than 85	Approx. 670 h

To date, neuroimaging research studying RTI has been performed using techniques other than ERPs, primarily Magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI). A full review of the technologies behind fMRI and MEG are beyond the scope of this chapter, interested readers are directed to Papanicolaou (1998). Briefly, MEG measures the magnetic fields corresponding to the electrical activity of the brain. These magnetic fields pass through the scalp with little resistance and distortion from the skull and scalp. This low resistance/distortion gives MEG both very good temporal resolution (millisecond accuracy), and good spatial resolution, allowing researchers to identify the sources of activity inside the brain. In contrast, fMRI is a hemodynamic method that records information from the metabolic processes in the brain. fMRI provides for detailed images of both the anatomy and metabolic processes of the brain with high spatial resolution but lower temporal resolution than ERP or MEG

Similar to the ERP studies reviewed above, Prior studies using MEG to identify differences between children with RD and typically developing children show a characteristic brain activation profile that varies with level of reading proficiency. These differences appear as differences in laterality based on reading ability. Children who are at risk for RD tend to show more diffuse activation as well as more activation in the right hemisphere than children who are not at risk for RD. Consequently, children who are not at risk demonstrate much greater activation in the left hemisphere than children who are at risk for RD (Papanicolaou et al. 2003).

Work using fMRI as a tool for exploring language, the development of language, and learning disabilities has been reviewed elsewhere (see Schlagger and McCandliss 2007; Price and McCrory 2005).

In one of the first studies of the relation of neural changes and intervention response, Simos et al. (2002) used MEG to investigate a pseudo-word rhyming task in children both before and after intervention. In a sample of 16 children ranging from 7 to 17 years old, the investigation found differences (lower activation in children with RD) between typical readers and children with dyslexia in the posterior superior temporal gyrus (STGp), inferior parietal areas, inferior frontal gyrus (IFG), and middle temporal gyrus (MTG). A laterality effect was also found, showing that typical readers exhibited more activation in the left hemisphere, when compared to right hemisphere activation, an effect not present in the children with dyslexia. These laterality differences between groups were no longer significant after the reading intervention, a change due to an increase in brain activation found for the children with dyslexia. The authors called this effect a "normalization" whereby children with dyslexia exhibiting one brain activation profile underwent a successful reading intervention (see Table 2) and then generated a brain activation profile more similar to that of the typical readers.

In a later MEG study, Simos et al. (2005) compared poor readers (high-risk) and typically developing (low-risk) children using both a letter-sound task and a pseudo-word reading task. The study included 33 children, ranging in age from 5.6 to 7.2 years old. Results showed that prior to a reading intervention, group differences were located in Temporo-parietal (TMP), IFG, and occipito-temporal (Oc-T). There was also a laterality difference in the TMP region, resulting from typically developing readers showing more left hemisphere activation than poor readers. After intervention, the authors reported that 13 children in the high-risk group were adequately responding to intervention based on reading assessments, whereas three children were classified as inadequate responders. Inadequate responders were not quantified statistically, but little change was seen in MEG activation maps. Comparison of adequate responders and typically developing children showed that after reading intervention, the initial difference in IFG activity was no longer significant, but differences remained in the Oc-T region despite increases in activation in the adequate responder group. Latency differences between the groups were also identified for the Oc-T, TMP, and IFG, whereby after intervention onset latencies in the RD (authors term: high-risk) group were not significantly different from the low-risk group due to decreases in activation latency for the high-risk group. The authors argued that the reduction of differences between groups was due to normalization of the brain following a reading intervention. The remaining differences between the groups, TMP lateralization, and Oc-T activation were identified as compensatory mechanisms.

In two studies using MEG as an investigative tool, Simos et al. (2007) observed brain changes in at-risk readers (7–9 years old) before and after a reading intervention, using both a real-word reading task and a pseudoword reading task. Results after intervention were compared to activation maps before intervention. For the word task, activation in the posterior aspect of the MTG and TMP region increased, latency decreased in left hemisphere MTG, left TMP, and right hemisphere Oc-T, while latency in the dorsolateral prefrontal and premotor cortices increased. In the pseudoword reading task, activity and latency in the left TMP increased. Again the authors noted that these effects were normalizing and bringing the imaging profiles more in line with typically developing children.

Consistent across all three of these MEG studies (Simos et al. 2002, 2005, 2007) are findings that children who improved in reading ability through participation in a reading intervention showed changes in brain activation (summary in Table 2). In Simos et al. (2002) and Simos et al. (2005), children who were previously poor readers generated brain activation patterns similar to those of the typically developing control group at the completion of the reading intervention. Additionally, there is evidence in Simos et al. (2005) of a compensatory mechanism in children who are poor readers after reading intervention whereby activation is present in brain regions that are not active in the typically developing control children. These normalization and compensatory mechanisms are specifically reported in three of the major cortical regions that have frequently been found to be involved in reading: (1) ventral pathway Occipital-Temporal; (2) dorsal pathway (temporo-parietal area, Wernicke's area); (3) left frontal (Broca's area, Inferior Frontal Gyrus, insular cortex). These areas are believed to be involved in visual-orthographic recognition, phonological decoding, and phonological and articulation tasks, tasks reflecting the processes involved in word reading (Perfetti and Bolger 2004; Pugh et al. 2008).

Using fMRI as a tool of investigation, Temple et al. (2003) reported initial group differences between poor readers and typically developing controls using a letter rhyming task with a sample of 32 children, 8–12 years old. The intervention used the Fast ForWord program, a computerized phonological processing intervention. Children who completed the intervention showed increased activation in the left hemisphere's TMP cortex as well as increased activation in the IFG. Additionally, other brain regions that were not active in typical reading children became active in the poor reading group following intervention. These regions included the right frontal gyri (inferior, middle, and superior), MTG, cingulate gyrus, left hippocampal gyrus, left inferior frontal gyrus, and thalamus. Neural changes within poor readers that approach the neural activations of typical reading children suggested that the brain is normalizing over the course of a reading intervention. Additionally, changes to other brain regions that were not active in the typically developing group, such as those noted by the authors near the TMP and IFG, and identical to TD children suggest compensatory mechanisms are also active, similar to those reported by Simos et al. (2005).

Aylward et al. (2003) used both a phonological processing and a morpheme processing task (visual tasks) in combination with fMRI. The sample included 21 children, between 10 and 12.5 years of age. Prior to the reading intervention, typically developing children produced greater activation in the left hemisphere's inferior and middle frontal gyri during the phonological processing task, as well as greater activation in the superior parietal region (which was lateralized with greater left hemisphere activation within typically developing students). These differences were no longer significant following reading intervention due to significant increases in activation in the dyslexic subjects and decreases in activation in the control subjects. Despite all of the changes following reading intervention, the authors note that some differences still existed in the left middle and inferior frontal gyri as well as the left superior parietal lobe. During the morpheme mapping task, initial differences were found in which control subjects exhibited more activation in the right fusiform gyrus and right superior parietal region. Both differences were no longer significant after intervention due to reduction in activation in this area in the typically developing participants. Since this study only reported changes in dyslexic children that matched the control group, the mechanism of change is more normalization than compensatory.

Shaywitz et al. (2004) identified group differences between poor readers and typically developing children using fMRI and a pre-post design with both an experimental and community based intervention compared to a control condition. The sample included 77 children, aged 6.1–9.4 years. Using a cross-modal (auditory-visual) letter identification task, the experimental intervention group showed increased activation in brain activation from pre-intervention levels in the IFG (bilateral), left superior temporal sulcus (STS), Oc-T region and parts of the middle and inferior occipital gyrus as well as the lingual gyrus. The authors identified normalization in the Oc-T and compensatory changes in the right frontal areas.

Meyler et al. (2008) found group differences in areas of brain activation as measured by fMRI between typically developing readers and poor reading 5th grade children (total sample 28 children) using a sentence comprehension task before, immediately after, and 1 year after reading intervention. Before reading intervention, poor readers showed less activation than good readers in the left hemisphere's middle and superior occipital, inferior and superior parietal regions, postcentral gyrus and angular gyrus. Group differences were also found in the right hemisphere's inferior parietal and supramarginal gyrus. Following a reading intervention, most of these group differences became non-significant due to increases in activation in the poor reading group. Remaining differences present in responders but not present in typically developing children were found in the left superior parietal, occipital, thalamus, putamen, insular cortex, precuneus, left middle frontal, and postcentral gyrus areas suggest the addition of a compensatory action in the brain.

Similar to work reviewed here using MEG, all fMRI investigations of reading interventions show evidence of normalization of brain activation in poor readers who complete a reading intervention. These normalizations also involved the reading circuit, described above. In three of the four fMRI studies reviewed here (summary in Table 3), Temple et al. (2003), Shaywitz et al. (2004), and Meyler et al. (2008), brain regions were demonstrated to be active in poor readers that were not active in typically developing control subjects. These findings, like those of Simos et al. (2005), support the notion that some compensation mechanism exists in the brains of poor readers following intervention that is recruiting different networks in an attempt to perform the same reading tasks as typically developing control subjects.

Table 3 List of differences, evidence for normalization and compensation in previous MEG and fMRI studies

Author (year)	Imaging technique	Differences	Normalization	Compensation
Aylward et al. (2003)	fMRI	Left IFG, MFG, superior parietal, fusiform	LH IFG, MFG, superior parietal	None
Meyler et al. (2008)	fMRI	Middle and superior occipital, inferior and superior parietal, postcentral gyrus, angular gyrus	Inferior parietal, postcentral gyrus, angular gyrus	Putamen, right insular cortex, inferior frontal, medial frontal, superior frontal, left cingulate, right precuneus, postcentral gyrus, vermis of cerebellum
Shaywitz et al. (2004)	fMRI		IFG, Left STS, Oc-T, middle and inferior occipital gyrus, lingual gyrus	Right IFG, Caudate, STGp
Simos et al. (2002)	MEG	STGp laterality, inferior parietal, IFG, MTG	STGp laterality	None
Simos et al. (2005)	MEG	TMP laterality, IFG, Oc-T	IFG, Oc-T	TMP laterality
Simos et al. (2006)	MEG	TMP, Oc-T, MTG	TMP, Oc-T, MTG	None
Simos et al. (2007)	MEG	MTG, Oc-T	MTG, Oc-T	None
Temple et al. (2003)	fMRI	Left TMP, IFG	TMP, IFG	Right inferior and superior frontal, MTG, anterior cingulate

6 Studying RTI with ERP

While previous work has already accomplished a great deal in studying reading disabilities and RTI using MEG and fMRI, the use of ERPs offer a series of advantages. ERPs are both cheaper, and more accessible to researchers and considerably more portable than either MEG or fMRI. It is now possible to transport an ERP system into schools and perform testing on a much wider array of children than may be assessed in a laboratory. New research conducted by the author (Molfese, submitted) has investigated ERPs from 128 electrodes were collected in response to performing a word rhyming task on three groups of children: (1) typically developing children reading at grade level; (2) children adequately responding to a reading intervention, who are reading at grade level; and (3) children not responding to a reading intervention, who are not reading at grade level. Results found that ERPs were able to differentiate all three groups of children in the P100, with typically developing children showing the largest amplitude P100 peak, followed by adequate responders, followed by inadequate responders. Furthermore, in the P300 peak, laterality differences were found for the typically developing children, while no laterality differences were found for the remaining two groups. These results map directly onto those of Simos et al. (2002, 2005, 2007) in terms of being able to differentiate the three groups of children as well as finding laterality differences. Given these findings, the lost cost of ERP systems with high portability, future research of reading disabilities in children could easily employ multiple time points in order to track children through normal development, including the transition to from pre-reading to early literacy.

7 Summary

This chapter has introduced the fundamentals of ERPs, including some of the technical aspects, which may influence interpreting results from different ERP studies. Next, we discussed the difficulties of studying RD regardless of technique to stress that even with the strictest controls on ERP methodology, the operational definition of RD can greatly influence the results of a study. With these technical considerations in place, we reviewed general findings from a series of ERP studies of RD in children. The ERP task, sample characteristics, and ERP peaks with key findings are presented in Table 1 for the ERP studies reviewed, and Tables 2 and 3 for MEG and fMRI studies considering RTI. The concept of RTI was introduced alongside the studies using both MEG and fMRI with consistent findings that adequate response to intervention is accompanied by in most cases normalization in the brain of children with RD to more closely resemble the brain activation profiles of typically developing children. Finally we reviewed recent ERP findings of using ERPs within the RTI framework with a nod in the direction of further study involving more fine-grained sampling of the developmental process of learning how to read.

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A Model of Brain Activity of Young as Compared to Adult Dyslexic Readers and Outcomes After Intervention

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1 Introduction

This study was designed to determine whether the cognitive deficits that young dyslexics, who have completed their early stages of reading acquisition but are not fully fluent readers, display during reading and reading-related tasks are similar to those of adult university students dyslexics who have been exposed to reading for many years; and whether the outcomes of intervention are different in the two age groups. This study used behavioral, electrophysiological and source estimation of brain activation to answer these questions.

> Dyslexia is a specific learning disability that is neurobiological in origin. It is characterized by difficulties with accurate and/or fluent word recognition and poor spelling and decoding abilities. (Lyon et al. 1993)

For years researchers have been endeavoring to determine why 10–15% of the population is unable to acquire reading skills despite sufficient intelligence, motivation and learning opportunities, as well as a lack of visual, hearing or primary motor impairment (Vellutino et al. 2004). Most of the research into dyslexia has been carried out in children in the early stages of reading acquisition, during the formation of reading processes, while little has been studied about whether the characteristics of young dyslexics are similar to those of adult dyslexics.

The literature on adult dyslexics indicates that dyslexia diagnosed in childhood remains into adulthood, and these adults can be classified as either compensated or non-compensated dyslexics (Lefly and Pennington 1991). Compensated dyslexics successfully overcome their word decoding difficulties, as evidenced by decoding accuracy. However they continue to decode words slowly, which impairs various reading-related cognitive abilities such as comprehension (Bruck 1992, 1998;

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Brunswick et al. 1999; Lefly and Pennington 1991; Shaywitz et al. 1999; Ben-Dror et al. 1991; Gallagher et al. 1996).

Research on compensated adult dyslexics points to the poor reading performance of this group compared to age-matched regular readers. A wealth of consistent evidence suggests that the source of dyslexics' central word decoding deficit lies in difficulties with the phonological system (Snowling 1995; Bruck 1992, 1998; Snowling and Nation 1997; Snowling et al. 1997; Shaywitz et al. 1999; Shaywitz 1996; Leong 1999; Gottardo et al. 1997; Flowers 1995; Elbro et al. 1994; Ransby and Swanson 2003). Phonological processing is the ability to use information on the sound structure of language for processing written and spoken language. Compensated adult dyslexics were found to be slower and less accurate than the control group during vocal reading of familiar and unfamiliar single and multisyllabic words (Bruck 1992), during pseudo word reading (Ben-Dror et al. 1991), and during performance of phoneme segmentation tasks (Bruck 1998). They are insensitive to omissions at the beginning and end of words (Bruck 1992). They have difficulty with a rhyming task when the stimuli are presented in an auditory manner (Nicolson and Fawcett 1994), and have low sensitivity to phonological disharmony (Levinthal and Hornung 1992). Their automatic processing is impaired, especially on phonological tasks. This group's ability to acquire phonological decoding remains consistently slower (Yap and Van der Leij 1993). These findings are important in view of the overwhelming evidence that phonological processes, especially phonological awareness and segmentation ability, are crucial for the development of precise reading, and that without phonological decoding (converting the visual letter into its sound) readers are unable to learn the alphabetic principle (Share 1994; Treiman 2000).

The majority of studies concluded that the basic phonological ability of compensated adult dyslexics is similar to that of young readers at the reading acquisition stage (Bruck 1990); and that phonological ability continues to contribute to reading accuracy, reading rate and spelling ability in adulthood (Shaywitz et al. 1999). Regardless of the measure used to examine phonological ability, phonological processing is a unique and consistent predictor of reading ability (Gottardo et al. 1997).

Additional evidence has indicated another source of reading difficulty among dyslexics: the failure of orthographic processing. Orthographic knowledge is related to the visual information of a word: the letters and their order determine the word and contribute to spelling ability as well as the ability to identify the visual pattern of a word (Corcos and Willows 1993; Wagner and Barker 1994). The literature on orthographic processing in dyslexics is not consistent. Some studies have found that adult dyslexics have trouble perceiving and organizing global information including visual information; that is, they have a visual perception problem affecting the orthographic channel following stimuli screening (Lovegrove 1993). Similar orthographic patterns cause confuse dyslexics and prolong their response time to given tasks as compared to regular readers (Levinthal and Hornung 1992). Other studies reported that one of the main characteristics of adult dyslexics is spelling errors and letter problems stemming from lack of orthographic knowledge (Shaywitz et al. 1999; Elbro et al. 1994; Brunswick et al. 1999). Still other research found that adult dyslexics who are sensitive to orthographic patterns use this ability to recognize words as well as regular readers (Bruck 1990).

Some adult dyslexics have problems with both the phonological and orthographic channels (Ransby and Swanson 2003; Bell et al. 2003). These readers are unable to create orthographic patterns and continue to rely on phonological decoding even though it is inaccurate. Other dyslexics activate their accurate orthographic system to compensate for their impaired phonological system (Siegel et al. 1995; Ben-Dror et al. 1991).

In summary, there is evidence to support the view that both young and adult dyslexics exhibit the same deficit characteristics, such as difficulty and slowness in phonetic segmentation, slow reading rate, and slowness in carrying out reading-relevant cognitive tasks, including naming and symbol identification.

Recent advances in brain imaging have given us the means to identify areas of the brain that are involved in the reading process, and the differences in brain activity and morphology between regular and dyslexic readers (Breznitz and Lebovitz 2008). The main differences are in the left hemisphere where the language areas reside. Two left posterior areas are critical for fluent reading: one around the parieto-temporal region, which is involved in word analysis (phonological processing) and meaning, and one in the occipito-temoporal region, which is part of visual word recognition. These areas are activated less in dyslexic readers. In contrast, the left anterior area (Broca's area), which is responsible for word pronunciation, is activated more in dyslexic readers. These findings have been consistent among children and adult dyslexics. Several right hemisphere areas were found to be activated in older dyslexic readers during reading, possibly representing a compensatory mechanism that helps them read (Shaywitz et al. 2008).

1.1 The Current Study

The differences in the cognitive profiles of young and adult dyslexics and the differences in brain activity of the two age groups were investigated by behavioral and electrophysiological measures. The electrophysiological measure consisted of event-related brain potential (ERPs), which reflect changes in electrical activity of the nervous system related to external stimuli or cognitive processes occurring in the brain. They provide information online before the appearance of a behavioral response (Neville et al. 1993), and do so by means of real-time imaging of the neural system's responses to sensory stimulation in milliseconds resolution (Bentin 1989). ERP will give us information on the timing of processing – not the location – and help us understand the origin of the slowness in the processing of dyslexics.

1.2 The Participants

Two groups of adults and two groups of children were studied; each age group made up of two subgroups – a subgroup of dyslexics and a subgroup of age-matched regular readers.

Participants in each age group were matched for age, IQ, gender, socio-economic status (SES) and handedness. All were Hebrew speakers (mono-lingual), with normal hearing and vision and no known neurological problems.

Participants performed a variety of behavioral and electrophysiological tasks that examined reading and reading-related abilities in order to establish the cognitive profile of each age group. In addition, each group completed 15 sessions of reading intervention (the Reading Acceleration Program) in order to examine the outcome and benefits of the intervention.

1.2.1 Adults

The dyslexics were 15 compensated (Lefly and Pennington 1991) university students, 20–27 years of age, who had been diagnosed as dyslexic both in childhood and in adulthood. They were diagnosed again upon entering the university as part of a request to receive learning accommodations. They were all at least one SD below average in word and pseudoword reading accuracy and rate as compared to the regular readers subgroup. Fifteen Haifa University students comprised the adult regular readers group, 20–27 years of age.

1.2.2 Children

The dyslexics were 15 fourth grade dyslexic children selected from the Haifa Municipal Center for Learning Disabilities. They were all at least 1 SD below average in word and pseudoword reading accuracy and rate as compared to the regular readers subgroup. The regular readers group consisted of 15 fourth grade regular readers recruited from a school in a middle-class neighborhood in the north of Israel.

1.3 Procedure

The behavioral tests were administered to each participant individually; the children's group at school and at the Haifa University learning disabilities Testing Center for the adults. All behavioral tests were administered at one sitting and all electrophysiology tests in another sitting. Adults provided signed informed consent, and the parents of the children signed informed consent forms.

The two reading subgroups in each age group were tested for accuracy and reaction time on all tasks, and for the latency and amplitude of ERP components identified in the brain activity studies. The EEG data were also analyzed with the LORETA program to estimate the source of the cortical activation.

1.4 The Gap Measure

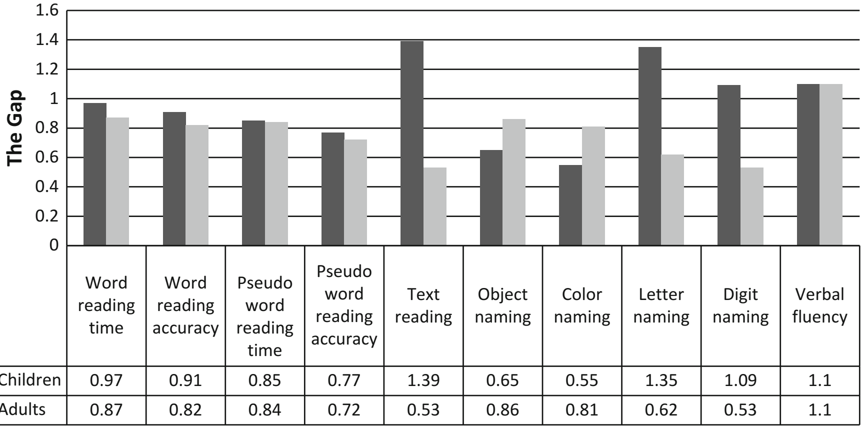
The differences between the adults and children with dyslexia compared to the regular readers in each age group were studied by calculating a gap measure. This measure is the mean of the gap between the dyslexic group and that of the regular readers as expressed by the standard deviation of the two groups together. The measure gives the number of standard deviations included in the difference between the means of each age group. As the gap between groups widens, the values increase. A comparison of the gap size in each age group indicates the intensity effect of the achievement gap beyond years for young and adult dyslexics.

2 Results

2.1 The Behavioral Reading and Reading-Related Tasks

The dyslexics in both age groups read words, pseudo words and text less accurately and slower than the regular readers, but with no differences in reading comprehension. The dyslexics in both age groups were slower in the naming tasks and in the speed of processing task (coding), and produced fewer words in the verbal fluency task. In the memory task, a difference was found only in the adult group where the dyslexic readers had a smaller digit span than the regular readers. (For a full description of the tasks and the results see Shaul 2005). The gaps between the regular and dyslexic reader in each age group are presented in Fig. 1.

As seen in Fig. 1, the gap in pseudoword and word reading (accuracy and fluency), and verbal fluency was similar in the two age groups. The gap in object and color naming was larger among the adults, due perhaps to the fact that the regular readers improved in the rate of naming of non-alphabetic symbols and the dyslexics remained slow. In contrast, the gap in text reading, and letter and digit naming was smaller among the adults; it appears that the compensated dyslexic adults use meaning, which improves their text reading. Naming of alphabetic symbols also improved in the adult dyslexics, even though it was still slower than regular readers of the same age.



	Word reading time	Word reading accuracy	Pseudo word reading time	Pseudo word reading accuracy	Text reading	Object naming	Color naming	Letter naming	Digit naming	Verbal fluency
■ Children	0.97	0.91	0.85	0.77	1.39	0.65	0.55	1.35	1.09	1.1
□ Adults	0.87	0.82	0.84	0.72	0.53	0.86	0.81	0.62	0.53	1.1

Fig. 1 The gap between dyslexic and regular readers in each age group – behavioral measures

2.2 *Basic Speed of Processing Tasks*

The basic speed of processing of the systems relevant for reading (visual and auditory) were studied by four oddball tasks that required the participants to distinguish between two types of stimuli – one frequent (nontarget) and one rare (target).

2.2.1 Auditory Tasks

Nonlinguistic – Stimuli were target tones of 1,000 Hz and nontarget tones of 2,000 Hz.

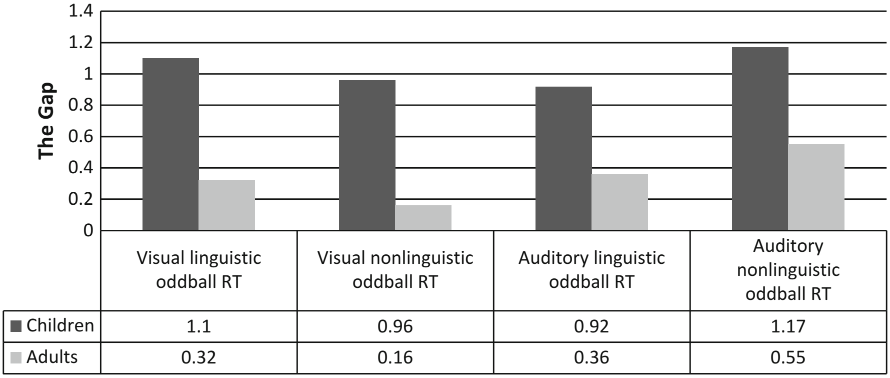
Linguistic – Stimuli were consonant sounds. The target was /t/ and the nontarget was /b/.

2.2.2 Visual Tasks

Nonlinguistic – Stimuli were two meaningless shapes one-quarter mm high presented in the center of the computer screen.

Linguistic – Two Hebrew letters were presented in the center of the computer screen. The target was the letter “bet” (/b/) and the nontarget was the letter “chaf” (/k/).

In the adult group, the dyslexics had a longer reaction time than the regular readers on all four tasks, but there were no significant differences between the groups on the four rare stimulus recognition tasks in the auditory and visual modalities, whether the stimuli were linguistic or nonlinguistic. A significant difference was found in accuracy of the visual and auditory linguistic tasks: the adult dyslexics were less accurate in identifying the rare linguistic stimuli.



	Visual linguistic oddball RT	Visual nonlinguistic oddball RT	Auditory linguistic oddball RT	Auditory nonlinguistic oddball RT
■ Children	1.1	0.96	0.92	1.17
□ Adults	0.32	0.16	0.36	0.55

Fig. 2 The gap between dyslexic and regular readers in each age group – reaction time (*RT*) on the oddball tasks

Among the children, the dyslexics' recognition was significantly slower than that of the regular readers on all four rare stimulus recognition tasks in the auditory and visual modalities, whether the stimuli were linguistic or nonlinguistic. No significant difference was found between dyslexics and regular readers in accuracy of any task.

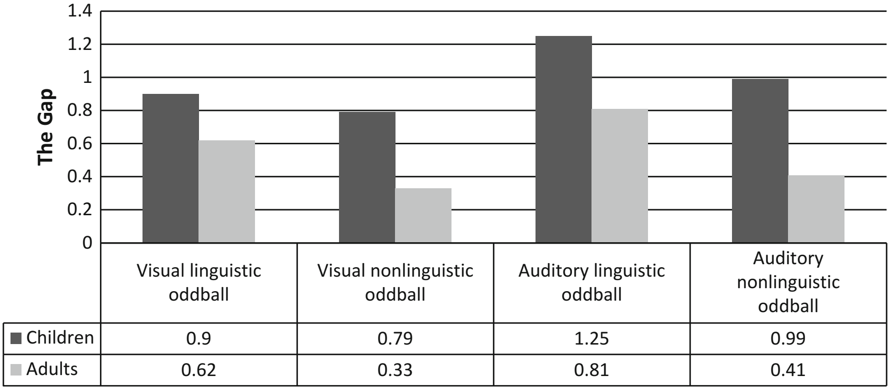
Electrophysiology measures revealed a significant age effect for the P300 component which reflects information processing of the stimulus (Erez and Pratt 1992). P300 constitutes a central measure of synchronized information processing during cognitive decision performance (Palmer et al. 1994). An abundance of research evidence has indicated that this component appears following both rare and frequent stimuli and is related to updating in working memory (Isreal et al. 1980), to the quality of categorization, and to the allocation of cognitive resources required for task performance (Wilson et al. 1998).

The component appeared later among the children, with a higher amplitude in all tasks. A main effect for the group was found only in the auditory linguistic task, where the P300 appeared later among the dyslexics in both age groups.

The gap analysis was calculated for the behavioral (Fig. 2), and electrophysiology data from the oddball tasks (Fig. 3).

The gap between the dyslexic and regular readers was smaller in the adult group on all four tasks. The gap between dyslexic and regular readers in basic speed of processing decreased with age, especially in the visual system. The gap remained large in the auditory processing, which is relevant for the phonological processing in reading; the largest gap was seen between the dyslexic and regular adult and children readers on the auditory linguistic task, which requires discrimination between two syllables – an ability that is required in the process of reading acquisition.

A similar pattern was seen in the electrophysiology data (Fig. 3), where the gap between the dyslexic and regular readers was smaller among the adult group on all four tasks. The gap in the appearance of the P300 component latency between dyslexic and regular readers decreased with age, especially in the visual system. In addition, the gap was smaller in the nonlinguistic stimuli as compared to the linguistic stimuli, and remained larger in the auditory linguistic processing, which



	Visual linguistic oddball	Visual nonlinguistic oddball	Auditory linguistic oddball	Auditory nonlinguistic oddball
■ Children	0.9	0.79	1.25	0.99
▨ Adults	0.62	0.33	0.81	0.41

Fig. 3 The gap between dyslexic and regular readers in each age group – P300 component latency of the oddball tasks

is relevant for the phonological processing in reading. The speed of discrimination between two different syllables remained difficult for both adult dyslexic and young dyslexic readers.

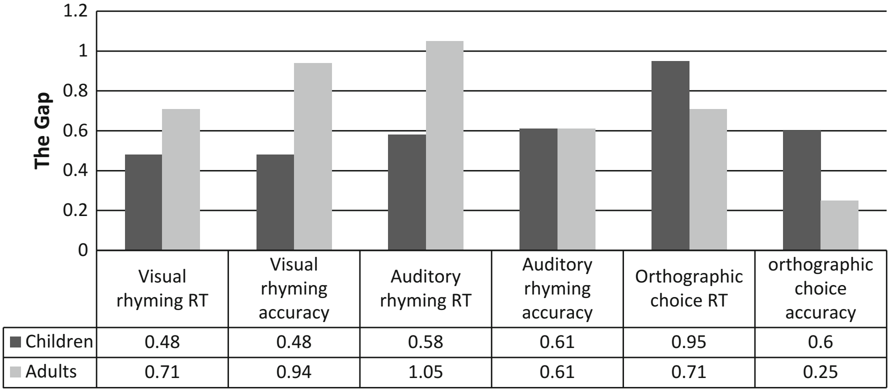
These experiments indicate that speed of information processing is not a general global characteristic, but rather related to the task being performed. From this, it can be concluded that speed of processing is task dependent. In agreement with other studies, speed of processing increased with age from a developmental point of view, but did not develop identically in all channels, especially in dyslexics. While adult subjects were generally faster than the younger subjects on most of the tasks, the gap between age groups changed on different tasks, and the development of the auditory-phonological channel in dyslexics differed from that of the visual-orthographic channel.

2.3 Phonological and Orthographic Tasks

Behavioral and electrophysiological measures were collected on the following three tasks given to both groups:

2.3.1 Phonological Ability

1. *Visual Rhyme decision* (Sarid 1997) – This task required subjects to make a rhyme-non-rhyme decision on a list of 120 pairs of Hebrew words presented visually on a computer display. The word pairs were divided into four categories of 30 words each.
   (a) Orthographically and phonologically similar rhyming word pairs.
   (b) Orthographically dissimilar and phonologically similar rhyming word pairs .



	Visual rhyming RT	Visual rhyming accuracy	Auditory rhyming RT	Auditory rhyming accuracy	Orthographic choice RT	orthographic choice accuracy
■ Children	0.48	0.48	0.58	0.61	0.95	0.6
□ Adults	0.71	0.94	1.05	0.61	0.71	0.25

Fig. 4 The gap between dyslexic and regular readers in each age group – phonological and orthographic behavioral measures (*RT* reaction time)

(c) Orthographically and phonologically dissimilar non-rhyming word pairs.

(d) Orthographically similar and phonologically dissimilar non-rhyming word pairs.

2. *Auditory rhyming decision:* This task was similar to the visual task, except the pairs of words were presented in the auditory mode by a sound blaster. The subject was required to decide whether or not the two words rhymed.

2.3.2 Orthographic Ability

Orthographic ability was tested in both groups by an orthographic decision (Sarid 1997). A sound blaster presented 90 pairs of Hebrew words in the auditory mode. The word pairs were divided into two categories: words written with the same letters but sound different (orthographic similarity and phonological dissimilarity); words written with different letters and sound different (orthographically and phonologically dissimilar). The subject was required to decide whether the two words were written with the same letters or not.

The adult dyslexics were slower and less accurate in most of the categories of the visual and auditory rhyming task. In the orthographic task, they were slower only in the decision of words written with different letters.

Among the children, dyslexic and regular readers differed only in reaction time to the rhyming and orthographic choice. No differences were found between the two groups in accuracy.

The gap between the dyslexic and regular readers increased among the adults as compared to the children in most of the phonological processing tasks (Fig. 4), with the exception of accuracy in the auditory rhyming task where the gap stayed the same in both age groups. In the orthographic task, the gap between the groups decreased in the adults. These results strengthen previous studies that demonstrated that adult compensated dyslexics continued to have difficulties with phonological processing (Shaywitz et al. 1998) and improved their orthographic processing, which may be a compensatory mechanism for them.

According to the electrophysiology data collected while performing these tasks, the P200 and P300 components were detected only in the visual rhyming task, in which no significant differences were found in the amplitude or latency between the dyslexic and regular readers in both age groups.

The gap analysis of these data strengthened the behavioral results: the gap increased in the adult dyslexics from 0.35 to 0.78 in the P200 and from 0.38 to 1.41 in the P300 component.

2.4 Summary

The gaps measures may constitute evidence of what actually remains of the dyslexia phenomenon in adulthood.

The gap measure of words and pseudo words was not only retained between the age groups but even enlarged. On the other hand, the gap between young and adult dyslexics on the ability to recognize words from context (vocal reading) was significantly reduced. This may indicate an additional compensatory mechanism developed among adult dyslexics during their years of print exposure. The context becomes a tool that simplifies their reading and helps them read faster. Thus, the effect of context on accurate word decoding exists for dyslexics, unlike for the regular readers, not in recognition of single words but in reading a meaningful text.

The gap in phonological ability and speed of processing increased in the adult dyslexics as compared to the youngsters. It seems that the dyslexics reached a certain level of processing of phonological tasks – an asymptote beyond which they could not improve their performance. Thus, the phonological task gap between accurate and dyslexic readers increased over the years.

Indeed, there is broad consensus regarding the function of phonology in reading – there is a substantial body of evidence indicating a close connection between low phonological skills and reading difficulties. Phonological awareness is considered to be one of the conditions essential to development of proper reading skills. The findings of this research study, together with those of others (Snowling 1995; Bruck 1990), show that the phonological abilities of adult dyslexics remain low, that a phonological processing deficit may characterize the dyslexic reader, and the trait persists into adulthood.

A different picture is seen regarding the quality and speed of orthographic processing tasks in this study. The gaps both in accuracy and reaction time between the age groups are reduced, indicating that the processing ability of dyslexics in the orthographic channel improves over the years. Training and exposure to print has an obvious positive influence, although, as will be seen below, the performance level and speed of adult dyslexics in this channel following intervention does not reach the level of adult regular readers.

The fact that adult dyslexics did not completely reduce the gap in orthographic processing compared to regular age-matched readers indicates that dyslexics also have a problem with the orthographic channel. It is possible that because reading relies on both orthographic and phonological processing (grapheme-phoneme exchange), the continued phonological processing deficit influences the orthographic deficit by blocking its maximum effectiveness. If, on the other hand, the orthographic channel is essentially a "healthy channel," its deficit will be less and it can function as a compensatory mechanism.

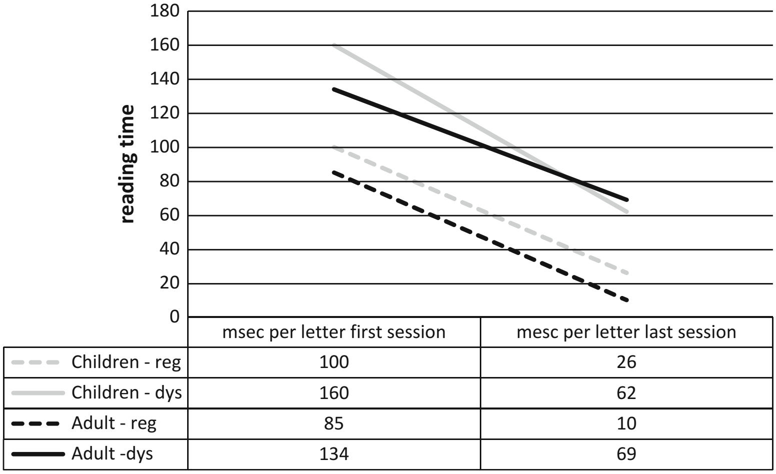
An examination of the gaps in basic information processing tasks at the sensory level (oddball tasks) clearly show that the adult dyslexics closed the processing gap in both the auditory and visual senses at the nonlinguistic processing level. On the other hand, the gap in their performance on accuracy on the visual and auditory tasks at the lower linguistic processing level (grapheme phoneme level) persisted into adulthood.

2.5 Intervention

The two groups of dyslexic and regular readers – both children and adults – underwent 15 sessions of reading intervention based on the Reading Acceleration Program (RAP) (Breznitz and Nevat 2004).

According to the acceleration phenomenon, when manipulated in an experimental setup, young and adult regular readers of various levels of reading ability as well as impaired readers increase their usual reading rate by 10–20%, and in doing so increase their decoding and comprehension skills (for review Breznitz 2006; Breznitz and Berman 2003; Breznitz et al. 1993, 1994; Breznitz and Leiken 2000; Breznitz and Share 1992). This manipulation was found to extend attention span and reduce distractibility, thereby overcoming some of the limitations of short-term memory relating to reading (Breznitz and Share 1992; Breznitz 1997b) and increasing word retrieval from the mental lexicon.

Each acceleration training session began with testing self-paced sentence reading for each individual. Next, a block of sentences made up of between 7 and 12 words followed by a multiple choice comprehension question which was presented to the subjects after reading each sentence. There were 40 sentences in a session for the adults study and 30 sentences for the children. Each sentence was presented and the letters in each item started to disappear one by one, starting at the beginning of the target sentence, based on the subject's best per-letter average reading time as calculated in the self-paced testing condition. The per-letter "disappearance rate" increased in steps of 2% (Breznitz 1997a, b). A staircase-like procedure was used. The "disappearance rate" increased only if the participant's answers to the probe questions were correct on ten consecutive sentences. In addition there was one non-training group for the adults and one for the children where the subjects routinely studied at school or at the University.



	msec per letter first session	mesc per letter last session
Children - reg	100	26
Children - dys	160	62
Adult - reg	85	10
Adult -dys	134	69

Fig. 5 The effect of intervention: the rate of reading in the first session of training as compared to the last sessions of training

All groups were tested behaviorally before and after the training with word, pseudo word and text reading.

The dyslexic children started at the highest point (they read the slowest), followed closely by the adult dyslexics. Although the dyslexic children were slower than the dyslexic adults at the outset, they became faster than the dyslexic adults after the intervention, indicating that the dyslexic children benefited more from the intervention. Nevertheless, the adult dyslexics did improve significantly and also read much faster after the intervention (Fig. 5).

The regular reading children were slower than the adults before and after the intervention program, and both age groups profited from the program significantly more than the dyslexic readers. It is noteworthy that the dyslexic readers in both age groups reached a reading level at the end of the intervention that was faster than where the regular readers started (Fig. 5).

Regular adult readers benefited the most from the acceleration program: 88% of them improved their reading speed. Only 51% of the adult dyslexics improved, although this improvement reduced their reading time by half.

Regular children readers also gained more than the dyslexic children from the intervention, but the gap between the dyslexic and regular readers was smaller among the children: 12% as compared to 37% in the adults (Fig. 6).

The central nervous system changes during development and as a result of a person’s lifetime experiences. The brain’s plasticity plays a central role in the normal development of the nervous system (Breznitz 2006) and exists in the adult brain as well, allowing for changes as a result of training. Long-term neuronal changes underlie learning in the adult brain as a result of training . In certain cases, training is related to increased cerebral activity and the expansion of active areas, which may persist for weeks following training (Karni et al. 1998).

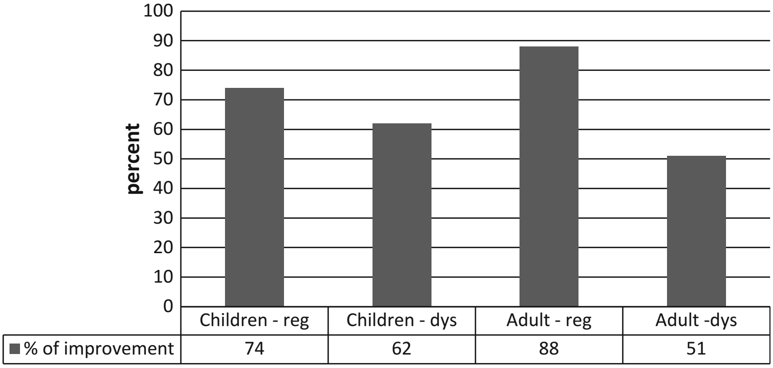


Fig. 6 The percent of improvement in reading rate after 15 sessions of acceleration training

In contrast, training may lead to decreased cerebral activity. One explanation for this is a sharper response to specific neuronal networks; i.e., following training there is increased activation but among a fewer numbers of neurons. Another theory maintains that training causes decreased activation in pre-frontal areas related to executive monitoring (Breznitz 2006).

The present study shows that the adult brain can change, implying a large degree of plasticity, even in processes that are well established. The regular adult readers showed the largest amount of change in their reading rate; despite being fluent readers, they improved their reading rate up to 12% more than their original reading rate. It seems that because the reading process is automatic and well established in their brain, it can be improved significantly and simply works much faster in the same track. The regular children's improvement was less than the adults, perhaps because the reading process is not completely mature and therefore is less susceptible to change.

The dyslexic readers displayed significant improvement in reading speed, but less than the regular readers because their reading process does not use the correct areas of the brain, preventing them from reaching the same rate of reading as the regular readers.

These results demonstrate that the acceleration program works and that fluency, and therefore comprehension, can improve.

2.6 LORETA – Low Resolution Brain Electromagnetic Tomography Analysis

The average ERPs for each subject were analyzed with the LORETA program for source estimation (Pascual-Marqui et al. 1994, 2002). LORETA calculates the three-dimensional current density distribution of the neural generators in the brain under the assumption that for each voxel the current density should be as close as possible to the average current density of the neighboring voxels ('contiguity'). Computations were made using a three-shell spherical head model registered to the

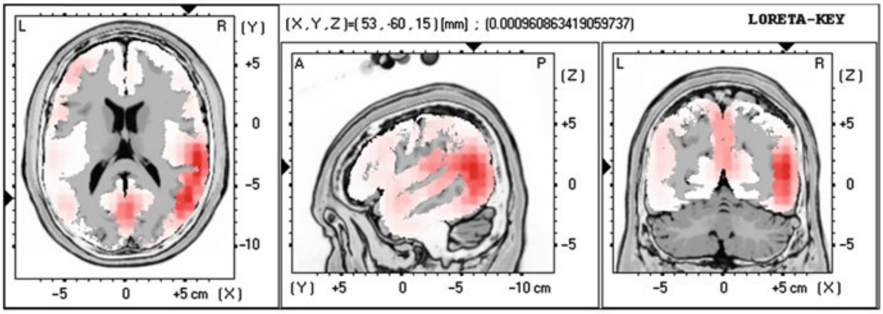


Fig. 7 P300 words dyslexic – adults

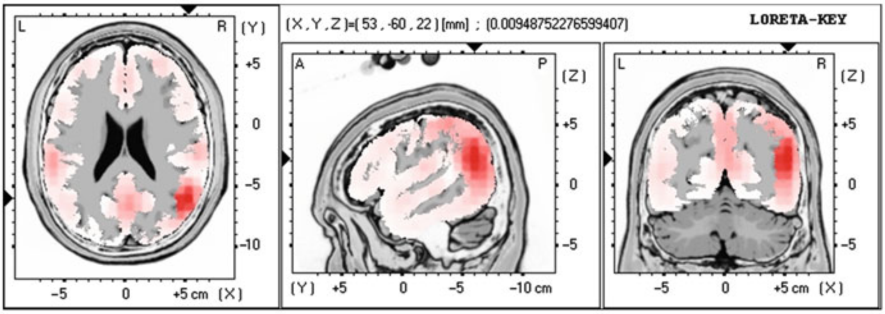


Fig. 8 P300 words dyslexic – children

Talairach space of the brain's gray matter. The procedure yielded current densities for 2,394 voxels, with a spatial resolution of 7 mm and a temporal resolution on the order of 3.9 mesc. Anatomical labeling of voxels was performed according to the MNI305 atlas (Collins et al. 1994).

Figures 7, 8, 9 and 10 present the areas of activation while processing words around the P300 component peak in children and adults from both the dyslexic and regular readers groups.

The highest degree of activation among the adult dyslexic readers (6.5 mA/mm^2) was exhibited in the right temporal lobe in the superior temporal gyrus (Brodmann areas 22 and 42 – audition areas). Lower activation (2.2 mA/mm^2) was found in the occipital lobe in the cuneus (Brodmann area 18 – vision area) and in the left frontal lobe (5.2 mA/mm^2) in middle frontal gyrus (Brodmann area 10 – related to cognition).

A similar pattern of activation was found in the dyslexic children but with lower and less broad activation in the right hemisphere and distributed low activity in the left temporal hemisphere and occipital areas. Fourth grade dyslexics have already begun to use their right hemisphere to help them process words, but not as efficiently as the adult dyslexics, and are still trying to use their left hemisphere as well.

The highest degree of activation among the adult regular readers (5.1 mA/mm^2) was exhibited in the left temporal lobe in the middle temporal gyrus (Brodmann

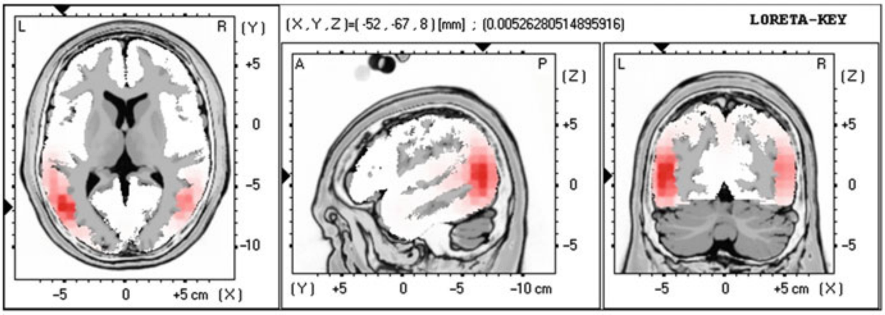


Fig. 9 P300 words regular readers – adults

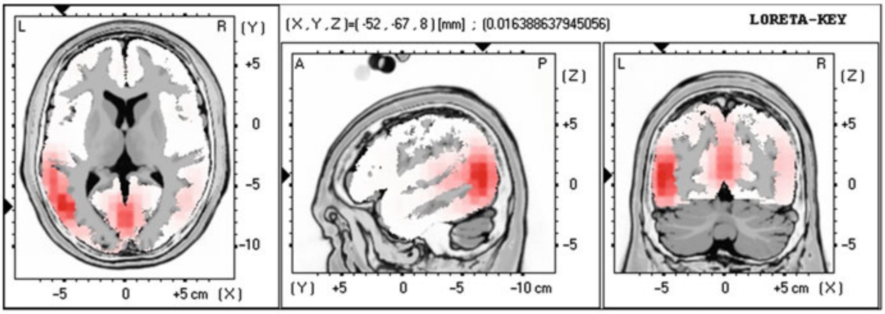


Fig. 10 P300 words regular readers – children

areas 39 – vision areas), and in the superior temporal gyrus (Brodmann areas 22 (Wernicke's area)). Lower activation (2.2 mA/mm^2) was found in the right temporal lobe in the superior temporal gyrus (Brodmann area 39 – vision area).

A similar pattern of activation was found among the regular reader children with the highest activation in the left temporal area. Additional activity was found in the occipital lobe in the cuneus. (Brodmann area 18 – vision area) and lower activation in the right hemisphere. It seems the regular fourth grade readers still need more perceptual visual information in order to process words, and have not reached full efficacy in automatic reading.

3 Summary

When the reading ability and reading-related measures are examined, the difference between regular readers and dyslexics is significantly smaller in the adults compared to the children on orthographic tasks, while the difference increases in adults on phonological tasks in both behavioral and electrophysiological measures.

A different cognitive profile was found for dyslexic children compared to adult dyslexic readers, in addition to the different outcomes of the intervention program in each age group. The profile of adult dyslexics is similar to that of the fourth grade regular readers in some aspects, including behavioral reaction time and accuracy in reading and reading related tasked; but, they share similar characteristics with the dyslexic children, mainly in brain activity patterns. It seems that even though the adult dyslexics manage to learn to read accurately, their reading fluency and speed of processing in the phonological route remain deficient even in adulthood. Dyslexic adults and children can improve their reading fluency with the help of the suitable intervention programs. Indeed, both age groups of dyslexics improved their reading rate significantly, the children more than the adults. This requires further investigation with additional types of interventions and long post-examination follow-up to see what remains of the intervention, and if there is a brain signature for the change.

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Optimizing Reading Enhancement: Evidence from Brain Research

Olga Chuntonov and Zvia Breznitz, Ph.D.

Approximately 25% of learners in the literate world are identified as suffering from some degree of reading difficulties or disabilities (OECD 2002; US Report 2005). Given the importance of the basic skills affected, and considering the prevalence of the phenomenon, if these disorders go unidentified and untreated, they impair the lives of the individual and society at large. Developments in neuroscience and specifically in brain science research into reading disabilities, have led to the formation of a separate scientific discipline. In order to better understand the underlying causes of reading disabilities, current research uses a wide array of advanced technologies to investigate the various aspects of both the regular and deviant expressions of the reading process. Tremendous advances have been made in the diagnostic domain. However, understanding the remediation aspects of learning disabilities is still very limited and needs to be developed. There is ample scientific evidence of the human brain's plasticity; its ability to change throughout our lifetime; to manipulate information; to learn new operations; to create new cells and slow down their mortality; and to expand and create neural networks. Such evidence has opened up new insight into the theoretical and applied studies of intervention and remediation of reading skills. It is conceivable that with the development of an adequate intervention program, the brain structure and activation patterns of people with learning disabilities may change and improve reading capabilities.

The current chapter will begin with a short review of the brain imaging techniques, followed by a review of literature regarding the brain's ability and readiness to adapt and change at different ages and in various situations. This will be followed by a summary of the ways that the brain operates during reading and reading-related activities, for both normal readers and those with reading difficulties. Finally, a brain training program that was created for improving the

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reading skills of dyslexic readers will be described. The program was developed by adopting the principals derived from the accumulated knowledge of neuroscience research that has utilized advanced neuroimaging technologies.

1 Research Tools, Technology and Methodology

Given that cognitive processing involved in a skill such as reading is dependent on different brain structures and the activation of various brain systems; and that these structures and systems operate at different sites, in different manners, and at different time scales and intensities; in order to understand the reading process, it is important to understand the biological constraints and characteristics of the brain when operating during this activity. The recent rapid development of non-invasive neuroimaging technologies has brought us closer to understanding the anatomical structure and function of different brain systems' activities when processing information in real-time (Galván 2010; Posner and Rothbart 2005; Varma et al. 2008). The currently leading brain-imaging technologies (see Table 2 for a summary) can be divided into two categories according to the type of information they provide about brain activity: high-resolution spatial information and high-resolution temporal information (Luck 2005; Tucker 1993).

1.1 High-Resolution Spatial Information

Technologies in this category have spatial resolution in the millimeter range, providing fine anatomical details, but their temporal resolution is limited and measured in seconds (Tucker 1993). Mostly, they require subjects to remain motionless for accurate imaging. The most popular tools in this category are:

Positron emission tomography (PET) – This technique uses radioisotopes to detect brain activity by monitoring changes in oxygen levels, glucose levels, and cerebral blood flow changes (see Phelps 2004 for a review). It enables identification of the brain areas that are activated during task performance (see Cabeza and Nyberg 2000 for a review of cognitive studies using PET). Scans require an injection of radioactive materials (which is both invasive and expensive), a restricted range of motion and confinement. Another disadvantage is the slow image capturing speed.

Functional Magnetic Resonance Imaging (fMRI) is another technique in the set of high spatial resolution tools group. It detects blood flow and local metabolic changes during task performance showing the connection between the different brain regions and the activation patterns of the brain (see Huettel et al. 2004 for a review). fMRI is noninvasive, does not involve exposure to radiation (enabling repeated measuring of the same subjects) and has excellent spatial resolution. However, it is a very expensive tool and very sensitive to the subjects' motions.

Integration with other imaging modalities is difficult, and it exposes participants to loud noises.

Through spatial resolution technologies, it was found that reading involves systems, mostly in the left hemisphere, such as an anterior system in the left inferior frontal region, angular gyrus, supramarginal gyrus and posterior portions of the superior temporal gyrus, fusiform gyrus and ventral occipitotemporal system (Goswami 2006; Krafnick et al. 2011; Pugh et al. 2001; Shaywitz et al. 2002).

PET and fMRI techniques have significant advantages, but due to their limitations they are unsuitable for use with children, for positive affect measures, and for monitoring ongoing cognitive activity under routine working conditions (Izzetoglu et al. 2005a).

1.2 High-Resolution Temporal Information

Technologies in this category are characterized by temporal resolution in the millisecond range and spatial resolution in centimeters.

Electroencephalography (EEG) measures electric fields at the scalp surface during mental activity. EEG measures a combination of many different neural sources of brain activity. Through EEG, neural responses to specific sensory, cognitive, and motor events, event-related potentials (ERP), can be extracted using averaging methods (see Luck 2005 for a review). The relatively low spatial resolution makes localizing the source of activity in the brain difficult and is the main disadvantage of EEG (Tucker 1993). On the other hand, EEG is successfully used with children and can be combined with other measuring tools relatively easily. The usage costs of EEG are significantly lower than those of the aforementioned tools.

EEG measurement data during reading tasks pointed to several evoked responses potential components (ERP's) at specific time and brain sites. In general, P100 ERP components were found to appear at the perception stage; N170 at the formation of the word patterns; P200 during phonological processing; P300 during working memory activation and N400 in semantic processing (Shaul 2008 for review).

Magnetoencephalography (MEG) is another functional imaging technique, which can be combined with MRI structural data to obtain a detailed picture of brain function mapping onto brain structure (magnetic source imaging – MSI). MEG measures magnetic forces on the scalp that are associated with the electrical activity of the brain (unlike EEG, which measures the electrical activity itself) (see Hansen et al. 2010 for a review; Papanicolaou et al. 2003). It provides a real-time, spatiotemporal map of brain activity. The main advantage of this tool is that the magnetic fields that are measured are not affected by surrounding brain structures, and when used together with MRI, a high-resolution functional/anatomical image is achieved (Simos et al. 2002).

Functional Near-Infrared Spectroscopy (fNIR) has recently been introduced as a new neuroimaging modality with which to conduct functional brain-imaging studies (see Workman and Weyer 2008 for a review). fNIR technology uses specific wavelengths of light (700–900 nm), introduced at the scalp, to enable a noninvasive method of measuring changes in deoxygenated hemoglobin (deoxy-Hb) and oxygenated hemoglobin (oxy-Hb) concentrations in the cortex during brain activity (Cope and Delpy 1988; Jobsis 1977; Rolfe 2000; Strangman et al. 2002). This technology allows researchers design portable, safe, affordable, noninvasive, and minimally intrusive monitoring systems. These qualities make fNIR suitable for the study of hemodynamic changes due to cognitive and emotional brain activity under actual, on site working and educational conditions. fNIR has been used to assess several types of brain functions including motor and visual activation, auditory stimulation and performance of various cognitive tasks – targeting the domains of attention, memory and executive function (Gratton et al. 1995; Heekeren et al. 1997; Hoshi and Tamura 1993; Izzetoglu et al. 2004, 2005b, 2007; Maki et al. 1995; Sato et al. 1999; Suto et al. 2002; Villringer and Chance 1997; Zaramella et al. 2001).

Some studies using fNIR technology specifically focus on the involvement of the frontal lobe in different aspects of language. For example, Sakatani et al. (1999) used near infrared spectroscopy to show the effect of aging on the left prefrontal cortex activity during a series of lingual and memory tasks. Quaresima et al. (2002) reported on the involvement of the left Broca's area in the process of a language translation task. Watanabe et al. (1998) correlated between language dominance and handedness. In addition, Hofmann et al. (2008) used near infrared spectroscopy to demonstrate the involvement of the left superior and inferior frontal lobe in the performance of lexical decision tasks. Support for these findings was found by Sela et al. (2011), where a lexical decision task (LDT) was studied by using fNIR among regular adult readers as compared to secondary school readers. Results demonstrated that adults had an advantage in their performance of the LDT in terms of accuracy and reaction time of their responses as compared to the 7th graders' group. Blood oxygenation measurements in terms of its minimum value and maximum time to reach its maximum value obtained from 16 voxel fNIR recordings revealed significant differences between groups (young vs. adult) and types (word vs. pseudoword) in the upper left superior and inferior frontal lobe.

The techniques briefly described here allow researchers to detect, localize and quantify brain activity associated with cognitive function, making it possible to assess brain mechanisms underlying reading and/or dyslexia. However, due to motor interference, most of the current brain-imaging techniques are limited only to silent reading and use with highly artificial and relatively short texts at the word or short sentence level, whereas reading in its natural context (connected texts) cannot be studied. The development of new fNIR techniques may open innovative research avenues to study oral reading as well as long connected texts. Studying reading using fNIR is only in its initial stages.

Table 1 Currently available research tools for the investigation of brain activity during task performance

Technology	Description	Advantages and disadvantages
High-spatial resolution		
Positron emission tomography (PET)	Radioisotopes are used for detection of brain activity by monitoring changes in oxygen utilization, glucose utilization, and cerebral blood flow changes.	Spatial resolution in the millimeter range. Disadvantages: Need to inject radioactive materials; restricted range of motion and confinement. Cannot be used with children or in the field. Low image acquisition rate.
Functional Magnetic Resonance Imaging (fMRI)	Captures blood flow and local metabolic changes of brain structures during task performance.	Noninvasive, no radiation exposure and has excellent spatial resolution. Disadvantages: expensive; highly sensitive to movement; exposes participants to loud noises. Use for some populations is limited. Cannot be applied in the field.
High temporal resolution		
Electroencephalography (EEG)	Measures electric fields at the scalp surface during mental activity.	Successfully used with children; can be combined with other measuring tools; lower in cost than fMRI and PET. The main disadvantage is the difficulty of localization of the source of activity in the brain.
Magnetoencephalography (MEG)	Measures weak magnetic forces on the scalp that are associated with the electrical activity of the brain.	Measurements are not affected by surrounding brain structures; can be used together with MRI to achieve high-resolution functional/anatomical image.
Functional Near-Infrared Spectroscopy (fNIR)	Uses light wavelengths introduced at the scalp to measure changes in deoxygenated and oxygenated hemoglobin concentrations in the cortex during brain activity.	Portable, safe, affordable, noninvasive, and minimally intrusive. Suitable for the study of cognitive and emotional brain activity under many working and educational conditions, as well as in the field.

These novel tools and methods have not only enabled research of the brain areas and processes involved in daily activities, such as reading, they have also provided us with evidence that the human brain can adapt and change throughout our entire lifetime, and not only in early childhood, as was previously believed. This property is of interest when dealing with reading difficulties since it gives an opportunity to improve reading through fundamental brain changes at any age.

2 Brain Plasticity

The human brain contains billions of neurons which are the basic units of information processing. The neurons are connected through networks that enable simultaneous information flow in the brain by means of electricity flows. The term "plasticity" is used to describe changes in structure, connections and behavior of the brain and its parts following experience (Jessberger and Gage 2008). Scientific literature now readily acknowledges that the human brain is flexible and able to constantly change throughout our lifetime; it can carry out manipulations and learn new operations even into adulthood (Draganski and May 2008; Eriksson et al. 1998; Fischer 2008; Gould et al. 1999b; Krafnick et al. 2011; Poldrack 2000; Stiles 2000). In fact, brain plasticity among adults is quite similar to the brain plasticity of children.

The novel technologies currently used in brain research have provided us with strong evidence that gray matter volume among animals and humans increases in both the young and adult (Boyke et al. 2008; Krafnick et al. 2011) as does myelination (Draganski and May 2008; Eriksson et al. 1998; Fischer 2008; Gould et al. 1999a; Gross 2000; Krafnick et al. 2011; Poldrack 2000; Stiles 2000). A substantial number of new brain neurons are generated daily (Galván 2010). Some of them survive and contribute to changes in the functionality of existing networks (Will et al. 2007). New synapses grow and the existing ones adapt to new situations, supporting adequate and close to optimal behavior (e.g. Ilg et al. 2008; Trachtenberg et al. 2002). The following sections will describe some of the most recent findings related to plasticity, demonstrating functional (modifications of the neural activation patterns) and structural brain changes (volumetric differences following experience) in addition to behavioral changes.

2.1 Increase in Gray Matter Volume

Increases in gray matter volume (GMV) were reported in several studies (see Table 2 for a summary), supporting the idea that some variants of plasticity are caused by anatomical alterations in human brain structure such as neurogenesis, increase in cell size or synaptogenesis (Will et al. 2007). This phenomenon was found in children, adults and elderly populations. In all cases, the increase was observed following training or learning periods. The tasks used in those studies ranged from tasks requiring mostly motor skills and coordination to tasks requiring high mental exertion.

An interesting population that was studied in this context was London taxi drivers. Training to be a licensed London taxi driver takes several years (up to 4 years) to acquire the complex topographical knowledge of the layout of the many city streets in London. Maguire et al. (2006), using whole-brain voxel-based morphometry, found that the taxi drivers have greater GMV in the posterior hippocampi, and reduced GMV in the anterior hippocampi when compared with controls.

Table 2 Gray matter volume (GMV) increases following training

	Population	Training description	Main areas affected
Maguire et al. (2006)	Taxi drivers	Navigation training	Posterior hippocampi
Draganski et al. (2006)	Medical students	German preliminary medical exam preparation	Posterior and inferior parietal cortex bilaterally
Busch et al. (2004)	Young adults	Juggling training	Mid-temporal area bilaterally and in the left posterior intraparietal sulcus
Boyke et al. (2008)	Elderly adults	Juggling training	Middle temporal area of the visual cortex, hippocampus and the nucleus accumbens
Scholz et al. (2009)	Young adults	Juggling training	Medial occipital and parietal lobe in cortical regions.

This pattern strengthened the longer a taxi driver was engaged in navigating in the city. A later comparison to London bus drivers supported the idea that the GMV changes were caused by navigation training involved in taxi drivers' work.

Draganski et al. (2006) found that learning-induced GMV increased in the brains of 38 medical students. The participants studied daily for a period of 3 months towards the preliminary German medical exam. A gray matter increase was reported in the posterior and inferior parietal cortex bilaterally. The posterior hippocampus demonstrated a continuous increase in gray matter not only during, but also after the learning period.

Several studies explored the effect of juggling on GMV. Busch et al. (2004) used whole-brain magnetic-resonance imaging to examine plasticity following juggling training. Structural changes occurred in the processing and storage of complex visual motion brain areas. An increase in GMV was documented in the mid-temporal area bilaterally and in the left posterior intraparietal sulcus.

In another study with young adults (Scholz et al. 2009), GMV increase following juggling training was found in medial occipital and parietal lobe in cortical regions. Interestingly, changes were detected not only in gray matter, but also in white matter volume. Significant increases in fractional anisotropy in white matter underlying the right posterior intraparietal sulcus were found and remained 4 weeks after the juggling was discontinued. There was no correlation between the changes in GMV and WMV, suggesting that those alterations are independent.

Similarly to findings in young adults, GMV increase was found in the middle temporal area of the visual cortex of elderly persons following juggling training (Boyke et al. 2008). They also demonstrated a significant increase in gray matter in the hippocampus and the nucleus accumbens.

To summarize, grey matter volume increases occur following training. When detected in the short term they are more likely to represent faster processes, such as changes in synapse density (Driemeyer et al. 2008), while changes seen long after the training begins are more likely to indicate the slower processes of neurogenesis (Krafnick et al. 2011).

Table 3 Evidence for adult neurogenesis in different species

Species	Research	Brain area affected
Adult humans	Eriksson et al. (1998)	Dentate gyrus
Marmoset	Gould et al. (1998)	Dentate gyrus
Macaque monkey	Kornack and Rakic (1999)	Dentate gyrus
	Gould et al. (2003)	Dentate gyrus
Tree shrew	Gould et al. (1997)	Dentate gyrus
Rat	Altman and Das (1965)	Dentate gyrus
	Cameron et al. (1993)	Olfactory bulb
	Epp et al. (2007)	Dentate gyrus
		Dentate gyrus
Mice	Zhao et al. (2003)	Substancia nigra
	Kempermann et al. (1999)	Dentate gyrus
	Lemasson et al. (2005)	Olfactory bulb

2.2 Neurogenesis

Until about half a century ago, dying neurons were considered to be irreplaceable in adults, since neurogenesis was thought to be impossible after a critical period in early childhood. Any structural modifications occurring later on were attributed to local synaptic changes.

It was demonstrated that the production of new granule cells is possible (Jessberger and Gage 2008) and happens in the adult brain of mammals such as mice, rats, rabbits, cats, macaque monkeys and humans (see Table 3 for examples). Several thousand new cells are born every day in the adult brain, while training more than doubles this number. The dominant mammalian brain parts in this process are the olfactory bulb and the dentate gyrus (Ninkovic et al. 2007; Zhao et al. 2003). Some other areas were also reported as producing novel cells, however there is mixed evidence documented in the literature.

One of the characteristics of neurogenesis seems to be the ability to control its rate, enabling slow cell birth (Zhao et al. 2003). Also, it appears that there is a direct positive association between hippocampus-dependent learning and neuron generation and survival (Epp et al. 2007; Gould et al. 1999a), while no such association was found for learning tasks that do not involve the hippocampus.

2.3 Prevention of Cell Mortality

Newborn neurons must be included in brain networks during the first weeks after their creation in order to survive. This process is successfully achieved in about 30–40% of the cells (Jessberger and Gage 2008). It is important to understand what factors affect cell mortality so that it can be prevented.

Intensive activity of the cells seems to prevent mortality, especially of newly generated neurons. Hippocampal-dependant learning prevents adult-generated neurons from dying (Epp et al. 2007; Gould et al. 1999a, b) by integrating them into existing networks. Moreover, as suggested by results of Waddell and Shors (2008), difficult and slowly mastered tasks are more effective for neuron survival.

2.4 Expansion of Neural Networks

Synaptogenesis, similar to neurogenesis, is observed in the adult brain following training or learning of new skills. New synapses create additional connections, strengthening existing networks or bridging between previously unconnected neurons (Fischer 2008; Trachtenberg et al. 2002). Constant synaptic density suggests that the creation and destruction of synapses is balanced.

According to the "brain growth hypothesis" (Fischer 2008) the brain is "rewired" in cycles or spurts, which correspond to similar spurts in acquisition or enhancement of skills. Most of them involve the prefrontal cortex. There is evidence linking the amount of stable newborn dendritic spines to learning and successfully performing tasks (Ilg et al. 2008; Xu et al. 2009).

In summary, a large body of data indicates that the brain's different structures are flexible and that it is capable of changing and adapting in response to stimulation, training, learning and challenge throughout a person's lifetime. The neural system is highly plastic, even among adults, and this plasticity is mostly the result of skill acquisition through training. In order to try and change the dyslexic brain by means of training, it is crucial to understand the similarities and the differences between the required and the actual brain activation patterns and structures involved in non-impaired versus impaired reading, to enable selection of the optimal training procedure and schedule.

3 Neuroscience and Dyslexia

Developmental dyslexia is marked by inaccurate and dysfluent word reading and/or spelling (British Psychological Society 1999) and persists into adulthood (Vellutino et al. 2004). Children with dyslexia may be impaired in the accuracy and rate of real word reading, pseudoword reading (decoding pronounceable words without meaning), accuracy and fluency of oral passage reading (overall time and smoothness), and spelling (e.g., Berninger et al. 2001; Lyon et al. 2003). These reading difficulties are present in dyslexia despite adequate intelligence, education, and socioeconomic status (Smith-Spark and Fisk 2007).

3.1 Brain Activation During Reading and Reading-Related Tasks

Based on previous research, it seems that at least three systems are involved in non-impaired reading, all primarily in the left hemisphere: anterior, temporo-parietal and occipito-parietal (Pugh et al. 2001). The anterior system in the left inferior frontal region is functional in phonological output. The dorsal parieto-temporal system, including the angular gyrus, supramarginal gyrus and posterior portions of the superior temporal gyrus, is engaged in rule-based orthographic to phonological processing and semantic analysis. The ventral occipito-temporal system, including portions of the middle temporal gyrus and middle occipital gyrus, is responsible for single-word identification (Goswami 2006; Krafnick et al. 2011; Shaywitz et al. 2002).

Anterior system (inferior frontal)	Parieto-temporal system	Occipito-temporal system
Phonological output	Rule-based orthographic to phonological processing, semantic analysis	Single-word identification

Eckert (2004) summarizes the main findings of imaging research for reading as engaging two systems, one for written (orthography) and one for oral language (phonology). Using the orthography system causes activity in the medial occipital cortex, fusiform gyrus, inferior parietal cortex, cerebellum, inferior frontal gyrus and superior temporal gyrus. Performing phonology tasks add to the above list the auditory cortex and insula. Maturation of the systems reduces activation of the areas in the right hemisphere.

The brain activation map of dyslexics differs from that described above (see Table 4 for a summary). They show reduced or absent activation of areas in the left hemisphere that characterize regular readers and they show activation of atypical areas in both hemispheres (Eckert 2004; Krafnick et al. 2011; Penolazzi et al. 2010; Shaywitz et al. 2002; Simos et al. 2002). For example, in a recent study, anterior right lateralization in linguistic tasks and left posterior lateralization during both phonological and orthographic tasks was recorded in reading-impaired subjects (Penolazzi et al. 2010). Let us now look into some examples of activation of brain areas during reading or reading-related tasks reported in the literature.

3.1.1 Inferior Frontal Area

Mixed findings are described in regards to activity recorded in the inferior frontal areas of dyslexics. Simos et al. (2002) found **normal activation** of the inferior frontal areas during performance of reading and phonologic processing tasks. According to Goswami (2006), the activation of the left inferior frontal gyrus is normal for dyslexics, while the other two posterior systems mentioned above (parieto-temporal and accipito-temporal) were not found to be active, in contrast to the normally-reading population. Others record **hyperactivity** in the inferior frontal area of dyslexic readers as compared to non-impaired readers (Shaywitz and Shaywitz 2008). Eckert's (2004) findings suggest that the activity of the left inferior frontal gyrus is correlated with dyslexic adults with good reading accuracy but poor fluency, while dyslexic adults with both reading accuracy and fluency impairment show **no activation**.

3.1.2 Temporo-Parietal Area

In regard to the left temporo-parietal brain regions, the literature is consistent, showing **hypoactivation** for children and adults with dyslexia compared to normal readers. The left superior temporal gyrus, which attends to the sound structure of words at the level of phonemes, is considered to be critical in distinguishing dyslexic readers.

This dyslexia-specific profile was recorded by Shaywitz and Shaywitz (2008) for phonologically demanding (real and pseudoword reading) tasks. Children with dyslexia showed little or no activation of temporo-parietal areas in the left hemisphere according to Simos et al. (2002). In another study, dyslexic subjects exhibited less activation than controls in inferior parietal lobule and insula (Eckert 2004).

3.1.3 Posterior Temporal Area

Left posterior brain systems are described as being involved in the integration of auditory and visual information including connections between the occipito-temporal and the parietotemporal circuits. During phonological task performance, these posterior systems often exhibit **reduced or absent activity** in impaired readers (Shaywitz and Shaywitz 2008). Less activation for dyslexic subjects than for controls in the superior parietal lobule, the cerebellum, the middle temporal gyrus and the fusiform gyrus is reported (Eckert 2004). Simos et al. (2002) showed reversed hemispheric asymmetries of activation in posterior temporal regions when compared with a group of non-impaired readers (higher activity was recorded in the non-dominant right hemisphere, Table 4).

3.2 GMV in Dyslexia

Structural brain-imaging studies in dyslexia generally focus on the left temporal and parietal regions. The results of a voxel-based study (Brown et al. 2001) indicated gray matter reductions in the left temporal lobe (superior, middle, inferior, and mesial temporal structures) associated with dyslexia. Vinckenbosch et al. (2005)

Table 4 Left hemisphere activation levels during reading and reading-related tasks for dyslexic readers as compared to non-impaired readers

Research	Inferior frontal area	Temporo-parietal area	Posterior temporal area
Simos et al. (2002)	Normal activation	Hypoactivation or no activation	Hypoactivation
Goswami (2006)	Normal activation	No activation	No activation
Shaywitz and Shaywitz (2008)	Hyperactivation	Hypoactivation	Hypoactivation or no activation
Eckert (2004)	Normal activation or hypoactivation	Hypoactivation	Hypoactivation
Papanicolaou et al. (2003)		Hypoactivation	
Schulz et al. (2008)	Hypoactivation		
Brambati et al. (2004)			Hypoactivation

report significant reduction in GMV in both temporal lobes of dyslexic individuals. More specifically, in the left temporal lobe, reduced gray matter density in the middle and inferior temporal gyri was found. They also detected increased gray matter density located in the precentral gyri.

Cerebellar nuclei (Brambati et al. 2004), left posterior cerebellar lobe (Eckert et al. 2005) and right cerebellar (Brown et al. 2001) GMV was recorded as lower in the dyslexics compared to normally reading subjects. Attenuation of GMV was also found in the left inferior frontal region (Brown et al. 2001), bilateral inferior parietal lobe and temporal gyri (Hoeft et al. 2007), bilateral lingual gyrus and left supramarginal gyrus (Eckert et al. 2005).

4 Dyslexia and Cognition

Perception, attention and working memory are fundamental cognitive functions involved in reading. Studies show that individuals with reading difficulties, besides the phonological and orthographic deficits, are also characterized by poor cognitive abilities (Kearns 2010).

A direct link between performance of a memory task (listening span task) and reading ability was found (Leather and Henry 1994). Lower working memory (WM) capacity and faster decay were also reported for dyslexic readers (Horowitz-Kraus and Breznitz 2009). Based on working memory difficulties both in the language and in the numerical domains, de Jong (1998) suggested that children with reading disability have difficulty processing and storing verbal information at the same time. Similarly, according to Swanson (1993), a common working memory deficit was found for people with learning disabilities (either in reading or in mathematics). Numminen et al. (2002) proposed that the WM processes are qualitatively different in children with learning disabilities.

Turning to another cognitive aspect, it is easy to see how visual search and the movement of "attention spotlight" are relevant to reading. The ability to sequentially, accurately and effectively scan the visual field affects reading skill (Vidyasagar and Pammer 2010). As to general visual characteristics, Fischer (2009) suggested that the foveal skills of some dyslexics are less effective, while they have a higher than normal density of receptors in the periphery, accompanied by better integration of visual information across wide areas of the visual field.

In regard to the temporal aspects of cognition, people with reading and other learning disabilities tend to display longer perceptual processing (Breznitz and Berman 2003), a slow speed of processing and asynchrony between auditory and visual processing speed (Breznitz and Misra 2003) as compared to regular readers. Reaction time to reading-related stimuli is a distinguishing factor between good and poor readers. The higher the reaction time, the lower the number of decoding errors and the higher the comprehension. Dyslexics are also slower in performing dual tasks, Rapid Automatizing Naming (RAN) tasks, tapping tasks and motor functions combined with counting tasks (see Breznitz 2006 for a review).

5 Dyslexia, Intervention and the Brain

As described in the previous sections, the dyslexic brain is active in a different manner then that of normally-reading individuals during reading and when performing more basic cognitive tasks. We know, however, that the brain is a highly plastic neural system, and this plasticity can be induced by skill acquisition, melioration, and training. The question now is how, if at all, this property of the brain can be used in the field of education and learning. Specifically, will this ability provide hope to children and adults suffering from reading difficulties of various severity levels? Is it possible, by means of intervention, to create brain reorganization in such a way that will enable dyslexic individuals to read fluently or at least reduce the difficulty? Several research groups have been dealing with these questions recently and below we will review some of the major studies and findings in favor of the optimistic speculation.

Two trends can be found in the recent literature for the patterns of brain changes in reading difficulties (see Table 5 for a summary). One is referred to as "normalization": learning causing a "rewiring" of the brain to fit the "map" of normal readers. The other is "compensation": learning inducing the establishment of new brain circuits that are different from those of normal readers, to compensate for the lack of normal activity.

Simos et al. (2002) scanned eight dyslexic children prior to and after 80 hours of intensive training. Before the beginning of the training, the children showed the reduced activation of the temporo-parietal areas on the left and increased activation on the right typical of dyslexic children. Following the intervention, the children improved significantly in a basic word reading test, reaching average scores. Following intervention, the posterior portion of the left superior temporal gyrus showed increased activity, consistent with the "**normalization**" hypothesis.

Even though highly similar spatially, the temporal features were different from those of non-impaired readers. The activation of the left superior temporal gyrus was slower than in normal children, suggesting reduced efficiency. This study points out that reading difficulties can be significantly reduced by means of behavioral intervention, stimulating extensive brain changes to approach the "normalization" pattern.

A computer-based commercially available training program, called Fast ForWord Language (Scientific Learning Corporation, Oakland, CA) served as remediation method in a study by Temple et al. (2003). This program emphasizes auditory attention, discrimination, and memory, which are important cognitive abilities in oral language, phonological processing and listening comprehension. Twenty dyslexic children were scanned using fMRI prior to and after completing an 8-week remediation. At the end of the training period, the scores of the dyslexic children in language and reading tasks were in the normal range. As to brain activation, changes were seen both in areas found active in normal readers, demonstrating a "**normalization**" trend, and in several other areas, endorsing the "**compensation**" hypothesis. The intervention used in this research was successful in increasing neural activity in left temporo-parietal cortex and the posterior part of the left inferior frontal gyrus, however it did not reach the activation level of non-impaired readers. In regards to compensatory effects, increased activity was found in several of the right hemisphere regions, including right inferior and superior frontal gyri, and middle temporal gyrus. The authors suggest that the remediation program altered brain areas related to the sound structure of language, which led to improved language and reading.

Shaywitz and associates (2004) explored the effects of a phonologically mediated reading intervention. 49 dyslexic children were divided into two groups, 37 were individually trained and the rest received the training commonly provided by their schools. During the intervention, one-on-one tutoring took place daily for 50 minutes over 8 months. fMRI images were collected before the mediation, after the mediation and 1 year later. The results show significantly greater increase in reading fluency in the trained as compared to the non-trained group of dyslexic children. Neural activity developed in anterior (inferior frontal gyrus) and posterior (middle temporal gyrus) reading systems in the left hemisphere, once again supporting the "**normalization**" hypothesis. In the third scan the trained children exhibited activation in bilateral inferior frontal gyri, left superior temporal sulcus, and occipito-temporal regions which are important for automatic word recognition. Two right side regions reduced activation following the intervention: the right middle temporal gyrus and the caudate nucleus, suggesting the possibility of cancelation of the compensatory mechanisms present before the intervention.

In Texas, a group of 27 children with reading difficulties, who were non-responsive to reading instruction during the first grade, underwent a two-phase intensive reading instruction (Simos et al. 2007a, b). During the first phase, decoding skills were trained (based on the Phono-Graphic program) for 8 weeks for 2 hours a day, and the second phase emphasized word recognition skills (based on the Read Naturally program) for 1 hour for an additional 8 weeks. MEG recordings were performed before training, after the first phase and after the second phase of the training. Eight children had significant reading skill improvement following the intervention, while the others failed to improve. Those participants who had significant reading improvement following the intervention showed "**normalization**" of both the temporal and spatial brain activity to that of non-impaired age matching readers. On the other hand, participants who did not show behavioral gains following the intervention had alternative, "**compensatory**," neural changes. The results emphasize that individual differences in response to reading intervention exist and they are to be considered when the intervention is administered.

In Italy, a group of 14 dyslexic children trained for 6 months on a phonological task (a standardized rehabilitative software, the WinABC), for 10 minutes, 5 days a week on a home personal computer (Penolazzi et al. 2010). The EEG and behavioral data were collected during two sessions, before and after the intervention period. The training was found effective, improving reading speed and also increasing beta activity in posterior areas on the left and anterior areas on the right.

The same research group report in another paper (Spironelli et al. 2010) their analysis of N150 patterns, the component corresponding to the visual word recognition potential, in the same group of dyslexic children undergoing the phonological training described above and matched controls. In dyslexic children before training, the N150 was distributed across hemispheres, as opposed to that of good readers, where the N150 was left posterior. After the intervention, a shift to left posterior sites was found, and it was more pronounced in children with greater reading speed improvement. A direct link between reading performance improvement and hemispheric reorganization is shown, suggesting that training can lead the brain systems of dyslexic children to get closer ("**normalize**") to those of non-impaired readers.

The following study differs from those described above in the target population it explores. The authors (Eden et al. 2004) chose to focus on adults suffering from reading difficulties, who are the majority of the dyslexic population. The participants were 19 dyslexic and 19 normally reading adults. The dyslexic group was further divided into two groups, a control group and intervention group. The latter group received structured multisensory intervention by means of a phonologically-based commercial program. This program provided auditory, visual, and sensorimotor stimulation; imagery strategies were used to visualize and manipulate letters and words. The training was conducted in small groups, on a daily basis, with 3 hour sessions for 8 weeks. An increase in phonological awareness and reading accuracy was reported for the trained group, while this was not the case with reading rate and comprehension. Using functional brain imaging techniques, increased activation in the left hemisphere inferior parietal lobule, the intraparietal sulcus and the usiform gyrus was reported, in line with the "**normalization**" pattern. On the right side, activation increased in posterior superior temporal cortex and angular gyrus, superior parietal cortex, and inferior frontal cortex, supporting the "**compensatory**" pattern (Table 5).

Table 5 Summary of evidence for "normalizing" and "compensatory" brain changes following training

	RD participants	Training description	Behavioral changes	Normalization changes	Compensatory changes
Simos et al. (2002)	Eight dyslexic children, age range 7–17 years	80 h of training on computer-based programs (The Phono-Graphix program and Lindamood Phonemic Sequence program).	Significant improvement in basic reading test, reaching average scores.	Increase in activity of the posterior portion of the left superior temporal gyrus. The new circuit slower than in non-impaired children, suggesting reduced efficiency.	
Temple et al. (2003)	20 dyslexic children, age range 8–12 years	8-week training on a computer-based program (Fast ForWord Language).	Significant improvement in language and reading ability, reaching the normal range.	Increase in activity **in left temporo-parietal cortex** and the posterior portion **of the left inferior frontal gyrus**, though not reaching the activation level of non-impaired readers	Increased activity in **right inferior** and **superior frontal gyri**, and **middle temporal gyrus**.
Shaywitz et al. (2004)	49 dyslexic children, age range 6–9 years	8 months, one-on-one daily phonologically mediated reading trainings.	Significant increase in reading fluency following training.	Neural activity developed in **inferior frontal gyrus** and **middle temporal gyrus** in the left hemisphere. Right side regions reduced activation following the intervention: the right middle temporal gyrus and the caudate nucleus (suggest dismissal of compensatory mechanisms).	

Simos et al. (2007a, b)	27 children with reading difficulties, non-responsive to reading instruction during the first grade	8 weeks of decoding skills training (based on the Phono-Graphic program), 8 weeks of word recognition skills training (based on Read Naturally program).	Reading skill improvement for a sub-group of eight children.	Children who improved behaviorally showed increased degree of activity and reduced onset latency in the posterior part of the **middle temporal gyrus**, decreased onset latency of activation of the **lateral occipito-temporal region** and increased onset latency in the **premotor cortex**.	Children with no improvement had increased duration of activity in the **right temporo-parietal** region and **frontal areas, bilaterally.**
Krafnick et al. (2011)	11 dyslexic children, age range 7–12 years	8-week training on a computer-based program (“Seeing Stars”).	Significant improvement in performance of reading and reading-related tasks.	GMV increase in the left **anterior fusiform/ hippocampus** and **precuneus**.	GMV increase in the right **cerebellum** and **hippocampus**.
Penolazzi et al. (2010), Spironelli et al. (2010)	14 dyslexic children, mean age about 10 years	6 months on a computer-based program (standardized rehabilitative software, the WinABC).	Reading speed significantly improved.	Increasing left beta activity in **posterior areas**, more pronounced with greater reading speed improvement.	
Eden et al. (2004)	19 dyslexic adults	8 weeks of training on a computer-based program.	Reading accuracy improvement was achieved	Increased activation in the left hemisphere **inferior parietal lobule**, **intraparietal sulcus** and **fusiform gyrus**.	Increased activation in the right **posterior superior temporal cortex** and **angular gyrus**, **superior parietal cortex**, and **inferior frontal cortex**.

A study by Kujala et al. (2001) of 7-year old children in Finland showed that a relatively short training program can be effective in improving reading and showed plasticity in the auditory cortex. The training involved audio-visual matching (between a sequence of sounds and a series of rectangles presented on screen). The children trained for 7 weeks, twice a week, for 10 min each session. Following the training, behavioral measures showed significant increase in reading accuracy, which was associated with changes at the early automatic neural level of sound discrimination observed in EEG. This study supports the use of non-linguistic interventions for improvement of reading ability and brain plasticity.

A group of 11 dyslexic children was studied for behavioral and grey matter volume changes following an 8-week reading intervention. The training program, called “Seeing Stars” (Lindamood-Bell Learning Processes), emphasized integration of internal visual and phonological representations. The effects on reading and reading-related tasks indicated, that from the behavioral point of view, the intervention was successful. GMV was measured using fMRI at three times: before the intervention, at the end of the intervention and after a period of no intervention. Intervention-specific increase in GMV was found in anterior fusiform/hippocampus and precuneus (in the left hemisphere), and in the cerebellum and hippocampus (on the right), and it was maintained after the no intervention period (Krafnick et al. 2011).

Not only grey matter, but also white matter changes were studied in an attempt to understand the possible impact of intervention on reading. The networking of the neurons, which enables good communication between different brain areas, plays a significant role in cognitive performance in general, and reading skills in particular. Keller and Just (2009) investigated the hypothesis that reading difficulties might be caused by some properties of the white matter connecting brain areas involved in reading. A 100 hour program of intensive reading instruction was used as an intervention for 35 children who read poorly. Following remediation, the children showed a significant increase in phonological decoding ability and an increase in the neural transmission efficiency in the left hemisphere. The low fractional anisotropy (FA) among poor readers was increased following the training, most pronounced in the left anterior centrum semiovale. This research provides further support to the claim that behavioral treatment can cause improvement of reading ability and an increase in the structural integrity of the white matter cortico-cortical connections.

As can be seen from this brief summary of studies, both behavioral improvements and brain activation changes for reading can be achieved by means of training. A close connection between different brain alterations and reading skills was found, suggesting that given the proper training, the brain can be stimulated to “rewire” in a manner supporting normal reading. It remains to be resolved as to the exact type, duration, scheduling and other characteristics of the intervention program that will lead the dyslexic population to the enhancement of reading skills. It is important to note that individual differences in the behavioral effects and in the neural changes were reported, suggesting that the optimal training might need individualization and personalization.

6 Challenging the Brain: The Reading Acceleration Phenomenon and Training

6.1 *The Acceleration Phenomenon*

The acceleration phenomenon originated from the unexpected, counterintuitive and consistent data (Breznitz 2006) indicating improvement in word-decoding processes, reading fluency and connected text comprehension by accelerating the input of reading stimuli to each reader individually according to performance. The discrepancy that was found among all levels of readers between the actual performance (self-paced) and the observed ability (performance under time constraints at which information is being processed) (Breznitz 2006) has served as a basis for the acceleration phenomenon manipulation (Breznitz and Berman 2003 for review). The acceleration phenomenon has been demonstrated in both typical and developmentally reading disabled readers (DRD) of different ages (Breznitz 2008). It was also replicated in different languages, including English (Berninger et al. 2011), Dutch (Snellings et al. 2009), German (Korinth et al. 2011) and French (Plaza and Breznitz 2007). Several explanatory domains are possible candidates for accounting for these findings. Accelerating reading rate can aid the information processing system by overcoming the limitations of key cognitive elements in reading (see Breznitz 2006 for review). It was proposed that accelerated reading helps to increase the focus of attention on reading materials and reduce distractibility (Breznitz 1988; Breznitz and Misra 2003), effectively directs perception to the reading materials (Breznitz and Misra 2003), overcomes some of the limitations of working memory capacity and its rapid decay, thereby enhancing word retrieval from the mental lexicon (Breznitz 1997b; Breznitz and Share 1992; Horowitz-Kraus and Breznitz 2009; Shiran and Breznitz 2011) and bypasses some of the phonological difficulties exhibited in the word-decoding process (Breznitz 1997a). Accelerated reading rate was found to improve the dyslexics' grapheme-phoneme correspondence by enhancing the integration between visual and auditory processing (see the "asynchrony theory," Breznitz 2006, 2008; Breznitz and Misra 2003). In spite of its complexity, reading might share some important elements with basic perceptual-motor skill learning, which has been shown to profit from enhanced speed of stimuli input. There is ample evidence showing that processing time can be effectively shortened through the imposition of objective, individually set, time-constrained parameters on sensory input during task performance. An effective approach to the induction of more efficient perceptual learning is to have these time limitations further shortened according to performance gains, as training progresses (Karni and Bertini 1997; Karni and Sagi 1993). Moreover, time-limited training can result in robust improvements in performance, even in adulthood and in basic perceptual tasks, and the gains are consolidated in memory. In summation, it can be concluded that for several cognitive reasons, all levels of readers have the ability to read faster than their routine reading rate and by doing so decode and comprehend the text more effectively.

The above-mentioned research provided the framework for the development of a computer-based training program, the Reading Acceleration Program (RAP) (Breznitz and Nevat 2004), designed to provide effective interventions for reading enhancement of dyslexic readers. The concept of this program is based on accumulative data regarding the ability of the brain to change at all ages, the way that the brain acquires, processes, and retains knowledge, and the concept that challenging the brain will cause more effective performance, as was demonstrated in the earlier sections of this chapter.

6.2 The Reading Acceleration Program

The RAP is an individualized, computer-based training program that adapts to each subject's skill level. At the initial stage, the program measures the level of achievements of each subject in a diagnostic mode across 18 items and individually adapts the training accordingly. The program includes a large data set of reading items for readers ranging in ages from 4th grade to adult. The items are comprised of narrative and informative connected texts (1.5–3.5 lines each) at various levels of difficulty, with a multiple-choice comprehension question following each item. The order of items presented during the training is randomized. Each training unit includes 25 training sessions, about 15–30 minutes each. Each session contains 50 items (based on the subject's age). The subject is requested to train four times a week, and can do so individually without mediation of a counselor or a teacher's help.

6.2.1 The RAP Training Procedure

Before the first training session, the initial presentation rate for the first session is established for each subject. This is based on the highest per-letter reading rate achieved in the diagnostic mode of an item that is correctly understood when the subject reads the items at self-paced reading rate.

Each item in the training sessions appears on the computer screen fully and begins to be erased from the computer screen letter-by-letter in the direction of reading. Acceleration is achieved by using the following adaptation pattern: Whenever a participant makes more than two comprehension errors within ten consecutive items, the program decreases the erasure rate by 2 ms/letter. If participants answer correctly in eight out of ten consecutive items, the erasure rate remains constant. If only one or no comprehension errors occur within a sequence of ten sentences, erasure rate is increased by 2 ms/letter (Breznitz 1997a, b). In this way, erasure rate is adapted five times per training session. Each new training session starts at the rate that was reached at the end of the previous session.

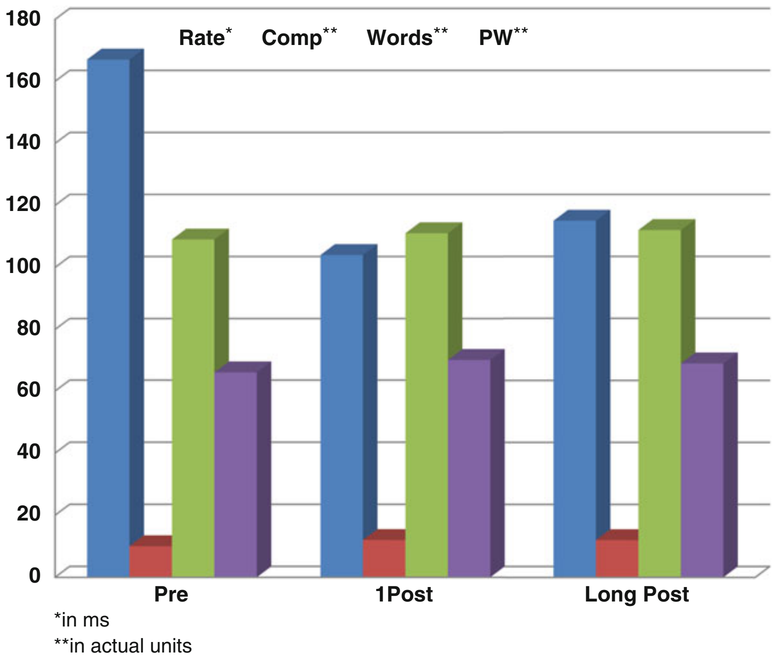

Fig. 1 The RAP effect on regular leaders at grades 3–4 (N = 40): pre-, post- and long-term post-training effect objective measures

At the end of a unit of training sessions, the program has an additional diagnostic mode. This final stage measures the self-paced reading rate of the subject after the training has been completed.

6.2.2 The Experiments

Several experiments in different languages were designed to verify the effect of the RAP. Subjects were 3rd–9th graders and adult university students. The samples included regular and dyslexic (−1.5 s.d. reading score) readers.

Generally, in most of the studies, dyslexic readers improved reading performance. The effects were shown in post-training objective measures. For example, Breznitz and Amiel (2010) and Brande (2011) trained 3rd–5th grade dyslexic and regular Hebrew-speaking readers by comparing several training protocols. Among others, the intervention programs included training with and without the acceleration manipulation and training with and without a nonlinguistic program. Each training program included 24 sessions of about 15–20 minutes each for 3–4 times per week. Pre- and post-test comparisons revealed a clear superiority of the accelerated reading training on decoding and comprehension of both groups; however, the dyslexic readers' reading performance gained the most from the RAP (see Figs. 1 and 2). Also, Berninger et al. (2011) reported positive effects on

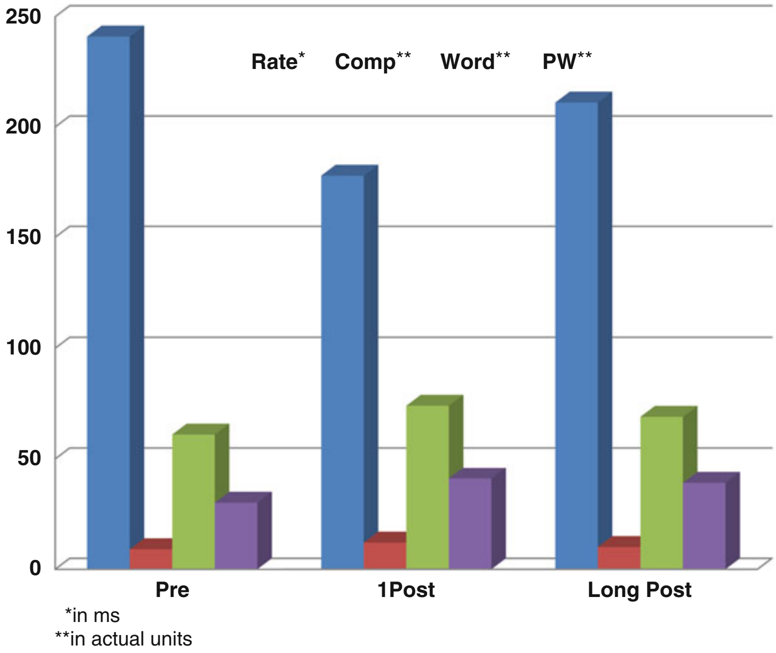

Fig. 2 The RAP effect on dyslexic leaders at grades 3–4 (N = 40): pre-, post- and long-term post-training effect objective measures

reading fluency in samples of English-speaking impaired readers in 4th–9th grades. Similar results were obtained in French (Plaza and Breznitz 2007) and in Arabic (Shany and Abu Ahmad 2010).

Snellings et al. (2009) applied the RAP training to Dutch children with and without reading impairments, but used only nine training sessions. Similar to Brande (2011), they compared the two groups, which received either accelerated or self-paced reading training. After this relatively small number of training sessions, the authors could show that participants could be pushed to read significantly faster without a substantial loss of comprehension. Importantly, in Brande (2011) and Breznitz and Karni (2009), the effect of the RAP training remained for at least 6 months after training. The 6 month results were better than reading achievements prior to training, but not as good as the immediate post-training results, suggesting that the dyslexic readers might need constant "booster" support.

What is it about the RAP training that challenges the brain? It can be suggested that the imposition of time constraints (acceleration phenomenon) and the use of complex material in training, enhance brain and behavior processing and result in much improved, higher competency in reading fluency and comprehension. Furthermore, forcing the readers to read faster seems to improve cognitive task performance such as perception and working memory (Korinth et al. 2011; Shiran and Breznitz 2011). Moreover, in Breznitz and Karni (2009), a study on adult dyslexic readers, the effect of RAP training was also shown in brain parameters (Table 6).

Table 6 The effects of RAP training on reading skills: decoding fluency and comprehension among adult university students (N = 62)

	Pre-RAP training		Post-RAP training		
	Mean	S.D.	Mean	S.D.	T
Decoding: Correct words per minute	78.18	13.79	84.15	10.46	3.66**
Decoding: Errors in connected text	6.18	4.64	3.36	2.29	3.05**
Fluency: Reading time of connected text in sec (247 words)	372.96	162.95	261.28	71.94	3.97**
Comprehension: Number of correct answers (out of 20)	14.01	1.02	18.26	1.28	3.71**

**$P<.05$; $P<.01$; $P<.001$

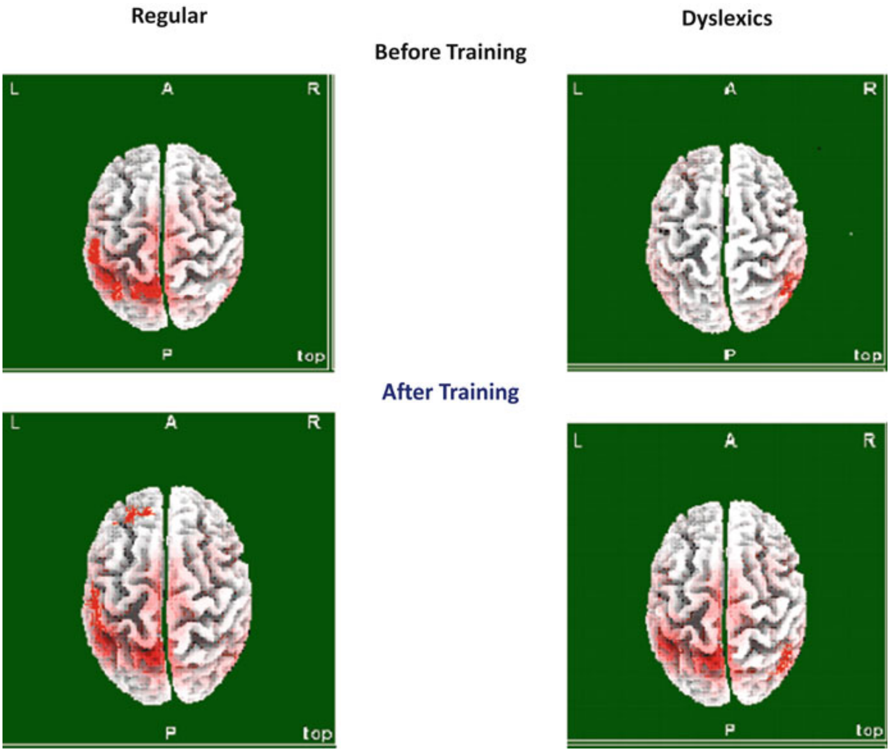

Fig. 3 Loreta at N170 ERP component during lexical decision task

Post-RAP training measures, such as brain imaging (fMRI) to determine areas of brain activation, (Karni et al. 2005) and electrophysiological measures (see Fig. 3) to determine temporal brain activation patterns (Breznitz and Karni 2009) and task performance, such as behavioral accuracy and reaction time parameters (Breznitz 2006 for review), indicated that the brains of dyslexic readers after RAP training enhanced and adequately used existing circuits ("**normalization**" hypothesis) as well as created new circuits (the "**compensation**" hypothesis) (Breznitz 2008).

It can be suggested that new brain circuits may be generated and alternative processing routines may be triggered as a result of an innovative training protocol incorporating time constraints and complexity. The RAP effect was found among young and adult dyslexic readers (Breznitz 2008) and supports the notion that changes in the brain may occur throughout one's lifespan. Because a brain system for reading never evolved in humans, the brain must rely on systems devoted to other skills. It is clear that adequate training can enhance brain systems to accommodate and process information that evolutionarily were not in their protocol. Overall, the results of the RAP training can be an example of establishing both novel fundamental and applied perspectives on literacy skill acquisition with potential impact for neuroscience, education and developmental psychology. By advancing the notion of skill as it applies to literacy, the Reading Acceleration Program will significantly advance the dialogue between literacy education and the neuroscience of skill acquisition and retention of knowledge among both typical and atypical learners.

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The Error Detection Mechanism Among Dyslexic and Skilled Readers: Characterization and Plasticity

Tzipi Horowitz-Kraus, Ph.D.

The error detection mechanism, which is part of the human cognitive control system, is intended to prevent an error repetition. Its activation can be measured by the elicitation of two event-related potential components: error (ERN) and correct-related negativities (CRN). This chapter details the evidence of the existence of this mechanism among dyslexics, despite their tendency to repeat reading errors. Because the mechanism is part of the brain's learning circuitry, its ability to change naturally during development and following intervention programs aimed at improving dyslexics' reading ability is also discussed.

1 The Error Monitoring Mechanism and Error-Related Negativity

Several studies have shown that when errors are made on a cognitive task, a neural mechanism is activated that elicits a negative electrical component, known as the Error Related Negativity (ERN) or Ne. The electrical activity of this component can be observed by electroencephalogram and by Event Related Potential (ERP) methodology (Falkenstein et al. 1991; Gehring et al. 1993). The ERN is evoked 0–160 milliseconds (ms) after an erroneous response and is characterized by a fronto-central distribution across the scalp, especially prominent in the anterior cingulate cortex (ACC) in the pre-frontal cortex (PFC) (Gehring et al. 1993).

Various hypotheses have been put forth as to how an ERN is evoked. Falkenstein et al. (1991) postulated that the monitoring mechanism is comprised of a "comparator," which compares the representation of the desired response with the representation of the actual response. Errors are revealed when a mismatch occurs between the two

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representations (Scheffers and Coles 2000), in which case an error signal is elicited towards the "action remedial system," which is responsible for correcting the action and delaying or repairing the error (Scheffers and Coles 2000). The degree of mismatch between the desired and actual responses is directly manifested in the ERN amplitude (Bernstein et al. 1995). Support for this hypothesis was provided by Sebastian-Galles et al. (2006), who demonstrated that the presence of the desired stimulus representation in comparison to the actual stimulus representation will evoke a larger negative potential than a situation in which one of the components is absent.

Other researchers examined the ERN component as part of the cognitive learning system in the brain (Gehring et al. 1993; Holroyd and Coles 2002). Gehring et al. (1993) demonstrated an association between the ERN and the number of error correction and error compensation mechanisms, although these mechanisms were shown to be secondary to the error monitoring duty of the ERN component. It was further hypothesized that the compensation and correction mechanisms are activated following evocation of the ERN, and that the ERN is directly related to the creation of the error signal rather than to the error correction process per se (Bernstein et al. 1995). According to another hypothesis, the error detection mechanism is activated as a result of conflict rather than by the actual performance of an error (Yeung et al. 2004); and that the time of appearance and degree of conflict is expressed in the ERN latency and amplitude, respectively. Other studies pointed to additional psychological factors influencing the error detection system, such as emotional factors: worries cause an increase in ERN (Hajcak et al. 2003); and motivation and empathy positively correlate with its amplitude – the higher the motivation/empathy the higher the ERN in case of a mistake (Santesso and Segalowitz 2009). Social skills were also found to be positively correlated with ERN (Dikman and Allen 2000).

Still other studies pointed to the evocation of another negative component, known as the correct-related negativity (CRN), which is elicited following a correct response (Pailing and Segalowitz 2004; Scheffers and Coles 2000). It was suggested that this component is evoked in response to imprecise perception or incomplete processing of a stimulus, which causes uncertainty regarding the desired response (Scheffers and Coles 2000). In addition to claims that the response evaluation process itself results in a CRN (Falkenstein et al. 2000), it has been argued that uncertainty about the quality of task performance may result in a CRN (Pailing and Segalowitz 2004).

Another study examined the effect of the demands of a task on CRN (Scheffers and Coles 2000). Using a Flankers task with a stimulus that adapted its color to the background throughout the experiment and became gradually less distinct, this study showed that when subjects evaluated their performance as definitely incorrect despite precise performance the CRN component is evoked with a higher amplitude. However, this component always appears with lower amplitude than that of the ERN, which appears after definite erroneous performance (Vidal et al. 2003). Furthermore, the CRN is not observed on tasks in which subjects are assured of their performance (Davis et al. 2001).

Subject's response time was also suggested to have an effect on the activation of the error monitoring system. Herrmann et al. (2004) demonstrated that reaction time to incorrect responses is usually shorter than for correct responses and indicates an impulsive reaction. Studies that examined the effect of reaction time on ERN evocation revealed that impulsivity does not enable complete processing of the stimulus and leads to an incomplete representation of the desired response. Thus, the response is executed prior to full target processing, resulting in the elicitation of an ERN (Herrmann et al. 2004; Pailing and Segalowitz 2004; Scheffers and Coles 2000). The ERN can also be evoked when the response is executed prior to stimulus presentation (Scheffers and Coles 2000). Furthermore, when subjects were forced to respond before the task time window, the level of ERN evocation increased even for correct responses. This elicitation was restricted to a time-constrained task from which subjects deviated (Vidal et al. 2003).

Nieuwenhuis et al. (2001) suggested that lower ERN amplitude is the result of the absence of one of the components (the desired or actual response) rather than a lack of correspondence between the two. In another study, subjects designated an expected end time beyond which they considered their performance to be "too late," resulting in the evocation of an ERN (Coles et al. 2001). However, when subjects' responses prior to the end of the test were determined by the subjects themselves without external pressure or impulsivity, an ERN was not evoked (Vidal et al. 2003). In addition, the ERN amplitude will be higher when the task instructions emphasized the importance of accuracy rather than time constraints (Scheffers and Coles 2000).

2 Location of the ERN and CRN Evocations in the Brain

Studies using electroencephalography as an experimental tool have revealed that the ERN component is elicited in the ACC (Scheffers and Coles 2000). The ACC, which is strongly connected to the PFC, sends and receives neural transmissions to and from regions in the PFC. The PFC is a highly developed neocortical area in primates. It is in charge of the cognitive (executive) control, which orchestrates between internal thoughts/intentions and a suitable action toward a desired goal. These abilities include top-down processes that humans engage in towards a certain goal such as planning, reasoning, language production, solving of complex tasks, allocation of attention resources, working memory (WM) abilities and performance monitoring (i.e., error detection, feedback evaluation). The executive control is capacity limited, which makes it difficult for some individuals to perform two tasks at the same time. The parts of the PFC activated most vigorously during executive control monitoring are the left dorso-lateral pre-frontal cortex (DLPFC) (Brodman area 9), and the ACC (Brodman area 24, 32), which is part of the limbic system. The left DLPFC is involved mainly in response preparation, allocating the attention demands for a given task, while the ACC is responsible for monitoring post performance (i.e., error and conflict monitoring) (MacDonald et al. 2000). The ACC is divided into sections that contribute in an unequal manner to monitoring activity and monitoring the response process (Luu et al. 2003). The dorsal region tracks the task parameters, such as feedback, while the Rostoventral region is responsible for evaluating the efficacy of responses (Luu et al. 2003).

The ACC's activity is related to the PFC insofar as this area suspends the "stimuli-reaction" presentation and is responsible for reaction choice and its delay. Moreover, the PFC distinguishes correct responses from error responses. Given that the ERN is evoked as a result of uncertainty regarding the correct response, it is also possible that this component is elicited from the ACC as a default in the absence of feedback from the PFC (Pailing and Segalowitz 2004).

Holroyd and Coles (2002) outlined a neurobiological explanation for the elicitation of ERN, based on the transmission of dopamine to the PFC by the basal ganglia. When there is a lack of correspondence between the desired and actual responses, and the outcome is worse than expected by the subject, there is a temporary decrease in the level of dopamine secretion from the mezencephalon to the PFC in general and to the ACC in particular. This decrease causes the pyramidal neurons in the ACC to de-polarize and generate the ERN potential. The ERN's dependency on dopamine has been illustrated in studies on Parkinson's patients, whose decrease in dopamine levels in the brain resulted in a smaller ERN as compared to controls (Falkenstein et al. 2001).

3 Research Fields in the Area of Error Monitoring

Most of the studies conducted in the area of error monitoring have demonstrated ERN and CRN elicitation in response to non-linguistic cognitive tasks, such as Flankers tasks (in which the subject is instructed to respond to a certain pattern in one way and to a second pattern in another way) or Go/No Go tasks (in which the subject is instructed to respond to a certain stimulus but not to another) (Herrmann et al. 2004; Scheffers and Coles 2000). These tasks depend mainly on perception, response regulation, and attention. Tasks requiring higher cognitive skills have also been used, such as the Four Choice Reaction Time task, which is time-constrained (Bernstein et al. 1995), and a Mental Rotation task, in which the stimuli are presented at an inverse or twisted angle (Band and Kok 2000).

Levelt (1983) was the first to examine the error monitoring mechanism in spoken language. Masaki et al. (2001) demonstrated that the ERN was elicited in response to spoken language errors on a Stroop task. Others argued that the ERN is part of language perception processing, with error negativity being elicited during articulation errors (Ganushchak and Schiller 2006) and errors in the auditory-linguistic domain (Sebastian-Galles et al. 2006). In Sebastian-Galles et al.'s (2006) study on error negativity among bilingual Spanish-dominant and Catalan-dominant speakers, the subjects were required to distinguish between words and pseudo-words presented in Catalan in the auditory domain. The researchers showed that in contrast to Catalan-dominant speakers, the Spanish-dominant speakers did not differentiate between correct and incorrect phonological representations and exhibited lower ERN and higher CRN amplitudes due to high levels of uncertainty. The researchers reported that the non-existence of the correct response representation resulted in a lower mismatch between correct and actual responses. In this case, a higher amplitude ERN was elicited in the Catalan-dominant group. Considering that the error monitoring mechanism exists in the auditory-linguistic domain, we tried to determine whether it existed also in the reading domain among skilled readers (Horowitz-Kraus and Breznitz 2008). We found that an error in recognizing a word as a real word in a lexical decision task elicited an ERN, and correct responses elicited a smaller negativity – CRN. Differences were found between error monitoring for pseudo-words reading, which represents decoding, and real words reading, which represents orthographic skills. Skilled readers exhibited a higher ERN for words, presumably due to a larger mismatch in their mental lexicon between the desired and the actual outcome. The claim that erroneous processing among regular processors elicits ERN in specific brain regions (Herrmann et al. 2004; Luu et al. 2003; Scheffers and Coles 2000) raises the question of whether this mechanism exists in impaired populations in general, and in learning disabled, both of whom exhibit PFC deficit or demonstrate executive control impairments.

4 E-Regularities in Activity of the Error Monitoring System

According to the literature, subjects whose PFC activation differs from healthy controls also show different ERN amplitudes. Segalowitz and Dywan (2009) pointed to psychopathy as affecting the general cognitive function, causing a reduction in ERN, and found that obsessive-compulsive disorder patients exhibit a higher ERN. Ito (2004), on the other hand, found that lack of dopamine neuroreceptor in the *substantia nigra* among Parkinson patients caused a reduction in ERN amplitude due to lower PFC activation (Ito 2004). Bi-polar subjects were found to have reduced ACC activity with slower reaction times than controls, but with similar accuracy rates (Gruber et al. 2004).

There are also several developmental disorders that cause a reduction in executive function ability, such as Attention deficit hyperactive disorder patients (ADHD) (Van De Voorde et al. 2010b; Lioti et al. 2005; Burgio-Murphy et al. 2007), dyscalculia (Burgio-Murphy et al. 2007) and dyslexia (Horowitz-Kraus and Breznitz 2008, 2009; Van De Voorde et al. 2010b; Burgio-Murphy et al. 2007). The error detection mechanism was investigated in these populations when data indicating executive control deficits among subjects with dyscalculia began to accumulate (Ashkenazi et al. 2009), and working memory problems, higher error rates and variable response times were reported in subjects with ADHD (Van De Voorde et al. 2010a). Results on ERN amplitude varied in these studies: some found it reduced among ADHDs (Lioti et al. 2005), others found its elicitation (Burgio-Murphy et al. 2007), no effect on its size (Wiersema et al. 2005), or no difference between error and correct responses (van Meel et al. 2007). This variability in results might be due to the task and/or age differences. The one study dealing with dyscalculia and error monitoring suggested a higher CRN due to abnormalities of this system among this group (Burgio-Murphy et al. 2007). Dyslexic readers were also found to exhibit higher error rate and variable response times compared to controls on cognitive tasks (Van De Voorde et al. 2010a).

5 Dyslexia and Reading

Dyslexia is characterized by slow and inaccurate reading (BPS 1999). Although the exact cause of dyslexia is not known, several theories have been raised to explain it (e.g., phonology: Snowling and Nation 1997; asynchrony theory: Breznitz 2006; orthography: Brunswick et al.; morphology: Nagy et al. 2006; slow speed of processing: Breznitz 2006, and self-teaching: Share 1995). All agree that dyslexics' reading is defined by repeated reading errors. Share (2004) argued that dyslexic readers exhibit difficulties in creating and/or storing and/or retrieving lexical patterns from the mental lexicon and that the decoding process of these readers is impaired. Compared to regular readers, their reading is characterized by a high incidence of word and letter transposition, word omission (Adams 1990), and hesitation (Facoetti et al. 2000).

Few studies have examined the error patterns of dyslexic readers. Thomson (1978) found a different pattern of errors in reading among dyslexic compared to regular 10-year-old readers, with the dyslexic children performing semantic errors while the regular readers performed syntactic errors. Another study examined the effect of the deliberate insertion of letter replacement errors on accuracy and comprehension during oral reading among good and poor young readers (Breznitz 1987). In some cases, those errors resulted in nonsense words ("toys"/"loys"), and in others in contextually unrelated real words ("bread"/"dead"). The regular readers were able to automatically identify and correct the errors, either by reading the word correctly despite the error or by reading it incorrectly at first and then correcting for the error. However, the poor readers did not identify or correct the deliberate errors and read the words incorrectly as typed. Likewise, Walczyk (1990) examined the ability of regular and weak fourth grade readers to identify logical mistakes that had been deliberately inserted into the text. It was concluded that impulsive children experience difficulty in detecting contextual errors because they use an erroneous global processing strategy for reading (Walczyk 1990).

Breznitz and Gilore (submitted) examined the response of fourth grade dyslexic readers to decoding errors compared to controls matched for chronological and reading age. The task required the reading of a text that contained target words which appeared a number of times throughout the text. The regular readers immediately corrected their inaccurate reading of any target words the next time they encountered the same words in the text, thereby ensuring that no errors were repeated during subsequent encounters. In contrast, the dyslexic readers made more errors when reading the target words despite previous encounters and did not correct their errors in subsequent encounters. In addition, the target word decoding errors were not consistent: the incorrect reading of the target words was different for each encounter.

The researchers concluded that the dyslexic readers lack stability in their accurate as well as inaccurate word patterns in the mental lexicon. It remains to be seen whether that lack of stable correct word patterns stems from an inability to monitor errors.

The "self-teaching" theory deals with decoding acquisition and focuses on the reader's ability to identify letter strings and encode them into words (Share 2004). This theory purports the existence of a self-teaching mechanism that enables the reader to translate printed letter strings into their verbal form (phonological decoding), a mechanism that facilitates the identification of new words and, in turn, the acquisition of precise reading. It is possible that there is a connection between the self-teaching and an error monitoring mechanism whose purpose is to correct errors and/or learn from them (Holroyd and Coles 2002). In other words, the same mechanism that enables precise decoding may also trace incorrect decoding moves so as to allow the reader to learn from them. Share (2004) suggested that the self-teaching mechanism is impaired or even absent in dyslexic readers.

6 Reading Errors Among Adult Dyslexics

The majority of studies conducted in the area of dyslexia have focused on young readers, who are primarily occupied with the initial and/or foundational stages of the reading process. While some adult dyslexics may succeed in overcoming and compensating for their decoding difficulties, others seem unable to overcome the problem. Consequently, the two groups are defined as compensated and uncompensated dyslexics.

Despite the attempts to compensate for the phonological failure, the reading of dyslexic readers is not completely without errors. Recent studies have indicated that adult dyslexics continue to experience difficulties performing different phonological tasks as evidenced by slower and less accurate performance compared to regular readers (Ransby and Swanson 2003). Since error monitoring is the component of the learning circuit responsible for preventing error repetition, the question arises whether a error monitoring exists in this group.

7 ERN and Dyslexia

A number of studies attempted to document the existence of the error detection system in dyslexics. Reading disabled children were found to exhibit a higher CRN for correct responses and no differences in ERN compared to ADHD subjects in a version of the Go/Nogo task, implying some impairment in error monitoring function (Burgio-Murphy et al. 2007). Others found smaller ERN-CRN gaps in reading disabled compared to non-reading disabled children due to lower ERNs for the Go/NoGo task (Van De Voorde et al. 2010a, b). The authors suggested that reading disabled children have problems with the detection of an error, reflected in lower ERNs.

We set out to determine whether there is a difference in the ERN during reading errors committed by adult university dyslexics and matched skilled readers. A lexical decision task was employed consisting of words and pseudo-words (Horowitz-Kraus and Breznitz 2008) – a design that also enabled us to differentiate between orthographic and phonological skills. Skilled readers exhibited lower ERN amplitude for pseudo-word errors than for word errors. Reading words as opposed to pseudo-words involves not only decoding skills but also semantic information. The higher amplitude of the ERN component exhibited during word decoding errors might represent wider dimensions of activation than occur with pseudo-words. The higher amplitude for words compared to pseudo-words might also be due to the larger mismatch between the neural representations for the actual and desired responses for words. It is possible that in the case of pseudo-words, which are meaningless, the desired response in the mental lexicon is absent, resulting in a lower ERN amplitude.

That the brain activity of dyslexic readers during error performance was expressed by the ERN component in this study, as it was in the skilled readers, was clearly shown. The finding of significantly lower ERN amplitude for the dyslexic readers may stem from the fact that both the dyslexic and skilled readers were university students with extensive exposure to printed materials and remedial assistance. Over the years the dyslexic readers probably managed to create a monitoring system for the detection of decoding errors in the brain, albeit a less-than-efficient one. Limited experience with correct word patterns stored in the dyslexics' mental lexicon may affect the development of an effective error detection monitoring system during reading (see also Share 2004 and Breznitz 2006). This finding might shed light on the reasons for the lack of a consistent error pattern in reading in this population.

There were no significant differences between the two groups in CRN amplitude for correct responses. It was lower in amplitude than the ERN when a task's uncertainty was low or when the ERN amplitude was high due to a detected error. However, the difference between the CRN and ERN amplitudes was significantly larger among skilled readers compared to the dyslexic readers. This discrepancy resulted from higher ERN amplitudes among the skilled readers, and lower ERN amplitudes among the dyslexic readers.

Based on these results, it can be suggested that a skilled reader's brain decodes automatically and therefore requires a reduced level of activity, and the electrical activity increases when errors are being committed. Both processes are apparent in the lower CRN and higher ERN amplitudes for these readers. In contrast, patterns of correct and erroneous processing are not always distinguished by the dyslexic brain during word decoding, and the information regarding the word is entered into the mental lexicon in an inefficient manner, resulting in a smaller difference between the CRN and the ERN amplitudes.

This study (Horowitz-Kraus and Breznitz 2008) also demonstrated a longer ERN than CRN latency and longer reaction times for both dyslexic and skilled readers. Thus, it is suggested that the errors made by both groups did not stem from impulsivity, guessing, or lack of attention to the task, but rather from hesitation and an attempt to find the correct answer. It is possible that the error monitoring function requires additional time for each group to detect an error.

The longer ERN latency for words compared to pseudo-words in this study suggests a longer search in the mental lexicon for the desired representation among both groups. These results broaden our understanding of the findings of another study that showed larger gaps in processing time for correct and incorrect responses among the dyslexics as compared to the skilled readers (Horowitz-Kraus and Breznitz 2010). During incorrect reading, the impaired reader may search for the appropriate representations in the mental lexicon, which takes longer and increases the reaction time; and, in the absence of those appropriate representations, the mismatch obtained leads to a lower ERN amplitude. The fact that no large difference is evident between the CRN and ERN amplitudes in the impaired readers may mean that their learning system in reading does not work effectively and their mental lexicon cannot be properly constructed.

An alternative explanation for the differences in ERN and CRN evocation among dyslexics cannot be ruled out. The mismatch theory (Falkenstein et al. 1991) claimed that there is a stage of multiple comparisons between neural representations of the actual and desired responses prior to the mismatch itself. It can be argued that among dyslexic readers, the error detection mechanism is impaired in the comparisons stage rather than in the mismatch itself. Further research is needed to clarify this point.

The deficit in the error monitoring system among adult dyslexics was found by us (Horowitz-Kraus and Breznitz 2009) also in the non-linguistic domain, (hence in a working memory task). Together with their poorer working memory abilities (Ackerman and Dykman 1993), dyslexic readers exhibited lower ERN amplitudes in errors made on the Sternberg task (Horowitz-Kraus and Breznitz 2009). It was assumed that the absence of the entire set of presented digits in their working memory (the phonological loop) resulted in a smaller mismatch. We also found a positive correlation between ERN and working memory abilities for both dyslexic and skilled readers, indicating that lower working memory capacity results in a lower ERN amplitude.

The reliance on working memory abilities exists also in reading, especially in the case of contextual reading. The differences between reading isolated and contextual words were previously studied using behavioral measures (Kutas and Hillyard 1983). Kintsch (1998) attempted to characterize the different stages of reading comprehension in the Construction-Integration model, which divides sentence reading into two phases: a construction phase and an integration phase. The construction phase focuses on the decoding of a single word and the elaboration of its semantic meaning in a bottom-up manner, while the integration phase entails combining words into sentences, paragraphs, and stories and is based on previous knowledge and context. Due to the different demands of these two reading levels, it was only reasonable to find differences in the error detection mechanism activity following the reading of isolated words vs. sentences. We found that errors in sentence reading yielded a lower ERN and a smaller ERN-CRN gap than following word reading for both dyslexics and skilled readers, but especially among dyslexics (Horowitz-Kraus and Breznitz 2011). Since sentence reading relies also on working memory abilities, and since working memory overload reduces the activity of the error monitoring system (Hochman and Meiran 2005), ERN following errors in sentence reading was reduced. As for the skilled reader, it can be assumed that decoding errors occur at the top-down level, during the integration phase, and not at the construction stage, which relies on basic skills already mastered. In this case, the mismatch might be lower but the conflict might be higher, resulting in a lower ERN and smaller ERN-CRN gaps.

An investigation of the behavioral differences (e.g., reaction times and accuracy) between correct and erroneous reading of sentences and isolated words and of letter naming among dyslexics and skilled readers revealed that errors yield longer reaction times in both groups (Horowitz-Kraus and Breznitz 2010). This might indicate that errors in reading among dyslexics occurred despite their attempt to process, and were not due to impulsivity. Another interesting finding was the positive correlation of reaction time for letter naming with errors for letters, words and sentences among both groups. Thus, the basic skill of letter naming underlies for words' and sentences' reading abilities. These results concur with those of Katzir et al. (2006).

In everyday reading it is possible to read a number of sentences, realize an error has been made, and then reread those sentences correctly. The reason for this delayed correction in contextual reading might be the appearance of the ERN component upon realization of making an error, rather than at the precise moment of error. Additional studies should be carried out to verify this assumption.

8 Error Monitoring in the Level of Processing

An interesting question arises as to why an error occurs. It can occur either due to a misperceived stimulus or to processing difficulties. Studies dealing with error monitoring conducted their studies with stimulus-locked components in order to provide an answer to this question. A number of them found differences between regular and dyslexic readers in amplitude and latency of ERP components, such as the N100, P300 and the P200 (see Breznitz 2006 for review). These differences may constitute evidence of a different pattern of brain activity in stimulus-level processing in these two groups of readers.

Other studies dealing with brain activity during reading identified the N400 component, which is attributed to higher cognitive abilities such as semantic processing and semantic integration (Breznitz 2001; Robichon et al. 2002). The N400 is a negative component, which is evoked approximately 400 ms post-stimulus presentation and is centro-posteriorly distributed (Breznitz 2001; Robichon et al. 2002). Kutas and Delong (2008) argue that the N400 is not evoked in response to any specific written or spoken word, but rather in response to a semantically meaningful stimulus. The researchers also claim that the N400 amplitude is affected by word frequency, repetition, location within the sentence, semantic association, and word predictability within the sentence.

Other studies demonstrated a stronger elicitation of the N400 component in response to a non-word, compared to the relatively minor elicitation evoked by the search for lexical meaning on a lexical decision task (Bentin 1987; Rugg and Nagy 1987; Sebastian-Galles et al. 2006). In addition, the N400 component was elicited with a higher amplitude when reading unexpected compared to expected sentence endings, leading the researchers to hypothesize that amplitude size reflects the ease or difficulty of retrieving previous knowledge from semantic memory (Kutas and Federmeier 2000).

Horowitz-Kraus and Breznitz (2008) found a higher N400 amplitude prior to errors than to correct responses both for words and pseudo-words among both skilled and dyslexic readers. This might reflect the incongruity during erroneous processing. When the skilled reader decodes a word in an erroneous manner it does not match any semantic meaning and therefore results in higher N400. However, dyslexics in this study exhibited a higher N400 prior to correct responses than skilled readers did, leading the authors to conclude that for dyslexics, a higher N400 might reflect a search for meaning to a printed word in their mental lexicon, which is impaired. This search was longer for dyslexics than for skilled readers, presumably because of their non-automatic word decoding, and resulted in a longer N400 latency and longer reaction time. This study pointed to different processing prior to erroneous reading among dyslexic readers in the semantic processing stage. Can these differences be changed?

9 Plasticity of the Error Detection System

Despite the well documented differences in brain activity among dyslexic readers, clinicians and researchers support the use of intervention programs and training in all sub-components of reading (e.g., fluency, comprehension, vocabulary, decoding and spelling). These programs rely on the human brain's plasticity and its ability to change its activity (Karni 1996; Poldrack and Gabrieli 2000). This plasticity is enhanced by task repetition (Poldrack and Gabrieli 2000) regardless of age (Stiles 2000; Karni 1996). Because error detection monitoring is part of the learning circuit (Holroyd and Coles 2002), a change in its activity can be attributed to training, and that training will be reflected by a change in ERN or CRN. Here we will review the effect of two intervention programs on ERN and CRN and on error monitoring.

9.1 A Change in ERN Following WM Training

Several studies showed lower WM capacity among dyslexic than skilled readers (Ackerman and Dykman 1993; Smith-Spark et al. 2003). However, it was also shown that its capacity can increase following training, and that this change is accompanied by a change in pre-frontal and parietal cortices (Olesen et al. 2004).

Others reported an increase in the P300 component associated with larger WM capacity and reading improvement following WM training (Shiran 2009). We also found lower WM scores and lower ERNs among adult dyslexics as compared to skilled readers following errors on a Sternberg – WM task (Horowitz-Kraus and Breznitz 2009). In this task, subjects were presented visually with a series of five digits that appeared one after another, and were asked whether or not a certain visually-presented digit appeared (Sternberg 1966). Both groups were trained on the Cognitive program (CogniFit Personal Coach CPC training program and database 2008) which trained WM on the visual, auditory, and cross-modalities domain for 24 sessions (8 weeks, 3 times weekly). Both groups exhibited an improvement in WM measures and an increase in ERN size following training, but dyslexic readers gained even more of an ERN increase than controls. This change was accompanied by a reduction of errors on the task. It would appear that the lower your starting point the higher you can go.

In accordance with the Mismatch Theory (Falkenstein et al. 1991), when the WM capacity increases following training, more units can be stored there. Therefore, in the case of a mistake on the Sternberg task, both desired and actual responses are present, which enables a complete comparison between the two, resulting in a higher mismatch and a higher ERN because the level of mismatch is reflected in the ERN amplitude (Bernstein et al. 1995). The improvement in reading together with the improvement in WM suggests that when training a basic ability such as WM, the higher abilities such as reading and decoding also improve. Both groups showed a long post-effect of training and preserved their larger ERNs with only a slight decrease. These results point to behavioral and neurophysiological changes following WM training among dyslexics that are reflected in ERN size and underscore the ERN as a possible marker of these changes. It is encouraging that WM is trainable in dyslexics, both by electrophysiological (ERN/CRN) and behavioral (WM capacity) measures, since it is a basic cognitive ability that affects reading (which was associated in Bernstein et al.'s study (1995) with more words read per minute).

As reading is the main deficit shared by dyslexic readers, a question arises as to the effect of reading training on the above mentioned parameters (ERN and CRN). Will training the specific deficit of this disorder have a greater effect on ERN? Is the change in ERN following training specific basic abilities such as WM or, in other words, can we extend it to be a marker for the effectiveness of higher-level training?

9.2 A Change in ERN Following Reading Training

The Reading Acceleration Program (RAP) is a reading training program based on speed as a means to improve reading abilities (Breznitz and Nevat 2004). The program removes the written material from the computer screen letter by letter, followed by a question to verify reading (for more details see Breznitz and Nevat 2004). This enhancement, or 'acceleration' manipulation, was found to increase attention span and reduce destructibility (Breznitz 1997a, b, 2001), and to improve WM capacity, which helps to improve reading (Breznitz 1997b). In accelerated reading more written units must enter the working memory system and match meaning in the mental lexicon (Breznitz 1997a, 2008)

Several studies emphasized the effect of this program on brain activity in general and on brain activity of dyslexic readers in particular (Karni 1996), which demonstrated a reduction in Broca's area (Brodman 44–45) in these readers following training. In another study (Breznitz 2006), training with RAP reduced reading errors and rate among children and adult dyslexic readers in several orthographies.

An increase in ERN amplitude was reported in adult university participants, both dyslexic and skilled readers, following RAP training, (Horowitz-Kraus and Breznitz 2011) associated with a higher accuracy rate following training. The increase in ERN-CRN gap was more pronounced among dyslexic readers than skilled readers. These results might reflect the effect of RAP training on the construction of the mental lexicon among dyslexics: since RAP increases the WM capacity, it is possible that more letters and syllables are combined into words, raising the number of words stored in the mental lexicon. It was assumed that the larger the mental lexicon the larger the mismatch between the desired and actual responses, resulting in a higher ERN and higher accuracy rate. The greater training gain displayed by dyslexics in improved reading scores and awareness of errors may also reflect the view that the lower the starting point the higher the subject can reach. Support for this assumption is the correlation of this increase in ERN with reading abilities.

9.3 A Change in ERN During Reading with Development

Another intriguing aspect of the error detection mechanism is its ability to change with age. ERN was found to increase from childhood to adulthood in a natural manner, without the use of intervention (Davies et al. 2004), and was associated with shorter reaction times. These changes were attributed to the physiological changes with age of the ACC and the PFC (myalinization, increase in dopamine secretion), which affect the psychological aspects involved in response regulation (e.g., control of behavior, self evaluation of response) (Davies et al. 2004). The PFC is activated more vigorously and quicker in adults, reflected in higher ERNs. All studies investigating this phenomenon concentrated on the non-linguistic domain, using mainly Go/NoGo and Flankers tasks. However, this phenomenon was also observed in reading among dyslexic and skilled readers. We found that skilled teenage readers also exhibited lower ERNs associated with lower accuracy and slower reaction time than skilled adult readers (Horowitz-Kraus, 2011), suggesting the same developmental characteristics of the error detection system also hold for reading, probably because of the maturation of the PFC and the natural development of reading ability over time. Because the teenagers who participated in the study were 12–15 years old, it was assumed that they had attained a reading efficiency similar to adults at the single word level (Chall 1983). This led us to assume that the mental lexicon develops with age, resulting also in more words that are recognized holistically. Based on these findings, one can conjecture that the mental lexicon is incomplete in childhood, and the resultant larger mismatch between the desired and the actual responses produces the higher ERN. This is also the reason for smaller amplitude differences between dyslexic and skilled teenagers than between dyslexic and skilled adults (Horowitz-Kraus and Breznitz 2011). Dyslexic readers exhibited the same developmental trend: their ERN increased with age, with an associated larger number of words and pseudo-words read per minute. However, since the ERN-CRN gap among the dyslexics was found to be smaller than among skilled readers, it can be claimed that although they exhibit a reading deficit, the error detection mechanism of the dyslexics is also plastic, although it is activated to a lesser extent than in skilled readers.

10 Epilogue

This overview of the field points to the existence of the error detection monitoring mechanism in the reading process. The activity of this mechanism is manifested on cognitive tasks in the elicitation of the ERN and CRN components during incorrect and correct responses, respectively. This mechanism is dynamic and adapts its activity, both behaviorally and electrophysiologically, to various levels of processing. Cognitive load on this mechanism may impair the error monitoring process, accounting for the decrease in ERN amplitude in both dyslexic and regular readers.

Previous reports argue that a low ERN amplitude stems from rapid or impulsive processing, which results in error commission (Scheffers and Coles 2000). One can extrapolate from this that the low ERN amplitude among dyslexics results from rapid and impulsive processing; this would be wrong, however, as evidenced by the amplitude of the N400 component amplitude in this group, which indicates an attempt at processing and a search for lexical meaning. Dyslexics' longer processing time during incorrect response was apparently due to their attempts at processing verbal stimuli. In general, the timing of processing is a function of the complex processes that take place during error monitoring. It is possible that the error monitoring process, which is comprised of a number of processing stages, was impaired in the dyslexic readers due to the slow speed of information processing. Given their slow speed of processing it would be interesting to examine whether the error monitoring difficulty is specific to the reading process or is a general error monitoring difficulty among dyslexics. Exactly what stage in processing fails and results in an error among dyslexics remains elusive. Whether it is at the perception stage, the processing stage, or the semantic level (as was suggested earlier) remains to be answered. Answering this question could point to the most suitable intervention programs for this population.

Moreover, this deficit in the error monitoring among dyslexics raises the well-known chicken and egg dilemma. On the one hand it can be argued that the lack of a stable mental lexicon results in insufficient word representations. This causes a smaller mismatch and higher levels of conflict because the desired response is missing, which results in a smaller gap between ERN and CRN amplitudes in dyslexics. On the other hand, it can be argued that due to an impaired error detection mechanism, the dyslexic reader cannot learn from his/her reading mistakes and therefore cannot construct a stable mental lexicon. A solution to this dilemma may come from examining the effect of linguistic training.

Recent research has documented the ability of the brain to change following training. As the error monitoring mechanism is part of a broader learning system in the human brain, the training programs described here may have trained the brain and taught impaired readers to learn from their mistakes. If the difficulty encountered by dyslexic readers in monitoring their reading errors is connected to their slow speed of information processing relative to regular readers, it is possible that reading training using the RAP, which includes rapid information processing, can lead to better decoding, improved efficiency of the error monitoring mechanism, and construction of a stable mental lexicon. These changes can be measured by ERN, whose increasing amplitude usually goes together with the increase in accuracy rate, making ERN a reliable electroencephalographic tool to measures the changes/effects of training. It is also encouraging that the dyslexic brain is able to change its activity following training even in its damaged domains, such as working memory and reading. Add to this the evidence that the dyslexic brain changes and improves its error detection monitoring in reading, as observed also among skilled readers, without any intervention program, and the value of interventions programs for this population becomes even more significant. Further research is needed, especially on the effect of intervention programs on the error detection mechanism in different developmental stages.

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Reading in More Than One Language: Behavior and Brain Perspectives

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A majority of people in the world today speak more than one language (Edwards 2004), though the contexts of bilingualism vary greatly. Some individuals are raised in bilingual environments or societies, others are faced with the need to learn the language of a new environment following immigration, and still others study a foreign or additional language in a school setting. Bilingual individuals differ in various dimensions including their proficiency in each of the languages and the age at which they were acquired, the degree to which they use each language for educational, recreational and economic purposes, and of most relevance for the present discussion, the level and trajectory of literacy development and attainment in each of the languages. Literacy development is a complex process even under the simplest circumstances of a monolingual individual learning to read in her native language. Various factors contribute to literacy acquisition and shape its outcomes. As will be described below, almost all the contributors to first language (L1) literacy are also involved in second language (L2) literacy, but L2 literacy is uniquely influenced by aspects of first language literacy and by transfer across languages. Further, there is much greater variation in the language proficiency and exposure patterns of individuals acquiring literacy in the L2 than is normally the case for L1 literacy acquisition. Thus, reaching a full description and understanding L2 literacy is a challenging enterprise.

A recurring theme throughout this chapter will be the interplay of commonalities and differences in first and second language reading. Some commonalities can be attributed to universal theories of reading (e.g. Perfetti 2003), because in all languages writing is mapped to spoken language, and the goal of reading is always extracting phonology and meaning from print. Other commonalities are most likely the result of cases where there are specific similarities between the pair of languages examined in a given study, for example, two alphabetic languages of similar transparency (e.g. Italian and German, Wartenburger et al. 2004).

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Divergences between first and second language reading can also be a result of different circumstances. In some cases, these differences will be a manifestation of inherent differences between the writing systems examined, exemplified by findings of similar differences between L1 readers of the two languages. However, in other cases differences will be a true manifestation of the added complexity of mastering two writing systems, and the unique two-way influence of orthographies on each other. Additionally, the specific attributes of L2 reading, such as limited proficiency in the spoken language, may also come into play.

In the first section of the chapter I will briefly describe bilingual language representation, focusing on the degree to which the two languages of bilinguals rely on common or distinct cognitive and neural substrates, at different levels of processing. I chose to include this section in the current review because it is important to remember that literacy constitutes only one facet of the complex skill of language knowledge and proficiency. Indeed, the acquisition of literacy presupposes some level of proficiency in the spoken language. As the goals of reading are the extraction of phonological and semantic information from print, we should consider how the phonological and semantic representations in the L2 map onto those of the L1, and the possible interactions between the two systems. Further, some of those interested in literacy development in speakers of two languages are less familiar with the body of research focusing on language representation more generally in bilinguals. I believe that this literature can have a positive contribution to research and theorizing about literacy development, and can inform work in this domain.

In Sect. 2, I will then present cross-linguistic research on reading, investigating how different orthographies are acquired and processed by native speakers of the respective languages. I will then rely on these two bodies of knowledge in Sect. 3 to consider how literacy is acquired in two languages, either simultaneously or consecutively, and how skilled reading is influenced by the presence of more than one orthography. Finally, after presenting the current state of knowledge, in Sect. 4 I will offer suggestions as to how differences in orthographic features might play out in literacy in various L1-L2 pairings.

1 Language Representation and Processing in Bilinguals

Research on how two linguistic systems are organized within the brain and cognitive systems of bilinguals has focused on three main issues. First, the question of representation, and the independence of each language or to what degree languages rely on shared resources at different levels – phonetic, lexical, semantic and grammatical. The second issue relates to language activation and whether the cognitive system can effectively “switch off” a language that is not task-relevant at any given moment, in order to allow for uninterrupted use of the other language. Finally, there is growing interest in the cognitive and brain mechanisms that control language selection and activation in bilinguals and second language learners – whether these are domain general or specific dedicated functions within the language system, a topic that will receive only brief attention in this chapter.

1.1 Semantic Representation

Most current models of bilingual language representation distinguish between lexical and semantic representation, claiming separate mental lexicons for the two languages, but a shared semantic network (Francis 2005; Van Hell and DeGroot 1998). The Revised Hierarchical Model proposed by Kroll and Stewart (1994; for a recent reassessment see Kroll et al. 2010) describes the development of the bilingual lexicon in second language learners. According to this model, at first words from the L2 activate their meaning only via words from the first language. However, with growing proficiency, words in the second language can activate their meaning directly, without first language mediation. Eventually, words in both languages have direct conceptual links to semantic representations that are mostly but not completely shared.

Evidence for shared semantics comes from findings of semantic priming effects from one of a bilingual's languages to the other (Basnight-Brown and Altarriba 2008; Keatley et al. 1994; Schoonbaert et al. 2009). Additionally, conceptual representations of words in the L2 seem to be shaped by L1 semantics (Jiang 2000) and recently is has also been demonstrated that a second language learned later in life can influence conceptual representations even when they are activated through the L1 (Degani et al. 2011). However, the degree of overlap in meaning between words in the two languages of bilingual speakers can be modulated by different factors, including word type (Van Hell and DeGroot 1998) and ambiguity in translation (Prior et al. 2007; Tokowicz and Kroll 2007).

1.2 Lexical Activation

As for activation, there is abundant evidence that, perhaps counter-intuitively, both languages of proficient bilingual speakers are constantly active. Thus, it seems that the intention to speak in one language is not sufficient to suppress all activation of the other language (for a recent review see Costa 2005). This might be especially true in non-balanced bilinguals speaking in the second language (Kroll et al. 2006), but is not limited to this population. Similarly, lexical candidates become activated in both languages, even in a monolingual setting, both for auditory (Spivey and Marian 1999) and, of greater interest in the present context, for visual word recognition (for a recent review see Dijkstra 2005).

I will first present research on cross-language activation in bilingual visual word recognition that has been conducted on populations that read two languages that share the Roman alphabet, most notably the work of Dijkstra and colleagues on Dutch-English bilinguals. Findings from several different paradigms have demonstrated convincingly that under these conditions word recognition and lexical access are language nonselective, meaning that word candidates in all the languages that the reader knows become active following exposure to the letter string.

To illustrate, Van Hell and Dijkstra (2002) asked participants to perform a lexical decision task in Dutch, their native language, and examined the effect of cognate status – cognates are words the have similar phonology and meaning across languages (*bakker* in Dutch and *baker* in English). All participants were highly proficient speakers of English, their L2. Participants in one group were also advanced learners of French, whereas the other group had only limited knowledge of French. Some of the Dutch words in the experiment had cognates in English and others had cognates in French, but never in both languages. Importantly, participants were recruited without any reference to their foreign language knowledge, and at no point during the experiment did they receive information that knowledge of languages other than Dutch was relevant for task performance.

Results showed significant cognate facilitation, expressed by shorter reaction times, for Dutch-English cognates by all participants, and for Dutch-French cognates by the high-proficiency French trilinguals. This means that although participants were performing a lexical decision task in their native and strongest language, the stimuli activated lexical information in a task-irrelevant weaker language. These findings constitute a strong demonstration of nonselective lexical access in visual word recognition, though a threshold level of proficiency in a language has to be met before information is automatically activated.

Effects of non-selective lexical access have also been demonstrated for interlingual homographs, words that share orthography but not meaning (and often differ in phonology as well) across languages. Thus, the word *room* in Dutch means cream. Several studies have found that interlingual homographs are processed differently than words that unambiguously belong to one of the languages (e.g. Beauvillain and Grainger 1987; Dijkstra et al. 1999). The direction of the effect (facilitation or inhibition) depends on the specific task parameters introduced in each study, but its presence is evidence that such stimuli activate representations in both languages. Finally, cross-language effects have also been demonstrated in experiments examining orthographic neighborhood (e.g. Van Heuven et al. 1998) and word frequency effects (Dijkstra et al. 1998).

There are only a few studies that have examined cross language activation in languages that do not share a script. Generally, semantic facilitation effects are found for languages that don't share a script (e.g. Chen and Ng 1989). An interesting study by Gollan et al. (1997) showed cross linguistic masked translation priming in a lexical decision task, for Hebrew and English, languages that differ not only in script but in reading direction as well (Hebrew is written from right to left). Primes in the L1 facilitated the processing of their translations in the L2, for both Hebrew dominant and English dominant bilinguals. The priming effect was stronger for cognates than for non-cognates. The authors ascribe this pattern of results to links between translation equivalents at the lexical level, and claim that the phonological form similarity of cognates results in stronger links for these items, when compared with non-cognates. They further suggest that distinct orthographies provide a salient cue for language membership of visual words forms, which can allow for more efficient lexical access, possibly limited to the relevant lexicon.

1.3 Neural Representation

Studies of brain function and language localization in bilinguals mostly give rise to results converging with the behavioral studies presented above. Generally speaking, first and second language processing are overall supported by the same brain areas, with extensive overlap with language areas identified for monolinguals. Nonetheless, brain activation patterns in L2 are modulated both by the proficiency in the language and in some circumstances by age of acquisition as well.

Studies examining bilingual language production in highly proficient bilinguals, regardless if they acquired the L2 at an early age or later in life, have found very similar patterns of activation for both languages. However, bilinguals with lower proficiency in the L2 recruited more brain tissue when producing words in the second language, and activation went beyond the classical language areas (Abutalebi et al. 2005). A study examining multilinguals who spoke four languages each, found that producing words in less proficient languages lead to wider left hemisphere activation, especially in prefrontal areas (Briellmann et al. 2004).

Studies of written and spoken language comprehension reveal similar patterns, at least as far as semantics are concerned – wider and more variable activation for less proficient languages (e.g. Dehaene et al. 1997), with minimal influence of age of acquisition. For example, a recent longitudinal study focusing specifically on single word processing examined native English speaking exchange students shortly after arriving in Germany and 5 months later, and compared the activation patterns for reading words in English and in German. Initially, words in German, the foreign and less proficient language, evoked greater frontal activations than words in English, the native language. However, several months later these differences were significantly reduced, due to the participants growing proficiency and experience in reading German. Thus, lexical-semantic processing of first and second languages converges onto similar networks when differences in proficiency diminish, and when both languages are alphabetic (Stein et al. 2009).

However, a different pattern emerges for syntactic processing. Wartenburger and colleagues (2004) tested three groups of Italian-German bilinguals: one group of highly proficient bilinguals who had learned both languages at an early age, and two groups of late learners – one of highly proficient speakers of German and the other of less proficient speakers. Participants read sentences in both languages, and performed two tasks in different experimental blocks. Results showed that when participants performed a semantic judgment task, answering the question "does this sentence make sense?", activation patterns were highly similar for L1 and L2 for both high proficiency groups, but low proficiency participants activated wider areas when processing the L2 than when processing the L1, corroborating previous findings. However, when participants performed a grammaticality judgment, answering the question "is this sentence grammatically correct?," a different pattern emerged. In this case, the early high-proficiency bilinguals activated highly overlapping brain areas for grammatical processing in the two languages, but both of the late learner groups showed significantly larger activations when processing grammar in the L2, in Broca's area and in subcortical structures. This last finding is especially striking, since in terms of their accuracy on the task, the high proficiency late learners were indistinguishable from the early learners. This study demonstrates that different aspects of language processing are variably sensitive to factors such as proficiency and age of acquisition.

1.4 Bilingual Language Representation – Conclusions

To summarize, behavioral studies show largely parallel and nonselective activation of the two languages of high-proficiency bilinguals. Thus, for bilinguals whose two languages share an orthography, it seems that words in any language activate both lexicons in a search for appropriate candidates. Further, visual word recognition is influenced by properties of the word in all the languages a person knows, at least beyond a minimal level of proficiency. For languages that do not share a script, it seems that lexical and semantic links again provide the means for cross language activation. Imaging studies demonstrate that L1 and L2 of highly proficient bilinguals are mostly supported by the same neural tissue. For less proficient users, processing in the second language recruits additional neural resources that often extend beyond classical language areas.

The large degree of overlap in language representation and processing for bilinguals might lead to the prediction that literacy related skills and abilities acquired in the L1 would be available for reading in the L2 as well, leading to strong positive transfer effects and commonalities in performance across languages. At the same time, the language non-selective access demonstrated for bilinguals could imply strong cross-linguistic interference in reading. Such effects might be expressed in transfer of non-appropriate strategies and schemas, and could necessitate bilingual readers to recruit control mechanisms that are not usually recruited by monolingual readers. A better understanding of how these issues might play out requires first a consideration of the degree of similarity of reading in different orthographies, and the possible differences arising from the unique properties of various writing systems. This issue will be presented in the next section.

2 Reading in Different Orthographies

Reading is a complex skill that relies on several linguistic and cognitive subcomponents (Vellutino et al. 2007). In acquiring literacy individuals must first learn to map orthography to phonology, a task that requires visual identification of letters, the ability to isolate spoken speech sounds or phonological awareness, and the working memory capacity allowing linking up one to the other. With time and practice readers acquire fluency in word decoding, allowing them to automatically map orthography to phonology and allocate attentional resources to the task of high level text comprehension. At this stage, extracting meaning from print also relies on syntactic and lexical knowledge of the spoken language, and on general cognitive, memory and inference skills. The specific roles played by the various subcomponents can change along the trajectory of literacy acquisition, and are also influenced by the characteristics of different writing systems. Most of the research reviewed in this section focuses on the earlier stages of reading, namely decoding and lexical access, whereas less time is devoted to reading comprehension.

Orthographies can differ in the basic mapping principles of graphemes to phonemes, and a main distinction is between logographic orthographies which represent phonology at the whole word or morphemic level, and alphabetic orthographies which are used in the majority of modern languages, and that represent smaller phonological units directly with letters or letter combinations. However, even alphabetic languages differ in the complexity of the system or orthographic depth (Katz and Frost 1992). Thus, certain orthographies, such as Spanish or German, are very consistent in the way that graphemes represent phonemes, whereas in other orthographies, such as Danish or unpointed Hebrew, the mapping between letters and sounds is less straight forward. Alphabetic scripts also differ in the level at which they are consistent, or the grain size of the correspondence between the orthographic and the phonological information (Ziegler and Goswami 2005). In this section I will review the implications that the differences outlined above between scripts have for literacy acquisition and skilled reading on the behavioral level, and for the neural basis of reading.

2.1 *Literacy Acquisition*

Several studies have compared the progress of literacy acquisition in different orthographies (e.g. Caravolas et al. 2003; Ellis and Hooper 2001; Seymour et al. 2003). Seymour and colleagues conducted a large-scale study of first grade children in 14 European countries, learning to read in as many different orthographies. Children learning to read consistent shallow orthographies made rapid progress in literacy acquisition. For example, children learning to read Finnish, Greek and German, which all have shallow and consistent orthographies, reached ceiling levels in accurately decoding both words and non words by the end of the first year of instruction. On the other hand, children learning to read more complex and less consistent orthographies, such as French or Danish, displayed relatively high error rates at a parallel point of instruction. Further, children learning to read in English were significantly delayed when compared to children acquiring literacy in other languages, and had error rates of over 50% even after a full year of instruction. The extreme difficulty encountered by children learning to read in English can be attributed to the great depth and opacity of the system, as noted by Share (2008).

It is difficult to directly compare reading acquisition in logographic orthographies, such as Chinese, to reading in alphabetic languages because of the inherent differences and the challenge of constructing parallel tests. However, children learning to read Chinese first receive instruction in Pinyin, an alphabetic script in which letters from the Roman alphabet represent phonemes in Chinese, in a highly transparent and consistent manner. Children learn this script rapidly, and become highly competent in decoding it (Hanley 2005), and continue to use it throughout elementary school at least, to allow them to pronounce novel characters independently. These findings can be seen as another example of rapid and successful acquisition of a shallow and consistent orthography. As for the development of competence in reading Chinese characters, children in mainland China are expected to master approximately 2,400 characters by the end of elementary school.

Besides learning rates and trajectories, the question arises whether literacy acquisition in different orthographies relies on the same underlying cognitive skills, a question that will receive more attention in Sect. 3, discussing the transfer of literacy skills between the languages of bilingual readers. Most research has addressed the role of phonological awareness in literacy acquisition, and the bidirectional influences between phonological awareness and learning to read. Thus, initial phonological awareness allows children to begin isolating phonemes and correctly establishing the mappings between them and the newly acquired graphemes. At the same time, increasing practice with letters and sounds leads to greater sensitivity to individual phonemes and an improved ability to manipulate them. Phonological skills, at least at the phonemic level, seem to have lower predictive value for literacy acquisition in Chinese, for example, than in alphabetic orthographies (Hanley 2005). Further, Ziegler and Goswami (2006) argue convincingly that the exact nature of the phonemic representations most important for effective reading acquisition varies across languages, as a function of their orthographic properties.

A recent cross-linguistic study investigated the role of phonological awareness, memory, vocabulary, rapid naming and nonverbal intelligence in predicting the reading performance of second graders across five orthographies, varying in their depth from transparent (Finnish) to relatively opaque (French) (Ziegler et al. 2010). Results demonstrated that phonological awareness was the strongest predictor of decoding and word reading in all the orthographies examined, followed by rapid naming that predicted speed of performance in most orthographies, and phonological memory and vocabulary that were weaker predictors of performance in some of the languages. Nonverbal IQ was not related to reading as measured in this study in any of the participating countries. More interestingly, however, the strength of the relation between phonological awareness and single word reading and non-word decoding was modulated by orthographic depth. Thus, phonological awareness was a weaker predictor of performance in transparent than in opaque orthographies. The conclusion is that the predictors of literacy acquisition and decoding in alphabetic languages are relatively universal, though the specific weights may differ depending on the characteristics of specific scripts.

2.2 Skilled Reading

In addition to literacy acquisition, skilled reading also differs across orthographies. The orthographic depth hypothesis (Frost et al. 1987) and the psychological grain size theory (Ziegler and Goswami 2005, 2006) both claim that reading in different orthographies is not identical and that the depth of an orthography, as well as the structure of a language, can influence skilled reading (Frost 2005). Specifically, it is argued that readers of shallow orthographies rely mainly on assembled phonology, namely recovering the phonological representation of the word from print, because in shallow orthographies this process is relatively easy and simple. Conversely, readers in deep orthographies rely more on larger phonological units, and/or use an impoverished and only partly-specified phonological representation to access the lexicon and retrieve lexical information that in turn guides the composition of a fully specific phonology and ultimately lexical access (Coltheart et al. 2001; Frost 2005).

A study demonstrating the influence of orthography on skilled reading was conducted by Ziegler et al. (2001), who compared adult readers of German, a shallow orthography, and English, a deep orthography, naming the exact same words and non-words. The English readers exhibited strong effects of body and rhymes, which are relatively large units. Conversely, the German readers' naming performance was affected by the number of letters, or overall length, of both words and non-words. The authors interpret these results as demonstrating that skilled readers of different orthographies rely on variously sized units that have proven themselves effective throughout the reader's experience with the orthography. Thus, readers of deep orthographies rely on large-sized units, whereas readers of shallow orthographies rely on the smallest possible units, namely single phonemes.

Frost (2009) has further argued that lexical access in languages that differ in morphological structure is qualitatively different, due to different organizing principles of the lexicon. In a detailed comparison of Hebrew and English, two alphabetic orthographies that are very different in morphological structure, he demonstrates striking differences in performance. There are strong effects of orthographic information facilitating word recognition in English and other European languages, both in masked priming (e.g. Davis and Lupker 2006) and in parafoveal facilitation (Rayner 1998). However, the effects of morphological information are not as consistent in these languages in both research methodologies. In Hebrew, on the other hand, the opposite pattern of effects is observed – robust facilitation from morphological information in masked priming (Frost et al. 2005) and parafoveal preview (Deutsch et al. 2000), but no influence of orthographic information (Frost et al. 2005).

Finally, orthographic features also influence eye-movements in reading, and specifically the size and nature of the perceptual span, the space of characters from which information can be extracted during a specific fixation (Rayner 1998). For readers of English and other European languages, the perceptual span is asymmetrical, extending only 3–4 characters to the left of the fixated word, but 14–15 characters to the right. In orthographies written from right to left, such as Hebrew, this asymmetry is reversed. Thus, the perceptual span extends further towards the direction of reading. Additionally, the perceptual span is significantly smaller for readers of logographic languages such as Japanese kanji and Chinese, extending 1–3 characters to the left of the fixated character, and 3–6 characters to the right. This is most likely because these orthographies are densely packed visually, so that each character carries more information.

2.3 Imaging Studies

Additional evidence for the claim that orthographies with different characteristics are not processed identically comes from studies examining brain activation during reading. A PET study comparing readers of English and Italian (a deep and a shallow orthography, respectively) showed that overall similar brain areas are involved in reading. But, readers of Italian showed greater activation of the left planum temporale, which is involved in sublexical phonology, whereas English readers had greater activation in the visual word form area when reading non-words, probably due to heavier reliance on a strategy of analogy to existing words than Italian readers, who most likely relied more on phonological assembly (Paulesu et al. 2000). These differences in brain function are driven by the differences between the orthographies of the two languages which lead skilled readers to adopt different strategies.

A second study comparing reading in English with reading in Spanish using fMRI reports similar findings (Meschyan and Hernandez 2006). Namely, when reading words in Spanish, a highly transparent orthography, the superior temporal gyrus which is implicated in phonological processing was more highly activated than when participants read words in English. Reading words in English, on the other hand, lead to stronger activations in visual processing and word recoding areas, at the occipito-parietal border. However, these findings must be interpreted with caution, because the participants in the study were more proficient in English than in Spanish, a fact that might have influenced the findings.

Finally, a recent meta-analysis compared brain activity in individuals reading different scripts, by including fMRI studies of single word reading in alphabetic European languages, in the two scripts of Japanese (Kanji and Kana) and in Chinese characters (Bolger et al. 2005). It is important to stress that all studies included in the meta-analysis recruited native speakers/readers of the relevant language. The results reveal convergence across these vastly different writing systems, and identify a network of three brain areas in the left hemisphere that support reading.

These include the superior posterior temporal gyrus (BA22), the inferior frontal gyrus (BA6) and the occipitotemporal region, with foci both in the posterior fusiform and in the mid-fusiform gyrus, identified as the visual word form area. At the same time, there were also areas of divergence across the scripts examined. The exact localization of peak activation within the broad areas was different for logographic scripts (Chinese and Kanji) on the one hand and the alphabetic scripts (European languages and Kana) on the other. Without going into too much detail, the logographic scripts tended to activate areas more consistent with larger phonological units, and those that support the synchronous processing of phonological and semantic information. Reading in Chinese lead to activations in right inferior occipital and posterior fusiform regions, in addition to the activation of these areas in the left hemisphere that was observed for alphabetic scripts (see also Tan et al. 2005). The authors postulate that these activations reflect the need of Chinese readers to process the complex spatial information of Chinese characters.

2.4 Reading in Different Orthographies – Summary

To summarize this section, there is behavioral and neural evidence supporting the claim that there are aspects of literacy and reading that are universal. However, the specific characteristics of different orthographies have also been shown to influence the rate and predictors of literacy acquisition, the performance of skilled readers and the neural substrates involved in reading.

As far as the performance of bilinguals reading in two languages, the universal aspect of these findings can lead us to expect behavioral and neural commonalities, and transfer or sharing of literacy related skills across languages. However, the extent of such commonalities will probably depend on the degree of similarity between any two orthographies examined. For example, children acquiring literacy simultaneously in two orthographies that differ markedly in consistency might display different learning rates. Additionally, the utility and effectiveness of transferring literacy strategies from an L1 to an L2 will again be modulated by the degree to which the orthographies in question rely on similar mapping principles. The next section will describe studies examining such questions, and suggest a framework for conceptualizing reading in more than one language.

3 Bilingual Reading

3.1 Literacy Acquisition in More Than One Language

There is a moderately sized body of research examining children acquiring literacy in more than one language. In many cases, children are native speakers of one language, and learning to speak and read the second language. Whereas children acquiring literacy in their L1 learn to read words and syntactic structures that are already part of their oral repertoire, learners of a foreign language need to learn the new alphabet, the meaning of new words and syntactic rules simultaneously as they learn to accurately recognize the written form of these features (Geva et al. 1997). In other cases, children are proficient bilingual speakers of two languages, and are acquiring literacy concurrently in both.

Oral language skills relevant for acquiring orthographic decoding abilities and fluent word reading, including phonological working memory (e.g. Gholamain and Geva 1999) and phonological awareness (e.g. Gottardo et al. 2001), are mostly found to correlate across the two languages of children learning to read in an L2. Further, a review of the literature reports robust correlations across first and second language for word and for pseudoword reading (Dressler and Kamil 2006). Interestingly, correlations are of a similar magnitude for languages that share an alphabet (e.g. Spanish and English, Durgunoglu et al. 1993) and languages that do not (e.g. Persian and English, Gholamain and Geva 1999). Another recent large scale review (Lesaux and Geva 2006) also reported that children acquiring literacy in English as a less proficient L2 did not differ significantly from native English speaking children acquiring literacy in their L1 on measures of word reading accuracy and spelling ability. Additionally, similar factors, including phonological processing skills, phonological memory and rapid naming predicted reading performance for all children. However, the specific properties of different orthographies have been found to influence the amount of exposure necessary for accurate and efficient decoding.

To illustrate this point, I will describe several studies focusing on word reading in Hebrew and English, languages that differ in script and in orthographic transparency – pointed Hebrew (which includes vowel information) is considered a shallow orthography while English is a relatively deep orthography. Geva et al. (1997) recruited native English speaking children in the first and second grade, who were acquiring literacy simultaneously in English, their L1 and in Hebrew, their less proficient L2. The authors report robust correlations across the two languages in measures of accuracy and speed in single word reading. At the same time, the morphosyntactic density of Hebrew influenced the development of reading skill, and hindered the children's ability to reach high efficiency in reading texts in Hebrew. A second study testing a similar population, but extending up to fifth grade (Geva and Siegel 2000), found that memory skills predicted word reading in both languages, but that children read more accurately in Hebrew, a shallow orthography, than in English, a deep orthography (see also Gholamain and Geva 1999). Further, the decoding errors committed in the two orthographies were qualitatively different, due to their different nature. Schiff and Calif (2007), on the other hand, examined Hebrew speakers in the initial stages of learning English as a foreign language, and found a strong correlation between L1 and L2 word reading only when there was a deficiency in Hebrew orthographic-phonological or morphological awareness. Thus, they concluded that high scores on Hebrew orthographic-phonological and morphological awareness tasks do not necessarily ensure successful English word reading, possibly because of the fundamental differences between the two orthographies.

All three studies, therefore, point to some overlap in basic reading skills across Hebrew and English, but these are limited by the orthographic differences between the two writing systems, and by the linguistic differences, specifically at the morphological level. Additional support for this conclusion comes from another relevant study that focused on readers of English and Arabic, a Semitic language with many similarities to Hebrew. Again, participants were children who were native speakers of English studying Arabic as a second language (Saiegh-Haddad and Geva 2008). Results showed a significant correlation between phonological awareness in English and pointed transparent Arabic, but morphological awareness in the two languages was not correlated

The studies reviewed so far in this section focused on lower level processes in reading, specifically decoding and fluent word reading, and found mostly similarities across the two languages of young readers, though these might be limited by the degree of typological similarity across language and orthographies. However, when investigating higher level literacy skills, most notably reading comprehension, somewhat different patterns of results emerge. On the one hand, in a review of the literature, Dressler and Kamil (2006) report significant transfer of reading comprehension skills across the languages of biliterate children. Similarly, Gelderen et al. (2007) demonstrated a relationship between L1 (Dutch) and L2 (English) reading comprehension in adolescents, and a strong effect of metacognitive knowledge on L2 reading comprehension. At the same time, they found that language specific knowledge in the L2 significantly influenced reading comprehension outcomes.

However, in a comparison of reading comprehension achievement of L2 compared with L1 readers, larger gaps are evident than is the case for lower level reading skills such as single word decoding. Thus, in the same review by Lesaux and Geva (2006) that found comparable decoding performance for native English speakers and learners of English as a second language the latter group exhibited significantly poorer reading comprehension, most likely because of decreased oral language proficiency and limited vocabulary knowledge.

There is no doubt that a main building block of reading comprehension is the proficiency level of the language, whether it is a first language or an additional language. Various facets of proficiency have been identified in this regard, including vocabulary knowledge, syntactic awareness (Lesaux et al. 2006) and morphological awareness (Koda 2007) for both L1 (Vellutino et al. 2007) and L2 (Durgunoğlu 2002; Lesaux and Kieffer 2010). Gottardo and Mueller (2009) expanded the Simple View of Reading model (Gough and Tunmer 1986), which was initially proposed in the context of L1 reading, to encompass reading comprehension in the second language, and tested Spanish speaking first and second graders learning English as a second language. Results demonstrated that listening comprehension, vocabulary, syntactic knowledge and decoding in L2 were good predictors of English reading comprehension. Lesaux and Kieffer (2010) found a higher rate of poor comprehenders amongst sixth grade English language learners than among their native speaking classmates, but all poor comprehenders, regardless of language background had poor vocabulary skills in English. A study of 4th grade children comparing native speakers and children learning English as a second language (Lesaux et al. 2006), again confirmed similar profiles for good and poor comprehenders, regardless of their language group.

Before moving on to describe research dealing with biliteracy in adult readers, I would like to raise the intriguing possibility that simultaneous, or sequential, acquisition of literacy in two languages might confer advantages and lead to faster or more efficient learning. Schwartz and colleagues (Schwartz et al. 2005, 2008) examined the literacy development of Hebrew in the first grade among Russian-Hebrew bilinguals and Hebrew monolinguals. Importantly, half of the bilinguals had started acquiring literacy in Russian before beginning schooling in Hebrew, and were thus biliterate, whereas the others were bilingual speakers of both language, but were monoliterate in Hebrew. Results showed a clear advantage for the biliterates over monolingual and bilingual monoliterates in measures of reading fluency and phonological awareness. The authors ascribe this advantage to their early exposure to the fully fledged Russian orthography, which enhanced their ability to distinguish consonants from vowels, a skill that was then transferred to Hebrew.

Bialystok et al. (2005) addressed a similar question, by comparing four groups of first grade children in Canada acquiring literacy in English: English monolinguals, and three bilingual groups: Spanish-English, Hebrew-English and Cantonese-English. All bilingual groups were highly proficient in their oral use of the two languages, and were concurrently learning to read in English and in their other language. The Spanish-English and the Hebrew-English bilingual children outperformed the Cantonese-English bilinguals and the monolinguals on a phoneme counting task, exhibiting stronger phonological awareness skills. These advantages are most likely due to their exposure to two alphabetic languages, which enhanced the development of phonological awareness because of its critical role in decoding alphabetic scripts. Further, even after controlling for differences in phonological awareness, the Spanish-English and the Hebrew-English bilinguals outperformed the monolinguals in a decoding task in English, and the Cantonese-English bilinguals were at an intermediate level. Again, what is important here is that the similarity between the two orthographies being acquired modulates the degree of transfer of skills. Learning two alphabetic languages, even if they do not share the same script (Hebrew and English), enhanced literacy development and allowed children to generalize their emerging skills to a greater degree than learning a logographic and an alphabetic script (Cantonese-English). Further support for this conclusion can be found in the fact that reading in the two languages was highly correlated for the Spanish-English and the Hebrew-English bilinguals, who were reading two alphabetic languages, but was not related at all for the Cantonese-English bilinguals (for similar findings of divergence between reading skill in English and logographic languages see Gottardo et al. 2001).

3.2 Second Language Reading in Skilled Adult Readers of an L1

In comparison with research on literacy acquisition in children, less is known about the development and stabilization of reading skills in adult second language learners or bilinguals. Still, in this section I will present studies concerned with visual and phonological processing of L1 and L2 in this population.

Green and Meara (1987) found significant differences in visual search for shapes and orthographic symbols (Roman and Arab letters and Chinese characters) among readers of the different languages. Readers of Arabic and Chinese were compared with readers of English and Spanish, and were found to process symbol strings differently. Most importantly, even when searching strings of Roman letters, the Arabic and Chinese native speakers maintained the same search pattern that they had displayed in their native language, despite being intermediate to advanced readers of English as a second language. The authors conclude that word reading strategies established for reading in the native language are transferred to the second language, and seemingly do not change to accommodate the orthographic specificities of the new script.

Several additional studies provide consistent evidence that features of L1 orthography influence the reliance on different mechanisms and strategies in L2 reading. Koda (1988, 1990) found that L2 learners of English who had an alphabetic L1 (Arabic, Spanish) showed superior grapheme to phoneme conversion in English than did L2 learners who were L1 readers of Japanese, a non-alphabetic language. The alphabetic L1 readers were also more significantly impaired when confronted with unpronounceable words in an English text than were the Japanese L1 readers. Further, Akamatsu (2003) found that readers with a non-alphabetic L1 background (Chinese and Japanese) were delayed to a greater extent when reading an L2 English text that had been visually modified by using case alternation than readers with an alphabetic L1 background (Persian). Finally, Wang et al. (2003) compared college aged native readers of Korean (an alphabetic script) and Chinese learning English as a second language, and found that the former group relied more strongly on phonological processing, whereas the latter relied less on phonology and more on orthographic information when reading single words in English. Taken together, these findings demonstrate that mechanisms and strategies shaped by features of the L1 orthography are transferred to L2 reading, and continue to exert their influence even in fairly advanced readers. Specifically, readers with a non-alphabetic L1 background continue to rely on visual information even when processing an alphabetic L2, which leads to less efficient word processing.

A recent study by Ehrich and Meuter (2009) found similar effects, but in the reverse direction. Native speakers of Chinese and English were compared on their ability to learn an artificial logographic orthography. Chinese speakers outperformed the English speakers in a lexical decision task on the newly acquired symbols, an advantage that stems from experience with a logographic script. This finding demonstrates transfer of L1 logographic processing that is parallel to the previously described transfer of alphabetic processing from an alphabetic L1 to an alphabetic L2.

Wade-Woolley (1999) compared the decoding ability of L1 readers of Russian and Japanese in their L2, English. The Japanese readers were impaired relative to the Russian readers on a phoneme deletion task, but outperformed them in tasks of orthographic sensitivity. The two groups did not differ in their English decoding ability, but seemed to reach these comparable levels of performance in different manners. The L1 Russian readers relied more extensively on phonological processing, but the L1 Japanese readers recruited their strength in orthographic processing. These findings provide further support to the notion of transfer from L1 to the L2, and demonstrate that different linguistic backgrounds can allow for the transfer of different linguistic component skills, leading to qualitatively different outcomes despite an overall matched level of performance.

Fewer studies have examined reading comprehension in adult populations, but the extant evidence again supports the notion of cross-linguistic transfer and the influence of both L1 and L2 skills on L2 reading comprehension. Koda (1992) investigated native English speaking college students learning Japanese as a foreign language, and found that lower level skills, such as letter identification and word recognition in Japanese significantly predicted reading comprehension. Similarly, Nassaji and Geva (1999) tested adult native speakers of Farsi, who were advanced learners of English as an L2. They found that phonological and orthographic processing contributed significantly to reading comprehension and reading rate, but only orthographic processing remained a significant predictor after accounting for effects of syntactic and semantic knowledge of English.

Meschyan and Hernandez (2002) investigated native English speaking college students, in the first semester of acquiring Spanish as a second language. Decoding skills in English were found to correlate highly with decoding skills in Spanish. Further, Spanish decoding skill was found to mediate the ability of English decoding skill to predict vocabulary acquisition and final course grade in Spanish. These findings attest to significant transfer of phonological-orthographic ability from the native language to the second language among college-age adults, albeit across two alphabetic scripts using the same Roman alphabet. The results further demonstrate the importance of lower level skills in the L2 for language learning in general.

Several studies focusing on fairly advanced bilingual readers of Hebrew and English give rise to interesting findings. In one study of college-age readers, measures of word and pseudoword reading in the two languages were correlated (Oren and Breznitz 2005), and participants were equally efficient in reading the two orthographies, despite their differences. A second study again found significant correlations across the two languages, this time in measures of sentence comprehension (Breznitz et al. 2004), but in this case significant advantages emerged for processing Hebrew, the native language, over English, the L2. Shimron and Sivan (1994) reported that balanced bilinguals read English texts faster and showed better comprehension over text presented in unvoweled Hebrew. However, no differences were found between reading in English and reading in voweled Hebrew. The authors ascribe these findings to the specific challenge of reading in unvoweled Hebrew which is characterized by a paucity of phonological information, as well as the overall morphological density of written Hebrew, in both forms.

Finally, Velan and Frost (2007) tested the hypothesis that the structural differences between Hebrew and English, especially in morphological richness, would lead to different effects in reading the two languages. Balanced Hebrew-English bilinguals were tested with a letter transposition paradigm. Previous research in European languages has demonstrated that priming can occur from words with letter transpositions, such as *gadren* priming *garden*, and that reading text including transposed words does not cause great difficulty for readers in these languages. Hebrew morphology is based on three-letter consonantal roots, and many roots share the same consonants but in different order, which might lead to increased sensitivity to letter position when reading Hebrew. In the study, participants were rapidly presented with sentences in English and in Hebrew, half of which included a word whose letters had been transposed. When reading in English, participants' ability to repeat the sentence was not impeded by the presence of a transposed word, and they were at chance level when requested to report whether a sentence had indeed included such a transposition. Strikingly, when reading sentences in Hebrew these same participants suffered a 20% decrease in accuracy in sentence repetition, and were highly accurate in detecting transpositions ($d' = 2.51$).

The correlations found across performance in the two languages of bilingual readers show that there are common underlying mechanisms that support reading generally. The importance of low level skills for reading in the L2, even in adults, has also been stressed. Finally, the research reviewed in this section demonstrates that the mechanisms of reading orthographies with different features and languages of different structure can vary even within the same individual. In some cases, patterns established through the L1 are carried over when processing the L2, whereas under different circumstances bilingual readers exhibit differential processing across their two languages. This last point will also become apparent in the next section, discussing the neural substrates for reading in the two languages of bilinguals.

3.3 Neural Substrates of Reading in More Than One Language

Several studies have examined the neural substrates involved in reading different languages, and have focused specifically on bilinguals. In this section I will focus on research examining the brain networks recruited by bilingual readers when reading alphabetic as opposed to logographic language. Because of the fundamental difference between these two types of scripts, and previous findings (discussed in Sect. 2.3) demonstrating that there are indeed differences between native readers of orthographies of these types, this bilingual population provides a powerful test case of the degree to which L2 reading relies on patterns established in the L1.

Nakada et al. (2001) examined bilingual and monolingual readers of English and Japanese, half with English as L1 and half with Japanese as L1. As might be expected, activation patterns for native readers in Japanese were different from those observed for native readers in English. Both groups showed activation of the left fusiform gyrus, but Japanese readers additionally showed activation of the left inferior temporal sulcus that was lacking from the English readers, whereas the English readers had significant activation in the lingual gyrus bilaterally, that was mostly absent from Japanese readers. More importantly, when reading in the L2 the bilingual participants, who were highly literate in both languages, showed activation patterns that were virtually identical to those displayed when they read in the L1. Thus, English natives reading in Japanese showed activation patterns similar to the ones they exhibited when reading in English, and the same was true for Japanese natives – their activation patterns were indistinguishable whether they were reading in L1 Japanese or L2 English. These findings are reminiscent of the behavioral findings presented in the previous section, regarding transfer of visual (Green and Meara 1987) and decoding mechanisms (Wade-Woolley 1999) from L1 to L2 reading.

A second study examining reading in Japanese English bilinguals (Buchweitz et al. 2009) made use of the fact that Japanese can be written using two distinct writing systems – Kana (syllabic) and Kanji (logographic). Kanji showed more activation than Kana in right-hemisphere occipito-temporal areas associated with visuospatial processing, because of the increased visual complexity of the logographic script. Reading sentences in Kana lead to greater activation in areas of the brain associated with phonological processing. When participants read sentences in English, an alphabetic language and their less-proficient L2, greater activation was found in the inferior frontal gyrus, medial frontal gyrus, and angular gyrus as compared to reading in Japanese. This additional activation is most likely associated with increased phonological processing of an alphabetic script and greater demands on verbal working memory, due to reduced proficiency in the language.

Perfetti and colleagues have studied different groups of readers of Chinese and English. Using event related potentials and source localization, Liu and Perfetti (2003) studied Chinese English bilinguals in a delayed naming task for Chinese characters and English words. Early components peaked earlier for Chinese, the more proficient language, than for English, the second language, and word frequency effects extended for a longer time window in English than in Chinese. Bilateral occipital areas were involved in processing Chinese characters, whereas the processing of high-frequency English words was limited to left occipital cortex. Chinese character reading also lead to strong right prefrontal activations, but English words activated more medial frontal areas.

In a training study, native English speakers with no knowledge of Chinese were taught 60 Chinese characters (Liu et al. 2007). Following training, passive viewing of the studied characters showed activation in the bilateral middle frontal area, and right occipital and fusiform cortex. These regions partially overlap with regions found in studies of skilled reading of Chinese but not of alphabetic languages (Bolger et al. 2005). A further study compared the brain activation of reading Chinese and English in two groups of participants: native English speakers studying Chinese in college, and proficient Chinese-English bilinguals (Nelson et al. 2009). Replicating the previous findings, native English readers displayed different patterns of activation when reading Chinese and English, and specifically recruited right fusiform areas for

Chinese but not for English. Thus, their activation patterns for Chinese were similar to those exhibited by native readers of the language. The proficient Chinese-English bilinguals displayed a different pattern of results – these readers activated fusiform areas bilaterally regardless of whether they were reading English or Chinese.

The native English speakers in both studies displayed accommodation of the brain's reading network to the specific features of the acquired writing system, in this case the visual complexity of Chinese characters. However, the native Chinese readers in the second study show assimilation, because they were reading their L2 using the same network that had developed for reading their L1 (see also Nakada et al. 2001). Nelson and colleagues (2009) suggest that this pattern of assimilation is due to the fact that the reading network established for L1 Chinese includes procedures sufficient for the graphic demands of L2 English without major change.

Recently, Tan et al. (2011), using fMRI, examined reading in L1 Chinese and L2 English in 10 year old children, who had been studying English for approximately 4 years. The results show overall similarities in brain activation patterns when children performed lexical decision in the two languages, including bilateral activations in fusiform areas, the inferior frontal gyrus and occipital areas. Activation patterns were also correlated with reading performance in both languages measured immediately before the scanning session and again 1 year later. Activation rates in the left fusiform gyrus during performance of the lexical decision task in English were significantly correlated with concurrent reading performance and significantly predicted gains in reading a year later. Moderate and non-significant correlations between fusiform activity and Chinese concurrent and future reading were also found. Most interestingly, however, left caudate nucleus activation was highly correlated with reading and reading gains in English, the L2, but not in Chinese, the L1. This last finding is related to the role of the caudate nucleus in inhibiting interference from the non-relevant language in bilinguals. This underlines the fact that skilled performance in the L2 necessitates successfully overcoming parallel activation of competing L1 forms, as discussed in Sect. 1.

The studies reviewed in this section reveal a complex pattern. The brain networks recruited for reading in first and second language clearly overlap and again reveal certain universals. However, the degree of accommodation necessary for reading a newly acquired L2 orthography that differs markedly from that of the L1 is determined by the specific properties of the two orthographies. Further, there are cases where readers of an L2 rely on brain networks that are distinct from those used by native readers of the same orthography, by virtue of the brain's reading network being shaped by the specific properties of the L1 orthography.

4 Summary and Conclusions

In this chapter, I reviewed research demonstrating that semantic representations are mostly shared across the two languages of bilinguals, that lexical access is language non-selective, at least when the two languages share the same script, and that the neural representation of first and second language is influenced by proficiency and age of acquisition. I have discussed how the trajectory and predictors of acquiring literacy in different languages are influenced by features of the language and the orthography, such as orthographic depth, morphological complexity and visual density of the script. Further, these same features have been shown to influence the performance of skilled readers of various orthographies, and to be expressed in the areas of the brain supporting reading. Finally, a review of the research of individuals who are literate in more than one language reveals a complex interaction between the nature of the scripts involved and the characteristics of the individual. Due to these complexities and as yet only partial coverage of research for different language pairings and different bilingual populations, there are certain inconsistencies in results that at this point in time still hinder our ability to reach a complete understanding of this multifaceted phenomenon. Most importantly, we have not yet reached a full picture of the reciprocal influences existing between first and second language reading, nor of the specific conditions under which native language reading strategies and mechanisms are transferred to L2 reading as opposed to conditions more conducive to the development of more independent L2 reading mechanisms.

Although further research focusing on specific L1-L2 pairings that vary in the degree of overlap in orthographic principles and features is called for, nonetheless the extant literature allows me to suggest several guiding principles. For pairs of languages that share the same character set, such as European languages using the Roman alphabet, the initial stages of L2 reading are facilitated (e.g. Kempe and MacWhinney 1996). However, skilled readers of such language pairs might suffer increased interference from the two lexicons, due to the lack of orthographic cues that might assist in limiting activation to the currently-relevant language.

More generally, from the reviewed research I wish to identify three relevant dimensions along which a given pair of orthographies can be judged as similar or more distinct: (1) Writing system, i.e. alphabetic or logographic; (2) Orthographic depth, or grain size; (3) Linguistic or typological similarity of the oral languages.

I hypothesize that greater similarity across these dimensions will result in greater transfer of literacy skills across languages in bilingual readers. Thus, a native reader of an alphabetic and orthographically shallow script can quite easily utilize decoding processes developed in the context of the L1 when attaining literacy and then reading fluently in a similarly shallow alphabetic orthography of the L2. However, increasing dissimilarity between the L1 and the L2 along these dimensions might lead to transfer of L1 literacy skills being less than optimal for L2 reading, or at the minimum will lead to differences in processing for L2 readers of varying L1 backgrounds, as reviewed above.

A central question in this regard is how much flexibility and plasticity exists in the cognitive and neural systems for developing L2 specific reading mechanisms. As is the case for second language in general, the answer to this question most likely depends both on the degree of oral and written proficiency in the L2 and on the reader's age and the entrenchment of L1 reading mechanisms (MacWhinney 2005). From the literature reviewed above, a likely possibility is that as in spoken language, beyond a certain point in development, L1 literacy is bound to leave an "accent" on L2 reading (Koda 2007). In this regard it is important to stress Cook's (2003) multi-competence framework, claiming that native speaker performance should not be the yardstick against which bilingual performance is measured. In this regard, acquiring literacy in more than one language often broadens a person's horizons and is a worthy goal, even if the L2 is processed in a manner that is qualitatively different, both cognitively and neurologically, from that common in L1 readers of the same language.

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Spelling Disability – Neurophysiologic Correlates and Intervention

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1 Introduction

Most of the research and our knowledge about dyslexia come from English-speaking countries. However, as orthographies differ with regard to script transparency, learning to read and write proceeds differently in different languages (Ziegler and Goswami 2006). Transparent orthographies have consistent grapheme-phoneme correspondences, while shallow (or 'deep') orthographies have partially inconsistent or relatively complex grapheme-phoneme correspondences (e.g., Borgwaldt et al. 2005). English has a shallow orthography with many unpredictable and ambiguous spelling – sound correspondences (Borgwaldt et al. 2005). The position of English as "an exceptional, indeed, *outlier* orthography in terms of spelling-sound correspondence" (Share 2008, p. 584) raises doubt whether studies of dyslexia from English-speaking countries can be generalized to other orthographies. German, on the other hand, is regarded as a transparent orthography with quite consistent grapheme-phoneme correspondences.

Stage theories of reading and spelling development (Ehri 1986, 2005; Frith 1985) propose that children progress through a series of qualitatively different stages. In each of these stages, different sources of knowledge are used. According to stage theories, children rely heavily on phonological strategies during the initial phase of learning to read and write. In later stages, phonological strategies are supplemented by morphological strategies. Children then use their knowledge of orthographic patterns and morphological relationships between words to spell grammatical morphemes. There is evidence that phonological strategies appear quite early in transparent languages. More specifically, several cross-language comparisons have shown that German-speaking children become accurate and fluent readers much earlier than English-speaking children (e.g., Aro and Wimmer 2003;

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Frith et al. 1998; Seymour et al. 2003). When spelling-sound relations are consistent, children obviously acquire grapheme-phoneme correspondence rules quite easily.

Studies with German-speaking children with dyslexia have shown that difficulties with phonological strategies (e.g. poor reading accuracy and poor phonological spelling) are particularly evident in the early phases of literacy acquisition (Landerl and Wimmer 2008). After a few years of schooling, most German-speaking children with dyslexia show slow, but accurate reading and are able to produce phonologically plausible spellings (Wimmer 1993, 1996; Landerl et al. 1997). However, they demonstrate major difficulties in orthographic spelling (Landerl 2001; Wimmer 1996). Interestingly, problems with phonological spelling in Grade 1 have been shown to be predictive of poor orthographic spelling later on (Landerl and Wimmer 2008). These results suggest that towards the end of primary education, German-speaking children with dyslexia use the phonological strategy effectively during the reading and spelling of most words, but have severe difficulties with morphological strategies.

Another interesting point is that the studies with dyslexic children cited above had selected children based on their reading performance. As it turned out, the children were also severely handicapped with respect to spelling skills (Landerl et al. 1997; Landerl 2001; Wimmer 1996). Importantly, difficulties in spelling have been shown to be highly persistent (Klicpera et al. 1993). Because of the pervasive spelling difficulties in German, most of our own studies have selected children based on their spelling performance. The aim of the present chapter is to summarize our research on the characteristics of spelling disability (which is in most cases accompanied by reading difficulties), by describing our findings on the electrophysiology of speech representations, genetics, as well as prevention and treatment.

2 Neurophysiological Indexes of Speech Perception and Spelling Disability

In our electrophysiological research on auditory function in spelling disability we have focused on the mismatch negativity component (MMN). MMN is a measure of both the ability to accurately discriminate between two acoustic stimuli presented in succession and reflects short-term auditory memory capacity. It is recorded not only when attention is actively directed towards the stimuli but also when a participant's attention is directed elsewhere. In a typical experimental setting, participants are presented a series of sounds while they watch a silent film. Traditionally, one of the sounds, e.g. /da/, would occur with about an 85% frequency. Infrequent presentations of a second sound, e.g. /ba/, would intersperse the /ba/ sound train 15% of the total presentation time. The successful discrimination of the speech sounds /ba/ and /da/ can be traditionally measured by the MMN at approximately 100–200 ms over fronto-temporal scalp sites after stimulus onset (Näätänen 1992; Näätänen et al. 2007). The traditional MMN is derived from subtracting the

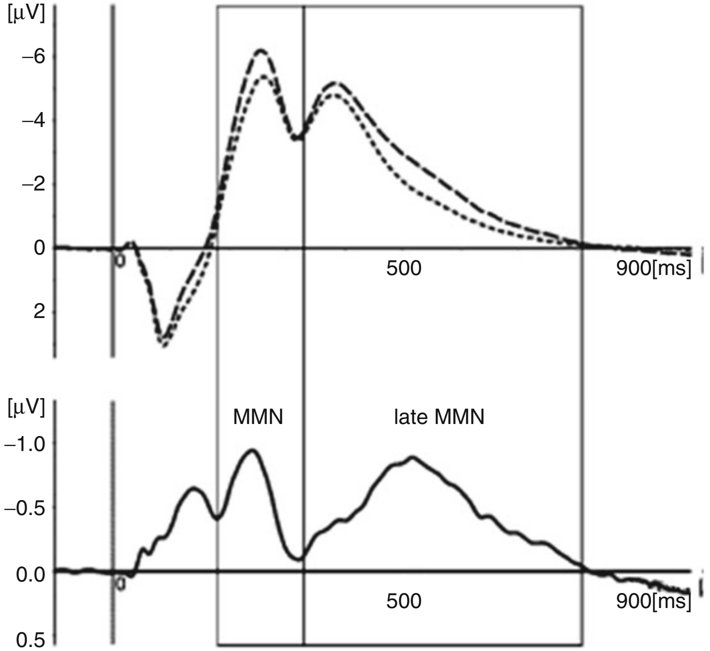

Fig. 1 Mismatch negativity. *Upper panel:* MMN Grand average curves (mean value of F3, Fz, F4, FC3, FCz, FC4, C3, Cz, C4) of a standard stimulus /da/ (*dotted line*) and a deviant stimulus /ba/ (*dashed line*). *Lower panel:* MMN (i.e. the difference between the standard and deviant responses). The first window demonstrates the traditional MMN (188–300 ms) and the second window demonstrates the late MMN (300–710 ms) (Figure from Czamara et al. 2011)

ERP activity associated to the standard stimulus from that of the deviant stimulus (see Fig. 1). It is obligatorily elicited from neural sources located both within the superior temporal plane of the auditory cortex and from frontal sources. The first source in auditory areas is related to sensory memory processing of the auditory features and to change detection (Näätänen et al. 1978; Giard et al. 1990; Näätänen 1992); whereas sources in frontal areas are thought to reflect automatic attention switching or stimulus contrast enhancement (Giard et al. 1990; Gomot et al. 2000; Opitz et al. 2002; Deouell 2007).

Although not always examined, a number of researchers have described MMN components occurring beyond the traditional MMN window (see Fig. 1; Alonso-Bua et al. 2006; Froyen et al. 2009; Hommet et al. 2009; Korpilahti and Lang 1994; Maurer et al. 2003, 2009; Schulte-Körne et al. 1998a, 2001a). In our studies, the detection of differences in complex speech sounds associated with spelling and reading disability was found to be primarily associated to a later MMN stage of auditory speech sound processing. A late MMN component is believed to be relevant for more complex cognitive processes; furthermore its latency suggests the involvement of different brain processes than those associated to the earlier, traditional MMN component. The later MMN is characterized by a broad negativity

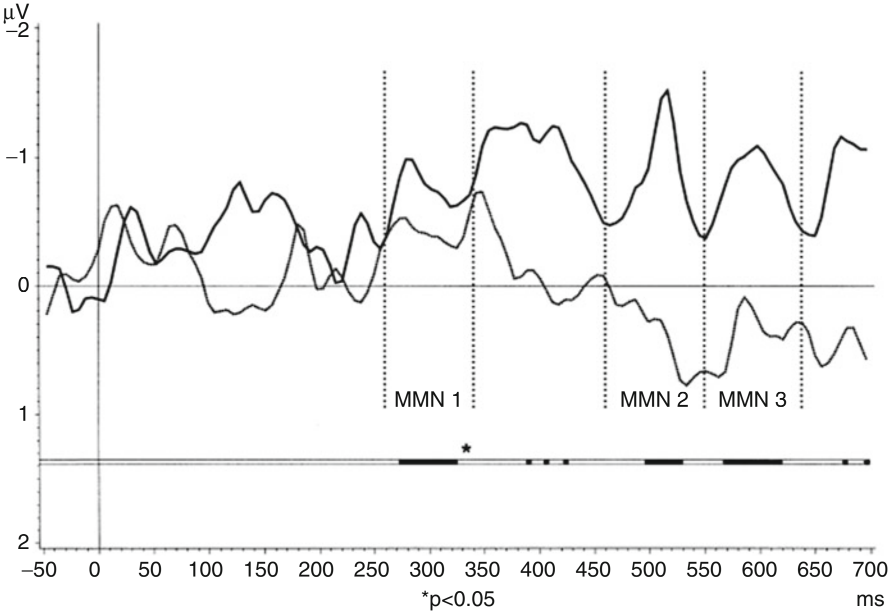

Fig. 2 Grand average of the MMN for speech stimuli in adult participants with and without dyslexia. The *solid line* depicts the control group; the *grey line* depicts the MMN of participants with a reading and spelling disability at Fz. *Black bars* indicate ranges of the curve with significant MMN values in the control group (Figure from Schulte-Körne et al. 2001a). *MMN 1 = traditional MMN time window; MMN 2 & MMN 3 = late MMN time windows*

over frontal-central areas and is mainly elicited by complex auditory stimuli like syllables and words. The generator has been measured over right central-parietal areas (Hommet et al. 2009). The functional significance is believed to be related to attentional processes (Shestakova et al. 2003), to long term memory (Zachau et al. 2005) and to letter-speech sound integration (Froyen et al. 2009).

Overall, our earliest research revealed that children and adults who were recruited based on their spelling disability and also had a word reading speed deficit exhibited a reduction in amplitude of a late MMN component (330–620 ms) when they were presented with consonant-vowel syllables such as /da/ and /ba/ but not to simple non-speech sounds such as sinus tones of 1,000 and 1,050 Hz (Schulte-Körne et al. 1998a, b). Although the traditional MMN window has been found to be attenuated in a number of studies in participants recruited for dyslexia (for review see Schulte-Körne and Bruder 2010), we found comparable early MMN time windows between subjects for both speech and non-speech sounds. In a subsequent study, we described two MMN components which occurred in later time windows peaking at 511 and 598 ms in adult subjects with no history of spelling and reading disability to the consonant-vowel syllables /da/ and /ga/. Adults with reading and spelling disability lacked entirely MMN in these time windows (see Fig. 2, Schulte-Körne et al. 2001a). Deviant complex tone stimuli patterns, as depicted in Fig. 3,

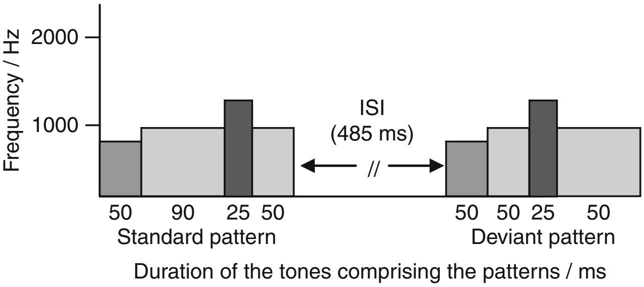

Fig. 3 Tonal patterns (standard and deviant) presented to adult participants with and without a reading and spelling disability. The vertical axis depicts the tone frequencies (720, 815, and 1,040 Hz). The horizontal axis depicts the duration of the single tones (ms). Between patterns an interstimulus interval (ISI) of 485 ms was used. The difference between the two patterns is that two segments of identical frequency (815 Hz) but different durations (segments 2 and 4) have been exchanged, thus the patterns differ only regarding the duration but not the frequencies of the tones (Figure adapted from Schulte-Körne et al. 1999a)

were also found to elicit a late component between 250 and 600 ms which was attenuated in those subjects with reading and spelling disability (Schulte-Körne et al. 1999a). Thus, clues to auditory perception deficits might be more related to later cognitive processes, which might involve more the integration of complex sound representations such as patterns of tones and speech sounds in the auditory cortex, and potentially interactions with long-term memory as well as factors pertaining to attentional mechanisms. Very simple sounds, such as sinus tones, do not seem to impact these later processes.

Altogether, our findings suggest that individuals with a reading and spelling disability can less accurately discriminate between differences of incoming complex auditory stimuli, in particular to speech sound stimuli, in comparison to individuals without a reading and spelling disability. In order to more precisely understand the relationship between speech sound discrimination, phoneme awareness and the discrimination of non-speech sounds, a structural equation model was built (Schulte-Körne et al. 1999b). The model underlined the importance of MMN amplitude to speech sounds for spelling ability independently from word reading ability. Together with phoneme awareness, speech discrimination abilities accounted for up to 42% of the variance found in spelling skills, whereas the discrimination of non-speech sounds did not contribute to the model. Therefore, it is plausible to postulate that deficient speech sound representations might impact and contribute to spelling deficits.

Skills required for the correct interpretation of phonemes are critical in solving tasks involving phonological awareness. The observed deficits in the ability to integrate complex sound representations might therefore lead to phonological awareness deficits, which have repeatedly been found to characterize spelling disability and dyslexia (Ramus 2001; Snowling 2000; Wagner and Torgesen 1987). But how does phonological awareness contribute to spelling? The most prominent hypothesis to explain how phonological awareness contributes to the acquisition of orthographic representations (which are necessary for orthographic spelling) is the self-teaching hypothesis (Cunningham et al. 2002; Share 1995, 1999). The self-teaching hypothesis proposes that orthographic knowledge is, at least partly, acquired as a result of the self-teaching opportunities provided by phonological decoding. Recent evidence suggests that spelling also fulfils a self-teaching function in the acquisition of word-specific knowledge (Shahar-Yames and Share 2008). It might therefore be argued that deficits in the ability to integrate complex sound representations lead to deficits in phonological awareness, which have a negative impact on the development of phonological abilities and the use of phonological strategies during reading and spelling. The resulting difficulties in word decoding and phonological spelling might lead to a lack of self-teaching opportunities and hence play a role in the development of difficulties in orthographic spelling.

3 Genetics and Neurophysiological Indexes of Speech Perception for Spelling Disability

Recently, our group has examined the relevance of the late MMN elicited by speech stimuli for the genetics of spelling disability (Czamara et al. 2011; Roeske et al. 2011). The genetics of dyslexia and spelling disability have a long history and a number of candidate genes have been reported (Paracchini et al. 2007; Scerri and Schulte-Korne 2010). Overall, it would seem that dyslexia and spelling disability are polygenetic, meaning that a number of genes contribute to the disorder itself. So far, five prominent genes, *ROBO1, MRPL19/C2ORF3, KIAA0319, DCDC2* and *DYX1C1*, have been identified. These genes are particularly interesting because they are involved in neural development, including neuronal migration and axon guidance. In line with this research, our group has provided the first evidence for the late MMN component as an endophenotype for dyslexia and spelling disability. Endophenotypes are biological markers of a disorder that are more closely related to the genetics of that disorder than the symptoms of the disorder itself. The identification of endophenotypes leads to faster detection of genes involved in disorder pathology, which in turn allows for the development of more precise intervention and therapeutic concepts (Gottesman and Gould 2003).

In our first study (Roeske et al. 2011) we were able to show how the late MMN was significantly associated to *SLC2A3,* a gene on chromosome 12 which had not yet been associated with dyslexia or spelling disability. The functionality of *SLC2A3* renders it a compelling candidate for developmental disorders, as it is the predominant facilitative glucose transporter in neurons during child development. Although more studies are required to be certain of the full significance of these findings, it is plausible that a reduction of the expression of *SLC2A3* might lead to glucose deficits in the brains of children with spelling disability. A reduction of glucose, or energy in the brain, might impact the development of speech sound discrimination skills and therefore might explain the attenuation of MMN to speech sounds in populations with spelling disability. In a subsequent study

(Czamara et al. 2011) we were able to show how the late MMN in children with spelling disability is associated to rare variants on the well known candidate genes for dyslexia *KIAA0319* and *DCDC2* both located on chromosome 6. Importantly, these findings suggest that the late MMN to speech stimuli, and not the traditional MMN, is influenced by genetics. Thus, the neurophysiological correlates of speech perception in spelling disability that are under genetic influence might be mainly related to later cognitive processes.

4 Prevention of Dyslexia and Spelling Disability

With regard to the prevention of dyslexia and spelling disability German research has mainly focused on improving phonological awareness. The connection between phonological awareness and reading and spelling skill is well known (Castles and Coltheart 2004; Schulte-Körne 2010), and many studies have demonstrated that phonological awareness can be promoted as early as in preschool (Bradley and Bryant 1983; Lundberg et al. 1988). Bus and van Ijzendoorn (1999) conclude from a meta-analysis with 17 US studies that a training of phonological awareness has a positive impact on children's acquisition of reading and spelling skills. The effects were even stronger when a training of letter-sound correspondences was included. These findings also apply to German speaking children (Schneider et al. 1997). However, results from a recent longitudinal study with German-speaking children show that preschool phonological training mainly affects children's reading and spelling skills during the early grades, but not so much in later grades. German findings have also shown that phonological training in later grades (grade 2–4) does not ameliorate spelling skills (Schulte-Körne et al. 2001b; Wimmer and Hartl 1991).

Among other factors, children's home literacy environment is related to their early literacy skills. A meta-analysis by Bus et al. (1995) found that reading to preschoolers accounts for 8% of the variance of later reading skill. Similarly, experimental studies demonstrate positive effects of interactive reading on children's vocabulary and reading acquisition (Whitehurst et al. 1994; Fielding-Barnsley and Purdie 2003).

Our own research on prevention focuses on the question of how findings regarding familial reading behavior (see Bus et al. 1995) can be transferred to German-speaking children. The aim was to design a program that combines an explicit training of phonological skills with the promotion of joint reading. We developed the program "Let's read!" (original title in German: "Lass uns lesen!"; Rückert et al. 2010c) which addresses families of preschool children. Parents are instructed to read regularly to their preschool children by focusing on dialogue reading (Whitehurst et al. 1994). This is implemented by stories that contain questions about the story and the child's everyday life. Additionally the training contains exercises to promote phonological awareness as well as common letter-sound-correspondences. The design of the program is illustrated in Fig. 4. Activities

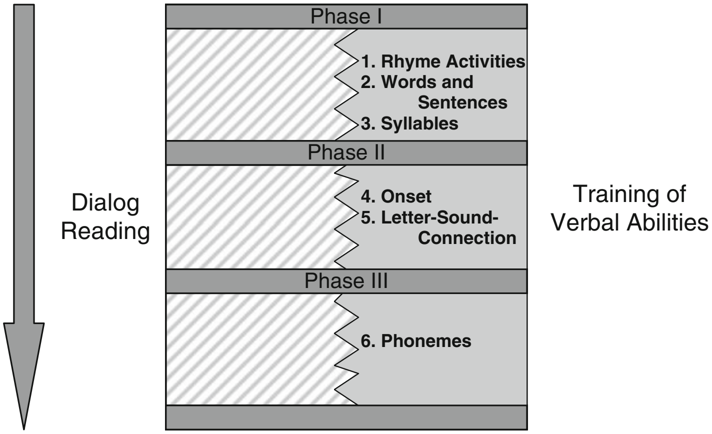

Fig. 4 Design of the prevention program "Let's read!"

Guessing Game

I think of something that begins with /L/!

or

I think of something that begins with /M/!!

or

Fig. 5 Exercise for the understanding of onset

are carried out over a 16-week period with 4–5 activities per week. They require about 10–15 min to be completed and consist of stories, poems, phonological exercises and games.

The effectiveness of "Let's read!" was evaluated in two independent studies (Rückert et al. 2010a, b). In both studies, parents received four instructional sessions where important theoretic background (e.g. literacy acquirement, the role of phonological awareness) and activities were presented. In addition, these sessions offered parents the possibility to exchange opinions about the program and discuss how to carry out the program during daily family life. Figure 5 shows an example for an activity designed to promote the understanding of onset of words sounds as the /m/ in mouth.

In *Study I* (Rückert et al. 2010b), effects of the program “Let’s read!” were compared to the German program “Hear, listen, learn” (Küspert and Schneider 2000), which is established in some German preschools and carried out by kindergarten teachers. In seven Munich preschools, children participated in prevention programs; either in “Let’s read!”, in “Hear, listen and learn” or in a combination of both programs. Effects were measured by German tests designed to identify children with a risk of developing reading and spelling deficits (*Bielefelder Screenings zur Früherkennung von Lese-Rechtschreibschwierigkeiten BISC* [*Bielefeld Screening for Early Detection of Difficulties in Reading and Writing*], Jansen et al. 2002; *Heidelberger Auditives Screening in der Einschulungsuntersuchung HASE* [*Heidelberg Auditory Screening*], Brunner and Schöler 2002).

Overall, parents were enthusiastic about the program, rated it positively and carried out the activities on a regular basis. All participating children revealed significant improvement with regard to their phonological skills. No differences could be observed between the three prevention groups. Thus “Let’s read!” which was carried out by the parents at home, had similar effects on children’s phonological skills as the preschool program “Hear, listen, learn” which was carried out by kindergarten teachers. Interestingly, children who received a combination of both programs did not profit more, which might be attributed to the overlapping program contents.

Study II was carried out in 2008/2009 at the Department of Child and Adolescent Psychiatry and Psychotherapy Munich. A detailed description was published in German (Rückert et al. 2010a). In this study, only the program “Let’s read!” was investigated. Program effects on phonological awareness and other literacy-related skills were measured in comparison to the development of a delayed treatment group. The sample was obtained by addressing an invitation letter to all families in central Munich with children born between November 2002 and November 2003. These families were randomly sent an invitation to participate in either the training group or the waiting group and 62 children participated in each group. After exclusion of all children who had already received instruction with “Hear, listen and learn” in preschool and after dropout, the final sample consisted of 36 children in the training group and 41 children in the waiting group. There were no group differences regarding age, sex or IQ. A parental questionnaire showed a high level of education among participating parents.

Measures of phonological awareness were divided into two different variables, rhyme and syllable awareness on the one hand and phoneme awareness (onset, rest word and phoneme synthesis) on the other hand. Furthermore, measures of vocabulary, listening comprehension and letter knowledge were taken. In the posttest session, phoneme analysis and ‘concepts of print’ (Clay 1979) were added. Parents filled out a protocol sheet with dates of activity, length of time spent on the training and contentment; children rated the activities on a smiley scale.

Results of the *protocol sheet* showed that parents carried out 94.14% of the planned activities. The feasibility of activities was rated between “very good” and “good”. Children also reported that they liked the program. Results for phonological awareness are presented in Table 1. For *rhyme and syllable awareness* as well as

Table 1 Training effects for phonological awareness

		Training group		Waiting group			
		Pre	Post	Pre	Post	p Interaction	Effect size
Rhyme and syllable	M	19.12	22.09	20.40	21.66	0.028	0.57
Awareness	(SD)	4.22	2.07	2.73	2.22		
Phoneme	M	8.69	16.00	8.85	12.68	0.002	0.54
Awareness	(SD)	6.15	5.65	6.31	7.13		

for *phoneme awareness* there were no group differences at pretest. A repeated measures ANOVA showed a significant main effects for time, but the main effects for group were not significant. Importantly, the interaction time x group was significant for both measures.

Among the *nonphonological variables* a trend for improvement was observed for story comprehension, while no significant effects were found for letter knowledge and vocabulary. For both *posttest variables* phoneme analysis and 'concepts of print' significant group differences were found.

In conclusion, both prevention studies have shown that parents can successfully promote children's phonological skills when using a structured program. These results show that the positive effect of promoting joint reading, which was previously demonstrated with English-speaking children, can be transferred to German speaking children. In combination with a phonological training, joint book reading has positive effects on children's phonological skills. However, further investigation concerning long-term effects is needed.

5 Effective Treatment for Children with Spelling Disability

Treatment approaches for children with spelling disability can be classified as either cause- or symptom-oriented. Cause-oriented programs target specific skills that are hypothesized to be the underlying causes of spelling disability (e.g., auditory or visual processing deficits). The idea behind cause-oriented programs is that eliminating a specific deficit enables children to overcome their spelling difficulties. Critics (e.g., Suchodoletz 2007) have argued that there is not a single cause of reading and spelling deficits, rather several factors seem to play a role (see also Vellutino et al. 2004).

Symptom-oriented programs focus directly on reading and spelling skills and have repeatedly been found to significantly meliorate reading and spelling ability in German dyslexic children (for a review see Mannhaupt 2002). A recent meta-analysis of intervention studies with German-speaking dyslexic children (Ise et al. 2012) found that symptom-oriented programs lead to significant benefits in reading and spelling, while the mean effect size for cause-oriented programs does not reach statistical significance.

As has been mentioned above, orthographic spelling is a major difficulty in German-speaking dyslexic children. Because of the highly transparent German orthography, dyslexic children often master basic phonological decoding skills within the first years of formal schooling (Landerl et al. 1997; Wimmer 1993, 1996). However, difficulties in orthographic spelling and the use of morphological strategies remain (Landerl 2001; Landerl and Wimmer 2008). Other than in English, orthographic spelling rules for German words are highly consistent. For example, in German words, a double consonant always marks a short vowel phoneme (e.g. *Bett* [*engl. bed*]), while English words may contain a double consonant either after a short vowel phoneme (e.g., *grass*) or after a long vowel phoneme (e.g., *ball*). Consequently, the majority of German words can be spelled correctly by applying orthographic spelling rules (in addition to phoneme-grapheme correspondence rules).

Although orthographic spelling rules can effectively guide the spelling of German words, they are not always explicitly taught during regular classes. Although it is not clear why, one reason might be the inherent complexity of these rules. For example, the complete set of spelling rules for double consonants is: (1) “If, within the same morpheme, a short vowel phoneme is followed by only consonant phoneme, then this consonant must be doubled” (e.g., *Mann [man]*, *Bitte [request]*), and (2) “If, within the same morpheme, a short vowel phoneme is followed by two or more consonant phonemes, then these consonants are not doubled” (e.g., *Tante [aunt]*, *Bild [picture]*). As a consequence, German students often lack sufficient knowledge of spelling rules. Eckert and Stein (2004), who asked grade 5 students to explain their spellings of previously dictated words, found that many students revealed incomplete knowledge of spelling rules (e.g., formulated incorrect or incomplete spelling rules) or failed to use spelling rules during spelling (e.g., produced incorrect spellings despite sufficient knowledge of spelling rules).

One of the most promising treatment approaches, at least in languages with consistent spelling rules, is to teach children how to spell words correctly by applying orthographic spelling rules. Rule-based spelling trainings therefore aim at enhancing student’s ability to effectively use explicit knowledge of spelling rules. For example, the *Marburg Spelling Training* (*Marburger Rechtschreibtraining*, Schulte-Körne and Mathwig 2009) depicts orthographic spelling rules graphically as yes/no decision-trees. Figure 6 depicts the decision trees for the spelling of double consonants. Importantly, as children work with the decision-trees, they constantly verbalize spelling rules, which in turn strengthen their explicit memory of these rules. In addition, children learn how to use explicit knowledge of spelling rules effectively during spelling.

The *Marburg Spelling Training* (Schulte-Körne and Mathwig 2009) successfully implements recommendations derived from educational research. For example, children practice actively and receive direct feedback regarding their performance. Importantly, the different spelling rules are introduced stepwise. That is, a spelling rule is practiced in a number of exercises with increasing levels of difficulty before the next spelling rule is introduced. Spelling rules that have already been learned are rehearsed on a regular basis. In addition, all training words can be spelled correctly by applying the rules that have already been learned. This was done to allow each child to give an errorless performance.

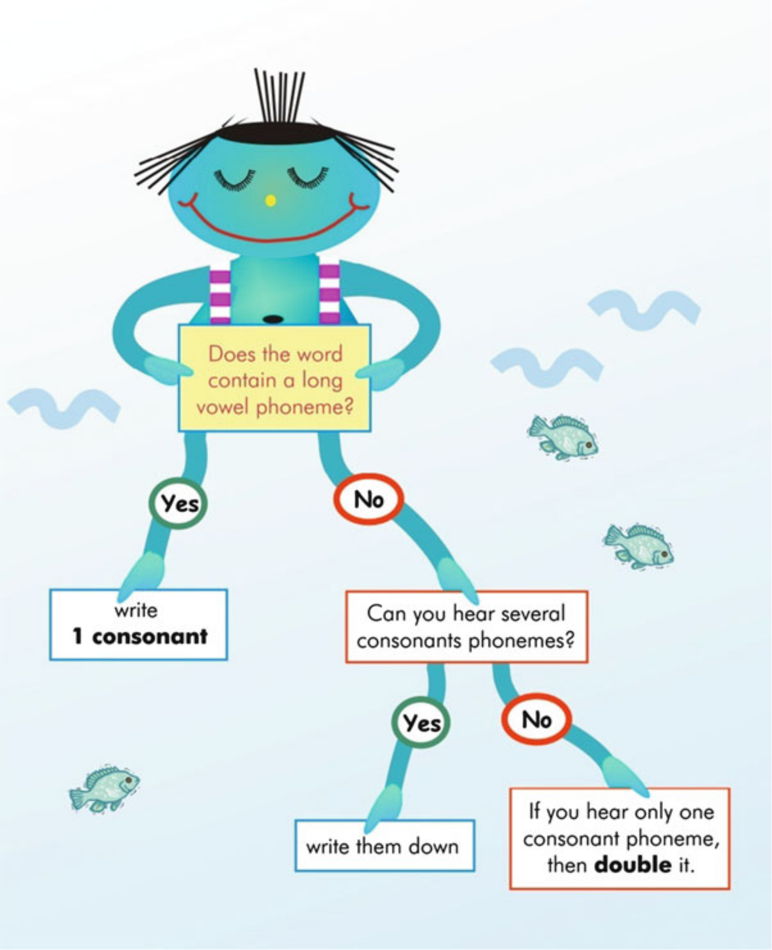

Fig. 6 Decision-tree for the spelling of double consonants (*Marburg Spelling Training*, Schulte-Körne and Mathwig 2009)

Three intervention studies have shown that the *Marburg Spelling Training* has a remedial effect on spelling and reading skills in children with spelling disability (grades 2–4). In a first study (Schulte-Körne et al. 1997, 1998c), the *Marburg Spelling Training* was conducted as a parent–child program. After 2 years of supervised tutoring by a parent, children ($n = 18$) had significantly improved their spelling ability (Cohen's $d = 0.53$). A second intervention study investigated the effectiveness of the *Marburg Spelling Training* in a school setting (Schulte-Körne et al. 2003). Twenty-one children were described as having spelling difficulties by their teachers and were included in the training group. They were trained with the *Marburg Spelling Training* in small tutoring groups twice a week over a 2-year period. Statistical analysis revealed that children significantly improved their reading (Cohen's d = 0.42) and spelling skills (Cohen's d = 0.59). A third intervention study (Schulte-Körne et al. 2001b) used a pretest-intervention-posttest design with a treatment group (n = 10) and a delayed treatment control group (n = 10). During the first treatment period, children in the treatment group received phonological awareness training. Children in the delayed treatment group did not receive any training during the first training period, but were trained with the *Marburg Spelling Training* in the second training period. For both groups, training was conducted twice a week in individual sessions over a 3 month period. Consistent with previous evidence, phonological awareness training did not improve children's reading and spelling skills significantly (see also Wimmer and Hartl 1991). The most likely interpretation of this finding is that the children had already mastered the alphabetic principle of the highly transparent German orthography. As expected, children in the delayed treatment group did not show a significant change during the first training period. However, their reading and spelling skills improved significantly during the second training period when they received the *Marburg Spelling Training* (Cohen's d = 0.50 for spelling improvement and Cohen's d = 0.74 for reading improvement).

Several studies have demonstrated that difficulties in spelling are highly persistent (Esser and Schmidt 1993; Klicpera et al. 1993). Error analyses of spelling mistakes produced by German-speaking dyslexic children in grades 4–6 revealed major difficulties in orthographic spelling, while only few phonologically inaccurate spellings were made (Landerl 2003; Landerl and Wimmer 2000; Wimmer 1996). That is, children continue to have difficulties with the use morphological strategies. Although children with poor spelling skills do not simply "outgrow" their difficulties, most of the available intervention programs focus on younger children (grades 2–4). We therefore developed a modified version of the *Marburg Spelling Training* for older students (grade 5 and 6), that focuses on improving orthographic knowledge and the effective use of morphological strategies.

The modified training program conserves the main themes of the *Marburg Spelling Training* (e.g., the use of decision-trees). In addition, each chapter contains exercises that are designed to enhance a deeper understanding of spelling rules. For example, children might be asked to explain the spelling of an inflected verb, which requires insight into the principle of morphological consistency. Because we intended to target the most common spelling errors of dyslexic children in grades 5 and 6, spelling errors produced by dyslexic children in our clinic were analysed prior to the development of the training program. The results show that older children still struggle with basic spelling rules, such as the spelling of double consonants. The first part of the new training program therefore rehearses basic spelling rules (e.g., the spelling of double consonants, markers of long vowel phonemes). The second part of the training program treats advanced topics that were not covered in the *Marburg Spelling Training*, such as the spelling of different s-sounds (*Gläser [glasses]*, *Grüße [greetings]*, *Küsse [kisses]*). In addition, the new training program contains age-appropriate word material, texts and decision-trees. Instead of depicting the decision-trees with the animal that was introduced in the *Marburg Spelling Training* (see Fig. 6), decision-trees are now shaped like metro maps. This was done because we wanted to meet the children's interests. In the German school system, primary school is usually from grades 1–4. With the transition to secondary school in grade 5, many children start using public transportation systems on their own and learn how to use road maps and timetables.

The effectiveness of the rule-based spelling training for older students was evaluated in a recent intervention study (Ise and Schulte-Körne 2010). In *Study 1*, students (grade 5) with spelling deficits (n = 10, treatment group) received 15 individually administered weekly intervention sessions on a weekly basis. A control group (n = 4) did not receive any intervention. In *Study 2*, the spelling training was provided to spelling-disabled children (grade 5–6) in a treatment group (n = 13) and a delayed treatment control group (n = 14). Analysis of spelling improvement (based on an integrated dataset from both studies) revealed that gains in spelling were significantly greater in the treatment group (Cohen's d = 0.75) than in the control group (Cohen's d = 0.35). It was also found that the training program had a remedial effect on reading comprehension (Cohen's d = 0.60) and significantly improved children's explicit knowledge of orthographic spelling rules (Cohen's d = 1.10). Interestingly, the average training-induced spelling improvement was slightly higher than the average improvement that was found in an intervention study that investigated children's (grade 2–4) responsiveness to short-term intervention with the *Marburg Spelling Training*. This finding indicates that rule-based spelling trainings might be used even more effectively with older students.

Together, our intervention studies on the effectiveness of the *Marburg Spelling Training* and its modification for older students indicate that difficulties with orthographic spelling and the use of morphological strategies can be alleviated by means of rule-based training programs. This finding is not only relevant for the treatment of German-speaking children, but also for treating dyslexic children learning to read and write other languages with transparent orthographies.

6 Conclusion

The aim of this chapter was to summarize our research on children with spelling disability. We have highlighted how research on prevention and treatment are effective for German speaking children with spelling disability and have shown that spelling disability is characterized by deficits in discriminating between complex sounds, in particular speech sounds, in both German adults and children with a history of spelling disability. So far, few studies have addressed the effects of treatment on neurophysiological processes in children with a spelling disability learning to read and write a transparent orthography. It would be of interest to understand if indeed treatment approaches ameliorate deficient brain processes, such as difficulties discriminating between speech sounds like /ba/ and /da/, and to understand if these effects are persistent or short-lived. In order to address this question, our group is currently conducting investigations aimed to understand how different treatment approaches, both a spelling rule-based intervention (*Marburg*

Spelling Training) as well as a treatment program focussed on tackling phonological and reading deficits in dyslexic children, affect the neurophysiological responses of these children's brains to speech sounds. In a recent study our group investigated different components of ERP in a pre-post intervention study design in order to evaluate neurophysiologic correlates of the rule-based spelling training. The results of this research should help to understand the relationship between the deficits we observe in these children and the deficits in processes such as those measured in neurophysiological investigations.

Probably the most promising area of research currently available for decoding spelling disability lies in understanding the genetics behind the disorder and elucidating relevant endophenotypes. In order to more accurately achieve these aims, very large collective samples are required in order to accurately pinpoint the sources of the genetic effects, which are often small. In the future, it will become increasingly important to more accurately characterize study participants in terms of their neuropsychological profiles and potentially in terms of their endophenotypic profiles. It is clear that disorders like spelling disability co-occur frequently with other disorders, such as reading disorder, math disorder or attentional deficit disorder. Because the genetics of these disorders are likely not entirely independent from one another, in order to specifically describe one disorder it will be critical to exclude participants with comorbid conditions. Finally, intervention and prevention programs might benefit from discoveries made in genetic studies.

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The Relationships Between Motor Learning, the Visual System and Dyslexia

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1 Introduction

According to a widely accepted definition of developmental dyslexia, a dyslexic reader is one who exhibits slow and inaccurate reading performance unrelated to his/her IQ level or educational opportunities (British Psychological Society 1999; Shaywitz and Shaywitz 2008). The reading deficits of developmental dyslexia persist into adulthood (Bruck 1992; Leonard et al. 2001). In the last few decades, a large body of research has produced a number of sometimes conflicting theories, which attempted to explain the phenomenon of developmental reading impairment. A large number of studies have shown deficient phonological processing as a core deficit in developmental dyslexia. The leading theory, the phonological deficit theory of developmental dyslexia (Share 1994; Snowling 1995; Stanovich 1988) suggests that dyslexic readers may suffer from an (unspecified) dysfunction in peri-sylvian brain regions, which leads to difficulties in generating and processing accurate and efficient phonological representations of speech sounds (Stanovich 1988; Temple et al. 2001). Other theories have been proposed for the reading deficits, with reference to more basic, underlying, neural processing deficits. The rapid sensory, auditory processing deficit theory (Tallal 1980) and visual processing deficit theory (Eden et al. 1996; Hari and Renvall 2001) suggests that dyslexic readers are less sensitive to rapidly changing (transient) visual and auditory inputs. Based on a very small number of post-mortem studies, but supported by psychophysical and neuro-imaging studies, it was suggested that the dyslexic brain is characterized by abnormal cell structures in the magnocellular pathways, specifically in the lateral geniculate nucleus (LGN) or the medial geniculate nucleus (MGN) of the thalamus, brain regions that serve as a relay station for rapidly modulated sensory input (Livingstone et al. 1991; Stein 2001). It was suggested that

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that the magnocellular deficit results in reduced sensitivity to motion and slower and less accurate visual or auditory information processing. Recently, the asynchronization theory (Breznitz 2006, 2008) was proposed, suggesting an impairment among dyslexic readers not only in speed of processing (which has been consistently found to be reduced) but also in integrating and processing information emerging from different sensory systems, specifically, the visual and auditory modalities. There is, however, only little direct neurobiological evidence in support of differences between dyslexic and skilled readers' brains. For example, Ectopia, an anomaly of brain cell migration, was described in the left peri-sylvian cortex of dyslexic readers' brains (Galaburda and Kemper 1979; Galaburda et al. 1985; Humphreys et al. 1990; Ramus 2004) and was suggested as a possible causative factor in the development of phonological processing deficits among dyslexic readers. In a series of studies during the last two decades, Nicolson and Fawcett developed and advanced a "cerebellar deficit" theory in order to explain the accumulating evidence for non-verbal and sensory-motor impairment among dyslexic readers (Fawcett and Nicolson 2008; Nicolson and Fawcett 2005, 2007, 2008). This theory is an attempt to elaborate on why reading impairment is often accompanied by other non-linguistic symptoms. In addition, the theory states that the well-established phonological deficit can arise from several neurobiological and developmental causes which are not specific to language. Therefore, in order to understand the phenomena of dyslexia it is important to identify and consider all related neural mechanisms. The theory specifically relates to two notions: cerebellar impairment and a deficit in automaticity.

2 Volitional and Non-volitional Motor Skill Learning

Almost every movement of the human body can be conceptualized as consisting of primary (volitional or otherwise) movements as well as posture and equilibrium movements, with the latter providing an effective base for the execution of the volitional movements (Lacquaniti 1992; Pollock et al. 2000). Thus, one cannot walk or execute a manual task without first stabilizing the body's posture and upright stance against the vertical forces (gravity) acting on each body segment, establishing balance by keeping the body's center of mass within its base of support, and maintaining that stability during the task, while providing proper posture as a base for organizing the dynamic coupling of different body segments and dynamically adjusting joint stiffness during the movement (Cordo and Nashner 1982; Massion and Woollacott 1996).

Postural responses can be altered by repeated experience. In studies where adult participants were exposed to repeated perturbations, their reactions changed following practice. Responses become gradually reduced in magnitude and fewer or different muscles are recruited to maintain posture and balance (Chong et al. 1999; Horak and Nashner 1986; Horak et al. 1989). It is not clear, however, whether and to what degree the posture and balance control mechanisms in adults can undergo experience-dependent changes when a novel volitional skill is acquired and retained in long-term procedural memory.

Movement skills are retained in long-term procedural memory. Procedural memory subserves the acquisition (learning) and retention of “how to” knowledge, such as the temporal and spatial characteristics of movement sequences, but also of perceptual and even cognitive skills resulting from repeated experience (Hauptmann and Karni 2002; Karni 1996; Karni et al. 1998; Morganti et al. 2003; Roth et al. 2005). The time-course of skill acquisition has been intensively studied in recent years, and can be conceptualized as a series of distinct phases wherein quantitative but also qualitative changes occur in both performance and the brain representation of the practiced task (Fischer et al. 2002; Karni and Sagi 1993; Karni 1995; Karni et al. 1998; Korman et al. 2003; Maquet et al. 2003; Walker et al. 2002).

The first phases of skill learning occur within-session (“on-line”). The first one is a “fast learning” phase in which large performance gains accrued with repeated iterations of the task, and subsequently, a plateau phase in which no additional gains occur despite continued practice is attained (Adi-Japha et al. 2008; Karni and Sagi 1993; Karni et al. 1998; Korman et al. 2003). The next phase is an “off-line”, between-sessions, latent phase wherein the gains in performance become resistant to interference and additional performance gains, in both speed and accuracy, may evolve. These later, delayed gains in performance require time, and often sleep, to be established and expressed (Karni and Sagi 1993; Korman et al. 2003; Roth et al. 2005). It has been proposed that these gains are related to procedural memory consolidation processes (Fischer et al. 2002; Karni and Sagi 1993; Karni et al. 1998; Korman et al. 2003; Maquet et al. 2003; Walker et al. 2002). The completion of each phase is essential for a successful initiation of the next phase and for an effective learning process (Adi-Japha et al. 2008; Hauptmann and Karni 2002).

3 The Touch Sequence Task (TST)

In a previous study (Sela 2011), a group of dyslexic readers and a group of skilled readers were compared in their ability to acquire a novel set of volitional manual movements while maintaining a quiet stance position. The participants stood, as stable as possible, on a forceplate, in front of a touch screen and were asked to touch, in a pre-defined order, using their dominant hand index finger, four circle targets that were located in constant locations on the screen. A trial was started as the target changed their color from black to yellow, and ended when the last target was touched (each touch returned the target color back to black). For each trial, the collected variables included the time of the touches (RT1 to RT4) as well as the Center of Pressure (COP) displacement (Winter 1995; Winter et al. 1996). Derived from the touch times, the time of the movement itself (Execution Time – ET), which was defined as the time between RT1 to RT4, was computed. In addition, the distance in cm between the most right and the most left COP location (ΔX) was calculated in order to find learning evidence within the posture control system. The training program consisted of three sessions (scheduled to the first day, the following day, and to a week following the first day), each session included 10 blocks, each block was made of 20 sequence repetitions (trials). The computation of the block's mean and standard deviation of each of the collected variables allowed for the analysis of the participant's ability to acquire the movement in both the volitional aspect (the block mean value of RT1 and ET) as well as in the non-volitional, posture control system (the block standard deviation of $\Delta X - SD\Delta X$).

The results of TST study indicated that the skilled readers showed both learning effects within the volitional motor system as well as within their posture control system. Thus, throughout the training schedule, RT1 and ET became significantly faster, and SDΔX became smaller. As for the dyslexic readers, learning effects were found in both RT1 and ET, suggesting an intact ability to acquire a novel procedural process. However, there was no evidence for learning within the dyslexic readers' posture control system (the dyslexic readers' SDΔX did not show a significant reduction as the training progressed). The comparison of the parameters between the two reading-level groups revealed that: (1) The RT1 of the dyslexic readers was significantly slower as compared to the skilled readers. (2) There was no difference between the groups as related to ET. Thus, once the initiation phase of the movement was completed (measured by RT1) their ability to learn the movement phase of the task was no inferior to their peers.

The different learning effects that were found between the three collected variables suggest that each of them represents a different sub-motor system. RT1 is the initial stage of the trial. It can be assumed that this time encapsulates processes such as (visual) perception, decision making, and initiation of a movement. ET is the time of the movement itself and may represent processes such as hand-eye coordination. SDΔX is presumably represents the support of the posture control system to the volitional motor learning procedure and its ability to adapt.

Based on the above, the results of the TST study may shed light on the relationship between the visual and motor control systems among dyslexic readers. The inferior dyslexic readers' RT1 may give support for several theories regarding the root of dyslexia, including the magnocellular (Livingstone et al. 1991; Stein 2001) and the rapid visual deficit (Eden et al. 1996; Hari and Renvall 2001) theories, which propose a relationship between dyslexia and a neurobiological deficit within the visual system. Furthermore, the posture control system strongly relies on the visual system (Kuo et al. 1998) and the lack of learning within the dyslexic readers' posture control system could occur due to a deficit in their ability to accurately process visual information (Barela et al. 2011). This can also be understood as evidence for the cerebellum deficit theory (Fawcett and Nicolson 2008; Nicolson and Fawcett 2005, 2007, 2008), which predicts that dyslexic readers' posture control system would be found to be inferior to that of skilled readers.

Consider the TST (or any volitional movement execution) in the context of the model proposed in Fig. 1 regarding the role of the visual system in the process of volitional movement execution. In order to produce a movement (the outcome of the procedure), different subsystems within the motor control system must be incorporated, among them the pre-motor system, the volitional motor control system and the posture control system. These subsystems rely on different, more basic modules or processes, e.g., the visual system. According to the proposed model, the visual system takes part in or serves each of these three motor

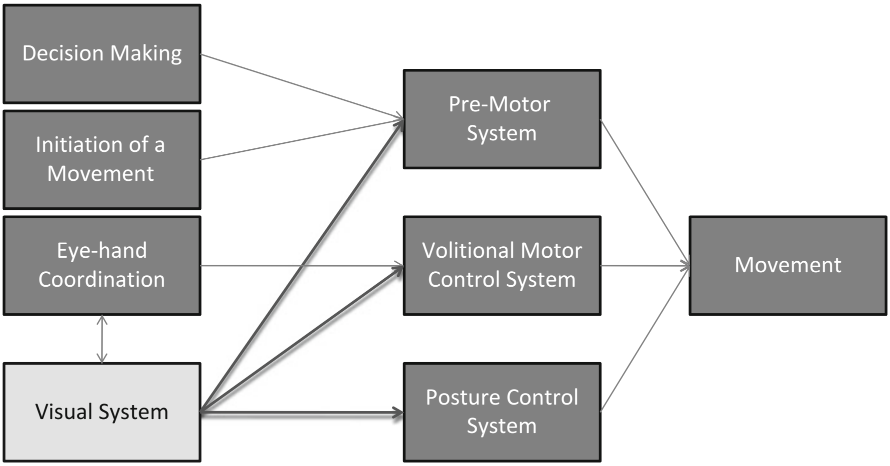

Fig. 1 The role of the visual system in the process of volitional movement execution

subsystems. Visual perception is an integral part of the pre-motor subsystem as the onset of the trial is a visual event (the change of the targets' color). Once the volitional movement is initiated and the hand moves between the different targets, the ability to appropriately control the hand trajectories highly relies on hand-eye coordination (Sosnik et al. 2004, 2007). Finally, the visual system plays a major role in the posture control system (Kuo et al. 1998).

The motivation of the current study was to investigate whether there are relationships between the visual system performance and the ability to acquire a novel motor movement. Specifically, we compared the results of the two reading-level groups in a battery of computerized tasks which were designed to test the visual system. In addition, we analyzed the relationships (measured by correlation strength) between the performance in the current study tasks and the TST.

4 Method

4.1 Participants

Twenty-five skilled readers (age 24.5 ± 3.4, 14 females and 11 male, 3 left-handed) and 15 dyslexic readers (age 28.6 ± 4.8, 8 females and 7 males, 3 left-handed), were paid to take part in a three-session training program in which the Touch Sequence Task (TST) was performed (Sela 2011). In addition, they performed a battery of computerized cognitive tasks. Dyslexic readers were identified as such by the University of Haifa student support clinic for learning disabilities. All dyslexic readers were re-verified as such by the One Minute Test (Shatil 1997), a test in which participants are required to read aloud as many items as possible from a given word list, within a 1 min interval. The skilled readers scored 113.28 ± 20.60 words while the dyslexic readers group scored 66.00 ± 30.50 words ($t_{(35)} = -5.572$, $p < 0.001$). All participants reported good health with no history of neurological, medical or musculoskeletal disorders that could affect motor performance. None of the participants reported chronic use of medications. Informed consent was obtained prior to each subject's participation in the study. The experiment was approved by the University of Haifa ethics committee.

4.2 Apparatus

TST: The test setup included a touch-sensitive screen and an AMTI AccuSway balance and posture sway measurement force plate (Advanced Mechanical Technology, Inc., Watertown, MA) for recording the participants' postural sway. The touch screen was used to display the touch sequence targets and to collect participants' touch times. The touch screen was positioned in front of the force plate at a distance of approximately 50 cm from the participant's shoulder (while standing on the force plate) and at a height of approximately 170 cm. The distance to the touch screen was set for each individual separately so as to afford a slight flexion of the elbow while performing the touch sequence. The touch sequence presentation and response recordings as well as the force plate output recording were controlled by a desktop computer using an in-house application and the AMTI data collection software. Matlab software (Version 2008a, The MathWorks, Natick, MA) was used to prepare data for statistical analysis using SPSS (Version 14, SPSS Inc., Chicago IL).

In addition, a separate computer set was used in order to run the MindFit Cognitive Test (Cognifit LTD – http://www.cognifit.com), as well as the Tapping and the Simple Reaction Time tasks.

4.3 Tasks and Collected Variables

1. Tapping – The participants were seated comfortably in front of a computer keyboard. They were asked to click on the spacebar as much as possible within a limited time interval of 30 s. The numbers of clicks as well as the time between two successive clicks were obtained. The time of the first click was excluded from the analysis. For each individual, the mean between-clicks time was calculated and used for further analysis.
2. Visual Simple Reaction Time (SRTV) – The participants were seated comfortably in front of a black computer screen. They were asked to click, as fast as possible, on the spacebar whenever a yellow circle appeared on the screen. The time between the circle onset and the participant's reaction was obtained. The time between two successive trials was jittered (1.5 ± 0.75 s). The task

consisted of 30 trials. The first trial was excluded from the analysis. For each individual, the mean reaction time was calculated and used for further analysis.

3. Auditory Simple Reaction Time (SRTA) – The SRTA's paradigm was identical to the VSRT's, with the exception of the use of an auditory stimulus (a 50 ms beep).
4. Spatial Simple Reaction Time (SSRT) (MindFit) – The participants were seated comfortably in front of a computer screen. A circle appeared on the screen in a pseudorandom location. The participants were asked to click, as fast as possible, using a computer mouse, on a circle which appeared in a pseudorandom location on the screen. The circle changed its location following each click. The task consisted of 16 trials. The time between the appearing of the circle to the click was calculated. For each individual, the mean reaction time was calculated and used for further analysis.
5. Visual Perception (VP) (MindFit) – Three animated pictures were presented at the center of the screen for a short time (750, 1,500, or 2,500 ms). The participants were asked to remember them. The moment that the pictures disappeared, four option sets were presented on the screen, each of the options consisted of three pictures. Only one of the four option sets was identical to the target set. The participants were asked to click on the option which included the exact picture set that was previously presented. The task included 12 trials. The task accuracy rate was used for further analysis.
6. Tracking (MindFit) – A circle appeared on the screen. The circle started to move within a curve. The participants were asked to follow the circle using the computer mouse. The tracking accuracy was defined as the amount of time in which the mouse cursor was completely within the circle, relative to the task total time (measured in percentage). The tracking accuracy was used for further analysis.
7. The Touch Sequence Task (TST) – The protocol of the task (Sela 2011) as well as the results are described above. The collected variables were the block's RT1, ET and SDΔX. In order to find the relationship between the current study tasks and the TST, the mean session's RT1, ET and SDΔX were computed and used in further analysis. The results presented in this report are based on the TST first session only.

4.4 Analysis

A *t*-test was applied to each of the collected variables in order to compare between the two reading-level groups. In addition, a Pearson correlation analysis was applied on each of the two reading-level groups separately in order to investigate the relationships within and between the current study tasks and the TST.

5 Results

Table 1 presents the mean and standard deviation of the dyslexic and skilled readers as well as the results of the between-groups *t*-test comparisons. Table 1 indicates that:

1. No significant difference was found when the two reading-level groups were compared in the number of finger taps within 30 s.
2. The groups did not differ in their ability to react rapidly to the occurrence of an auditory stimulus (SRTA).
3. The dyslexic readers were significantly slower in their reaction to a visual stimulus as compared to skilled readers (SRTV).
4. Moreover, they were significantly slower in their performance of the SSRT task.
5. The dyslexic readers were also less accurate in their ability to perform the VP task.
6. No significant difference was found when the dyslexic and skilled readers were compared in their ability to accurately follow a circle that moves in a curve on their screen (Tracking).

Careful examination of Table 1 revealed that the dyslexic readers' performance tended to be inferior as compared to that of the skilled readers in tasks that were 'visually' oriented and demanded reaction. However, in tasks that did not involve the visual system (Tapping, SRTA) or when hand-eye coordination was needed (Tracking) rather than reaction, the groups' performance did not differ.

A series of Pearson correlation analyses was used in order to find relationships within and between the current study's tasks and the TST's first session. The analysis was applied on each of the groups separately. The group of skilled readers showed a significant correlation between Tapping and SSRT ($r_{(24)} = 0.616$, $p < 0.001$), Tapping and RT1 ($r_{(24)} = 0.427$, $p < 0.05$), and SSRT and RT1 ($r_{(24)} = 0.491, p = 0.01$). In addition, a significant correlation was found between the Tracking task and ET ($r_{(24)} = -0.443, p < 0.05$). No significant correlation was found between any of the current study tasks and TST among the dyslexic readers group.

Table 1 The two reading-level groups' mean (and standard deviation) in the current study's tasks

	Skilled readers		Dyslexic readers		T
Tapping (ms)	186.76	(18.80)	196.23	(33.71)	1.088 (N.S.)
SRTA (ms)	305.16	(25.92)	316.48	(40.71)	1.018 (N.S.)
SRTV (ms)	288.57	(16.26)	309.28	(19.86)	3.346**
SSRT (ms)	689.38	(70.50)	782.81	(83.22)	3.468***
VP (%)	87.00	(9.65)	75.00	(10.54)	−3.34**
Tracking (%)	90.01	(7.96)	87.40	(8.07)	−0.903 (N.S.)

N.S. not significant

*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

6 Discussion

The purpose of the current study was to investigate the relationships between the ability to acquire a novel volitional motor skill and the performance of the visual system. Overall, the results of the current study support the notion that dyslexic readers suffer from a specific deficit in their visual system. Furthermore, to a certain degree, this visual deficit may explain their reduced ability to learn a novel volitional movement as compared to skilled readers.

The main thrust of the results of the current study was that different performance measures in the visual system related tasks (SRTV, SSRT, and VP) together with the between-groups indifference in the Tracking task may reflect different aspects and perhaps visual-motor subsystems engaged in the performance of the different tasks. The results of the TST study suggested an occurrence of at least two volitional motor control subsystems (Sela 2011). One is a pre-motor/executive system, which presumably includes processes such as the visual perception of the start cue (Gilbert et al. 2009; Li et al. 2004), decision making as to the ‘go’ signal (Song and Nakayama 2009), motor planning and initiation of the movement (Cisek 2007; Warren 2006). This pre-motor interval was represented by RT1. The second sub-system is a volition, manual control and execution motor system, represented by ET, i.e., the execution time. In the context of the touch sequence performance, this subsystem is presumably involved in the generation of the component movements in an accurate and fluent manner and also in the adherence to the syntax of the sequence (Sosnik et al. 2004), the execution of the movements themselves, and the coordination of the hand and eye, the generation and maintenance of visually guided movement (Land 2005; Sailer et al. 2005). Additional support for the assumption that these are two distinctive motor subsystems is taken from the between-groups comparisons which revealed a significant slowness in the ability to produce the first touch among the dyslexic readers and no impairment in terms of the ability to perform the volitional movement itself. The dyslexic readers’ performance was weaker in tasks which had a “response to a visual cue” component. However, they showed no inferiority in their ability to track, which suggests for intact hand-eye coordination. The first may be a reflection of the pre-motor sub-system’s ability to perceive the occurrence of a stimulus, identify its meaning, and initiate a motor response (equivalent to RT1). The second may reflect the ability of the participant to accurately produce a movement (equivalent to ET). Therefore, the current study data supports the notion that dyslexic readers may suffer from a specific motor control system deficit, accrued in the pre-motor control system, rather than a general motor control system deficit (Sela 2011).

The interpretation of the current study results may even be more specific and suggest that the pre-motor control system deficit among dyslexic readers stems from a visual system deficit. Previous studies investigated the relationship between the visual system and dyslexia (Barela et al. 2011; Eden et al. 1996; Hari and Renvall 2001; Stein 2001). The magnocellular theory (Stein 2001) suggests that an abnormal development of the magnocellular system constitutes a core deficit in developmental dyslexia and results in inferior performance of visual information processing, specifically the processing of rapid temporal changes and visual motion. In turn, this visual deficit presumably affects other cognitive and motor abilities. According to the current study's results, unlike the visually related tasks (SRTV, SSRT, VP), no between-groups differences were found in tasks where the visual system was not involved (Tapping and SRTA). Furthermore, the SRTA had an identical protocol to SRTV, with the exception of the stimulus type. The TST results (Sela 2011) proposed for a pre-motor deficit among dyslexic readers which was assumed to stem from the visual system. However, the results of the TST by themselves could not reject the assumption that the relative slowness of dyslexic readers in RT1 is due to a general sensory perception deficit which includes the auditory system (Galaburda et al. 1994) rather than a specific visual system deficit. In this context, the difference between the SRTV and SRTA results specifically points to the visual system as contributing to the inferior ability of the dyslexic readers to produce a motor response at the same speed as the skilled readers.

Finally, significant correlations were found between the skilled readers' performance in Tapping, SSRT, and RT1. Moreover, a significant correlation was found in their performance in the tracking task and ET. These correlations give additional support to the assumption for the occurrence of two distinctive motor control subsystems, the pre-motor subsystem and the volition (execution) motor control subsystem. It can be suggested that the former group of variables may share a common component, presumably the ability to manually respond to an external (visual) cue (Cisek 2007; Gilbert et al. 2009; Li et al. 2004; Song and Nakayama 2009; Warren 2006), and the later may share a different common component, seemingly the ability to accurately control an ongoing volitional manual movement (Land 2005; Sailer et al. 2005; Sosnik et al. 2004). Furthermore, the fact that the same trend of results was not found among the group of dyslexic readers may serve as supplementary evidence for a motor control system deficit among the dyslexic readers. In a recent study (Barela et al. 2011) the researchers studied the relationship between visual information and body sway among dyslexic children. They measured the participants' body sway while standing in an oscillated room. They found that the dyslexic children oscillated more than the control group. Furthermore, they found that although both groups were sensitive to the task manipulation, thus, coupled visual information (the room rotation frequency rate) with their body sway, the dyslexic children showed less coherence. Their results support the notion of a posture control system deficit among dyslexic readers (Fawcett and Nicolson 1992; Nicolson and Fawcett 1990, 2005; Stoodley et al. 2005). In addition, the visual information and the posture control system performance coherence among non-dyslexic children suggests for an interaction, or relationship, between the sensory (visual) and motor (posture) control system. The fact that the coherence values among dyslexic children were lower serves as evidence for a sensory-motor integration deficit among the dyslexic children. According to the current study's results, it may be proposed that non-impaired individuals show "coherence" in their performance across different tasks (Barela et al. 2011), reflected in between-tasks correlation strength. However, there is no evidence for the same "coherence" between the different tasks among the dyslexic readers. This, by itself, may serve as evidence for a general deficit in their motor control system, as, in addition for the lack of correlation in their "visual-response" related tasks (SRTV, SSRT, RT1), they did not show correlation in the hand-eye coordination tasks (Tracking and ET) as well.

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Numerical Cognition: From Development to Intervention

Orly Rubinsten, Ph.D.

The field of numerical cognition has seen an upsurge of research in the last two decades. Such research furnished the scientific community with knowledge about the basis of numerical abilities and the brain mechanisms involved. Nevertheless, it has little influence on math education. Also, treatment and remediation of cases of math learning disabilities have not been well established. This is due, in part, to the lack or rather scant connections between cognitive neuroscientists and educators and in part to the difficulty in translating cognitive neuroscience knowledge into methods and tools to be used in daily educational and remedial practice. The current part of the book is aimed at (a) describing the neurocognitive characteristics of typical and atypical development of numerical abilities, and (b) translating this knowledge to educational issues and remediation of atypical developing children.

One of the most notable findings about developmental mathematical abilities and disabilities is its specificity: a child can be extremely intelligent and stand out in many different ways, and have just one difficulty in numerical abilities. Today it is quite clear that to a certain degree, the brain develops to be numerically educated, often automatically and effortlessly. One hypothesis is that the brain of the newborn infant comes equipped with various domain-specific cognitive mechanisms such as the "number sense" (or the ability to implicitly and intuitively understand quantities) (Dehaene 2009). Others argue that the brain could very quickly learn (Verguts and Fias 2004). These domain-specific mechanisms are assumed to enable learning of different things such as mathematics (Butterworth 2005). Accordingly, to fully characterize the development of mathematical thinking it is essential to

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understand the evolutionary and developmental building blocks of quantitative thinking. This is what Tamar Ben-shalom, Andrea Berger and Avishai Henik describe in their review chapter. They discuss and develop the hypothesis that basic numerical abilities such as the ability to automatically process quantities and to associate between these quantities and their spatial position on the "mental number line" might be the antecedent of higher mathematical thinking.

In the following review chapter in this volume, Dana Sury and Orly Rubinsten suggest that on top of those core representations of quantities (Dehaene 2009), which are discussed by Tamar Ben Shalom and her colleagues, there is an additional and separate core cognitive ability which is the ability to represent ordered relations. They present cognitive, neuro-functional and developmental finding and show that just like the well accepted core representations of quantities, there are also several findings suggesting that ordinal judging is not an 'adult ability' but rather might be innately or evolutionary available to humans and animals.

It should be noted that current estimates indicate that more than 5% of children fail to show the typical development of such numerical abilities (e.g., implicit processing of quantities). Hence, a substantial proportion of the school-age population will have a specific learning deficit in mathematics (von Aster and Shalev 2007). Specifically, most diagnostic criteria use the term Developmental Dyscalculia (DD) to describe moderate or great difficulties in fluent numerical computations. Others specify DD as disorder in mathematics due to deficit in core numerical abilities (based on Berch 2005; Landerl et al. 2004; Rousselle and Noel 2007; Rubinsten and Henik 2005, 2006) (for an overview see Kaufmann and Nuerk 2005). However, the nature of DD has received scant attention from either clinicians or researchers, despite functional significance of mathematical abilities and numerical cognition (Duncan et al. 2007) for health numeracy (Nelson et al. 2008). Accordingly, in their review chapter, Korbinian Moeller, Ursula Fischer, Ulrike Cress and Hans-Christoph Nuerk describe two different optional cognitive origins of the symptoms of DD: the number sense vs. a variety of different basic numerical abilities. Also, they indicate that the diagnosis of DD is generally determined based on a discrepancy between chronological age and-age appropriate education. Interestingly, however, they show how the fact that there is no actual consensus as to the threshold score or cut-off point to be used in decision making, significantly hampers a clear and precise diagnostic evaluation of DD and have huge epidemiological implications. Their review leads them to argue that there are several different sub-types of DD and each needs to have a matching diagnostic and intervention tools. Those tools should target the specific cognitive deficit.

As an example, Liane Kaufmann and Silvia Pixner describe in their chapter other cognitive abilities that should be targeted during intervention. Specifically, there are not only domain-specific but also domain-general cognitive abilities (e.g., attention, memory) that were not designed to exclusively operate on specific contents but rather deal with varied content areas. Domain-general and domain-specific mechanisms do interact and these interactions are important for proper development (Blakemore and Frith 2005; Goswami 2006). Moreover, it has been suggested to cause mathematical disabilities (Kroesbergen et al. 2009; Kaufmann and Nuerk 2005; Rubinsten and Henik 2009). Conversely, for some cases of DD, such domain-general abilities and not only domain-specific may help compensate for specific disabilities in school-related topics. Kaufmann and Pixner suggest that different targeted intervention programs for DD should focus on separate cognitive aspects which correlate with specific DD subtypes (i.e., either domain-general or specific depending on the persons' cognitive profile). In that context, they describe two promising interventions for typically developing elementary school children [i.e., (1) training programs that aimed at fostering either basic numerical or spatial skills and (2) multimodal training aiming to re-teach number fact knowledge]. Despite the fact that the argument about the need for different interventions for different subtypes of DD, is being strongly supported by a broad scientific research which they review in their chapter, Kaufmann and Pixner emphasize that up to date there is no direct evidence showing that training of domain-general abilities will have valuable effects on calculation skills in children with atypical development such as DD. However, one such initial evidence is actually presented in the last chapter of this part of the book, in which Evelyn Kroesbergen, Jaccoline Van 't Noordende and Meijke Kolkman, provide evidence showing that, when there are no time constrains for training, combination of tasks which are focus on both number sense and working memory is the most effective training for children at risk for mathematical learning difficulties.

As can be seen from the five chapters of this part of the book, in recent years, we have witnessed efforts to create bridges between cognitive science and neuroscience on the one hand and education on the other hand. Several researchers have suggested that a new field is emerging: mind-brain-education (Ansari and Coch 2006; Goswami 2006; Rayner et al. 2001). All the chapters implicitly support such initiatives. In order to be able to inform education and intervention it is essential to understand the interactions between biology and numerical development, particularly in terms of developmental mechanisms. This has been indicated in all the chapters. The last three chapters focused also on the importance of familiarity with biological and cognitive foundations for creating tools for assessment and intervention.

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The Beginning of the Road: Learning Mathematics for the First Time

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The purpose of this chapter is to describe how numerical knowledge is typically acquired during early childhood. We will focus on the time period between kindergarten and first grade, describing the course of children's numerical development in this short, yet critical, period of time.

This age level is particularly intriguing since it is the first time children engage in a formal and fixed setting in which they learn and internalize the basic principles of numerical knowledge. Children at this age level are expected to learn some basic mathematical rules and concepts. They need to realize that their outside world can be organized in clear concepts of mathematical thinking and reasoning. Among these concepts are basic mathematical procedures (adding and subtracting), concepts of special numbers (such as the concept of zero) and the important associations between numerals and numerical magnitudes. During this period, individual differences can be seen in the ability to learn and execute numerical procedures.

We will discuss the up-to-date empirical evidence on typical development of numerical abilities, as well as the various factors contributing to the individual differences in the acquisition of these abilities.

Studies have found that even infants can process basic numerical values. A common theory today claims that we come into this world with inborn basic abilities to perceive and evaluate quantities (Berger et al. 2006; Bijeljac-Babic et al. 1991; Lipton and Spelke 2003; Nieder and Dehaene 2009; Starkey and Cooper 1980; Wood and Spelke 2005; Xu et al. 2005; Wynn 1995).

The main hypothesis that these type of studies share, is that humans are born with a core system of magnitude that develops throughout maturation and experience into the "number sense" (Butterworth 2005; Dehaene 1997). Feigenson et al. (2004) claimed that our representation of numbers relay on two core systems: (1) approximate representations of large numerical magnitudes and (2) precise representations

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of distinct and small numerical magnitudes. They suggested that infants and adults use the *first* system in order to represent large approximate quantities. Children rely on this system when learning to associate symbolic numbers to the pre-existing magnitude representations. The *second* core system is used by adults and infants as well, in order to keep track of individual objects.

Von Aster and Shalev (2007) argued that "*early preverbal core-system representation of cardinal magnitude provides the numerical meaning to number words and Arabic number symbols*." (p. 869). They described a hypothetical and useful four step developmental model of numerical cognition, based on Dehaene's triple code adult's model (Dehaene 1992). The first core system is the magnitude system, which enables a child to compare two sets of objects or events that differ in number. The second core system is the verbal number system that associates number words with quantities. The third core system is the Arabic number system, which associates numerals to quantities. With time and experience, the child learns to relate numerical quantities to Arabic symbols and basically becomes capable to use this knowledge for more complicated numerical manipulations. The main understanding that the child needs to learn about numerals is that for every specific quantity, there is a specific associated symbol. The last system in von Aster and Shalev's model is the "mental number line" system, which contains the automatic representations of numbers on a mental number line. When children use this information (the association between numerals and quantities) without effort or intention, it can be claimed that they have an automatic processing of this basic numerical knowledge.

The child at kindergarten age and in first grade has been exposed to a variety of symbols that his culture provides in order to associate inborn understanding to cultural language. During the last year of kindergarten and the first year in school, children learn for the first time (in a formal and more intensive way) the Arabic numeral system and its association to quantities, counting procedures and some basic operations in math (addition and subtraction).

1 What Do First Graders Already Know?

In studies of numerical knowledge and automatic numerical processing among adult subjects, researchers have found common behavioral effects that are considered to be evidence for cognitive numerical representation and processing of numerical value—the *Distance Effect* (DE), the *SNARC Effect* (Spatial-Numerical Association of Response Code) and the *Size Congruity Effect* (SiCE).

1.1 Mental Number Line: The Numerical Distance Effect and the SNARC Effect

The DE was first reported by Moyer and Landauer (1967). In their study it was found that when people are asked to decide which of two numerals is larger, responses are faster as the distance between the two numerals increases. The DE was replicated in many studies since then (Dehaene et al. 1990; Henik and Tzelgov 1982; Tzelgov et al. 1992). The DE is considered to be an indication for the existence of an analogical mental number line that contains representations of numerals. Mental number representations of numerically close numerals overlap more than mental number representations of distant numbers. Thus, interference is stronger for adjacent numerals compared with distant ones (resulting in longer reaction times to classify adjacent numbers).

Studies have also examined the development of the mental number line by examining the DE in children. Sekular and Mierkiewicz (1977) asked children to compare two digits. They found a numerical DE in kindergarten children and first, fourth and seventh graders. Duncan and McFarland (1980) found a similar pattern of reaction time (RT) in a comparison task of single-digit numerals in kindergartners, first, third and fifth graders, and adults. In both studies, the slope of the function between numerical distance and RTs decreased with age.

Duncan and McFarland (1980) suggested that young children usually show little evidence of conscious processing strategies and hence, are more affected by automatic cognitive mechanisms. Their study was the first to show that kindergartners and first graders already know the semantic meaning of numerals and they automatically compare between those values. Temple and Posner (1998) found the same effect in 5-year-olds using digits and arrays of dots for comparison. Since then, many studies have found this effect at various age levels (De Smedt et al. 2009; Holloway and Ansari 2008; Rubinsten et al. 2002)

Other evidence for a relationship between numbers and the mental number line in space is the SNARC effect. This effect appears when subjects are asked to react to numerical stimulus in a spatial manner. It was found that subjects are quicker to respond with a left side response to relatively small numbers and with a right side response to relatively large numbers (Dehaene et al. 1993; Fias and Fischer 2005; Hubbard et al. 2005; Wood et al. 2008). This effect is considered as support for the assumption that the mental number line is oriented from left-to-right, that is, small numbers are represented on the left side and large numbers are represented on the right. Also, there is a debate in the literature as to whether the SNARC effect is directly dependent on the mental number line or whether it is influenced by task demands (see Galen and Reitsma 2008).

However, it is interesting to understand at what age children present the SNARC effect. Berch et al. (1999) tested children from grades two, three, four, six and eight on a parity judgment task with Arabic numerals, by asking them to press a left or right response key. They found that only 9-year-olds (Grade 3) presented a SNARC effect. Galen and Reitsma (2008) claimed that perhaps the parity judgment task was too difficult for young children, and tested children from grades one, two and three when number magnitude was part of the task requirements (magnitude judgment task—comparison to five) and when it was irrelevant (detection task). Their results showed that in the magnitude judgment task (when the number magnitude was relevant), children as young as 7 years old (first graders) already showed the SNARC effect. In the detection task, when number magnitude was irrelevant, only 9-year-olds showed automatic access to number magnitude and exhibited the SNARC effect. Galen and Reitsma's interpretation was that 7-year-olds do not automatically activate semantic information of number magnitude, although they can associate between numbers and space on the mental number line. These associations appear only in tasks that require deliberate attention to number magnitude.

1.2 Association Between Symbols and Magnitudes—The SiCE

One of the most important pieces of knowledge a child must acquire at the beginning of mathematical learning is the associations between numerals and quantities. When this knowledge is well established and the child can use these associations without any effort and conscious intention, one can claim that this knowledge has become automatic in its nature.

A common paradigm to investigate automatic processing of knowledge is the classical Stroop task (Stroop 1935). Subjects are presented with a stimulus that contains two different dimensions (such as color and semantic meaning in a written word) and are asked to ignore one of the dimensions. If a subject cannot ignore the *irrelevant* dimension, it is a considered to be evidence for automatic processing of that irrelevant dimension. Studies have used different variations of this paradigm in order to investigate automatic processing. In the area of numerical processing, a numerical Stroop task can easily test whether the subject can or cannot ignore the numerical meaning of a numeral. Subjects are presented with two numerals (e.g., 2 3) that differ in their physical and numerical value. It was first found by Henik and Tzelgov (1982) that participants respond slower to incongruent pairs of numerals, where the two dimensions are in opposite directions (e.g., 3 5—the numerically smaller numeral is physically larger) than to neutral pairs, where the irrelevant dimension does not change (e.g., 3 3 in the physical task and 2 5 in the numerical task). Responding is fastest for congruent pairs, where the two dimensions are in the same direction (e.g., 3 5—the numerically smaller numeral is also physically smaller). Henik and Tzelgov named this effect the SiCE. This effect indicates that subjects cannot ignore numerical values of numerals, even if they are asked to focus only on the physical dimension and ignore the numerical values. The numerical dimension is considered to be processed in a non-intentional and automatic manner (Henik and Tzelgov 1982; Rubinsten et al. 2002; Tzelgov et al. 1992).

Rubinsten et al. (2002) examined the development of the SiCE among first, third and fifth graders compared to adults (see Fig. 1). Subjects were asked to decide which digit was larger (numerically or physically) in a numerical Stroop task. They found that for all age groups, children and adults showed a significant DE (as was found in the previous studies mentioned above). In contrast, at the beginning of first grade, children did not present a significant SiCE in the physical task (when the numerical value was irrelevant). This indicates that the irrelevant numerical value did not interfere with processing of the relevant physical dimension,

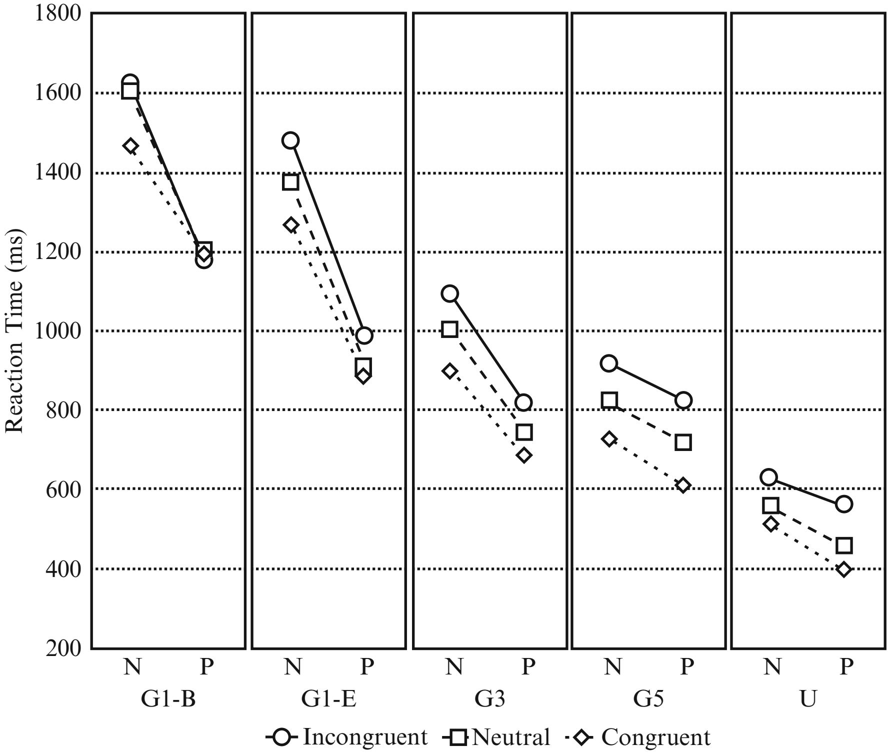


Fig. 1 The SiCE in beginning of first grade, end of first grade, third grade, fifth grade and university students. Relevant dimension *N* numerical, *P* physical (Taken from Rubinsten et al. 2002)

hence, the children did not process the numerical value of numerals automatically. At the end of first grade, numerical values were activated and interfered with processing of the relevant physical dimension. However, at this point the effect was only based on interference (incongruent trials were slower to process than neutral ones), and facilitation (neutral trials were slower to process than congruent ones) was lacking. In third and fifth grade and in adult students, the SiCE was present with interference and facilitation components in the physical task.

In addition, Girelli et al. (2000) also found a SiCE in the numerical task among first, third and fifth graders. However, in the physical task, a SiCE was found only among third graders. Mussolin and Noël (2007) also found the SiCE in physical comparisons only in second, third and fourth graders. In their technique, they tried to balance between the speed of perceptual processing and semantic processing. Numerals first appeared in the same physical size and then changed into different physical sizes. Their results indicated that even in second grade, children can automatically process the magnitude information of one- and even two-digit numerals. Also, in 2008, Mussolin and Noël found that numerical masked priming modulated the SiCE, relative to a neutral prime, in second, third and fourth graders.

They concluded that young children benefit from a relative synchronization between physical and numerical dimensions in order to automatically access the magnitude of two numerals.

Zhou et al. (2007) studied a population of kindergartners in China, in order to examine the automatic knowledge of numerical value at even younger ages. They used the same numerical Stroop task and asked the children to compare the numbers physically (which one seems bigger on the screen) or numerically (which one is larger in numerical value). They found the SiCE was significant in the physical task, meaning that the young children processed the semantic value of the numerals in an unintentional and automatic way. This result indicates that a representation of the semantic value of those numerals already exists at this age level. Zhou et al. related their results to cultural differences between Chinese children and the Western population of children studied so far. First, Chinese children have shorter pronunciation duration of digits than do children using other languages, which can help them in terms of working memory storage. Also, the Chinese based 10 numbering system can provide an advantage in early counting and they also use numbers to indicate the days of the week. Finally, Chinese families start to train their children at a young age in mathematics, in lessons after school.

From those studies it appears that the automaticity of numeral processing (the SiCE) starts to appear at the end of first grade and fully exists only from second grade, except for Zhou et al.'s (2007) results that showed this effect in kindergartners.

Our study (Ben Shalom et al. 2010) also examined automatic numerical processing at kindergarten age in Israel. Our hypothesis was that children in kindergarten would already exhibit automatic numerical processing of numerals, particularly due to the fact that children in kindergarten in Israel today learn the basic knowledge of numerals in a formal way. Also, in Hebrew, the numerical system indicates the days of the week (Sunday – "first", Monday – "second", etc.) similar to the Chinese language. We used the same numerical Stroop paradigm and presented children at kindergarten age (5-6-years-old) with two numerals. In one block the children were asked to decide which digit was numerically larger and in the second, which was physically larger. Our results showed that children presented a significant DE in the numerical task, which indicated that they already had a stable mental number line. Also, these children presented the SiCE by the end of kindergarten. This result indicates that those children already reached a certain level of automatic number processing (see Fig. 2). This replicates Zhou et al.'s (2007) results. Still, the pattern of reaction times in our study was not similar to the pattern for adults in physical comparisons of numerals. In the physical task (when the numerical value was irrelevant), the neutral pairs had the significant, fastest RTs.

Our results can indicate that at kindergarten age, it is easier to perform a physical comparison without any involvement of numerical values. This result might indicate a difference in the ability of participants at this age level to attend physical sizes, as opposed to numerical sizes.

Interestingly, this lack of facilitation or reverse facilitation can be related to studies of dyscalculia. Ashkenazi and colleagues (Ashkenazi et al. 2008) reported a similar reverse facilitation in a patient with acalculia following an infarct restricted

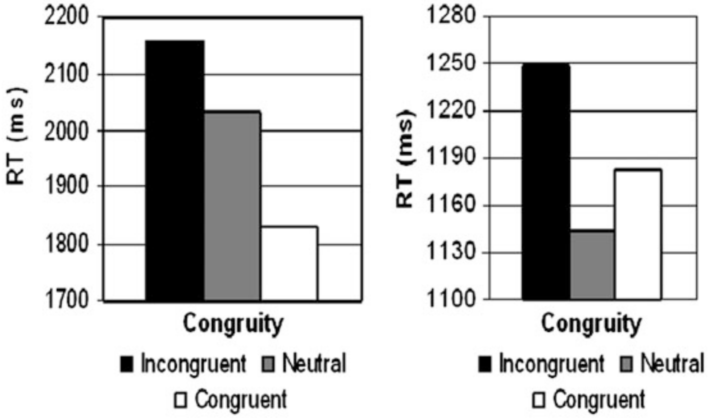


Fig. 2 Congruity effect (by reaction times) in the numerical (*left*) and physical (*right*) task

to the left intra parietal sulcus. In the studies of Rubinsten and Henik (2006) and Rubinsten et al. (2002), the results showed no facilitation component in dyscalculic adults or in first graders in the numerical Stroop task when the numerical value was irrelevant.

It seems that this pattern of no facilitation or reverse facilitation may appear in groups with dyscalculia or in younger subjects that do not have a long-term interaction with numbers and numerical procedures. These results need more investigation in the future in order to understand the mechanisms that are behind this pattern of reversed facilitation.

2 Brain Development and Arithmetic Knowledge

A very large body of research has found that brain activity is modulated by numerical processing. It was found that the parietal lobe, and more specifically the IPS (intraparietal sulcus), is one of the most important brain regions involved in number processing. This area and other parietal areas are activated during mathematical processing such as number operations, number identification, and numerical comparison, regardless of their notation, whether symbolic or non symbolic. Many researches have focused on the IPS region as a common area that is activated when comparing two numerosities and is sensitive to the numerical distances between them (Dehaene et al. 1993; Nieder and Dehaene 2009; Pinel et al. 2001). It was also found that the parietal lobes are activated during physical size comparison and brightness comparison (Cohen Kadosh et al. 2005; Pinel et al. 2004), for enumeration of small quantities (subitizing vs. counting, see Ansari et al. 2007), and are considered to be a target area for the investigation of the SiCE in the numerical Stroop task. A study by Cohen Kadosh et al. (2007) was conducted to investigate brain activity that can be seen when a SiCE occurs. In their study, it was found that the SiCE and DE modulated brain activity in the IPS and motor areas.

Studies have also tried to track the development of brain areas involved in number processing. Cantlon et al. (2006) investigated whether representations of non-symbolic quantities is related to symbolic representations in the brain. They tested adults' and 4-year-olds' brain adaptation to non-symbolic quantities. They found that the IPS was recruited in non-symbolic quantities processing, even in 4-year-olds when formal schooling in math had not yet begun. Regarding symbolic representation, Kaufmann and colleagues (2005) found that in the adult brain, the numerical Stroop task activated areas in the dorsolateral prefrontal cortex and anterior cingulated cortex related to attentional control. Larger distance between numerosities was followed by greater activation in bilateral parietal areas, including the IPS. Kaufmann et al. (2006) found that the same task activated different brain areas in 9-year-old children. Brain areas that were activated when there was a large numerical distance were frontal but not parietal. Only when the numerical value was irrelevant, frontal areas were activated, comparing the incongruent stimulus activation to the neutral one. Ansari et al. (2005) found similar results in 10-year-olds, who had activation in more frontal areas compared with adults, who had activation in parietal areas during a task of symbolic number comparison. In his review, Ansari (2008) claimed that those previous studies were evidence for a fronto-parietal shift in the development of number representation.

Using an ERP (Event Related Potentials) technique, Temple and Posner's (1998) study revealed that brain activity for numerical distance in symbolic representation appeared in a similar brain area and time window in adults and 5-year-old children. Szũcs et al. (2007) also found that brain electrical activation to numerical distance was the same for 9- to 11-year-old children and adults. However, looking into brain activity sensitivity during interference in incongruent trials (e.g., 3 2) and facilitation in congruent trials (2 3), in situations with a SiCE, different brain activity patterns were found for children compared to adults. Specifically, two wave components—the P300 and LRP (lateralized readiness potential)—were found to be different between those age groups. These brain waves were also found in Cohen Kadosh et al.'s (2007) research to be components that were modulated by the SiCE. In the children's group in Szũcs et al.'s study, the interference effect was more related to the LRP component (response conflict) than to the P300 (stimulus processing) when compared to adults. They concluded that different cognitive processes underlie children's and adults' performance in the numerical Stroop task. These cognitive differences should be considered when measuring the automaticity of numerical processing in children.

3 Individual Differences

Kaufmann and Nuerk (2005) claimed that: "*one has to keep in mind that average arithmetic development does not pursue a straight, fully predictable course of acquisition, but rather can be characterized by quite impressive individual differences*" (p. 144). Any school teacher will agree that many factors can contribute to individual differences in the classroom. For some children, individual differences improve their self esteem because they are ranked at the top of the class list. Some other children suffer from low self esteem and can feel very ashamed since they are located at the very bottom. What contributes and makes those lucky and not so lucky children differ in their academic success, especially in mathematics?

Academic achievement in mathematics is one of the most appreciated and valued achievements in life. Similar to reading abilities, many parents are concerned with their child’s progress in the study of math. When the child has serious problems in learning math and is very behind the other students in the classroom, often a diagnostic test is administered in order to evaluate if the child has a learning disability in mathematics, that is, *dyscalculia*.

We will discuss the latest studies regarding individual difference in the normally developing population. From the normal population we will try to conclude which factors contribute to the individual differences in mathematical learning that we can observe in class.

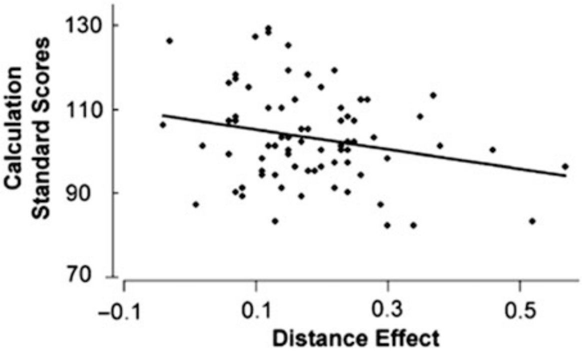
Studies have tried to predict a child’s performance in math by measurements of very basic numerical knowledge. Fayola et al. (1998) found that a child’s performance in neuropsychological tests involving sensory integration and finger organization predicted performance in simple arithmetic assignments. Also, Noël (2005) found that in first graders, measurements of finger gnosia were a good predictor of children’s numerical skills 1 year later. This suggests that early strategies of finger counting can be crucial for math performance in later stages.

Bull and Scerif (2001) found that basic mathematical abilities were correlated with different aspects of executive functions such as inhibiting a learned strategy and switching to a new one. They also found that mathematical abilities in children were correlated to working memory load and to the ability to inhibit irrelevant information. Mazzocco and Thomson (2005) found that performance in basic numerical assignments in first graders was associated with predictions of math learning disability. They measured numeral reading, number constancy, magnitude judgments of one-digit numbers and mental addition of one-digit numbers. Jordan et al. (2007) found that these basic numerical skills and their development during kindergarten could explain a significant variance of a child’s math scores at the end of first grade. In the research of Haldberda et al. (2008), a correlation was found between the non verbal approximation ability of 14-year-olds and their basic math achievements in kindergarten, and their symbolic math achievements in third grade.

Regarding laboratory measurement of reaction times, few studies have tried to correlate some of the behavioral effects that we mentioned earlier (DE and SiCE). For example, Holloway and Ansari (2008) found significant correlations between DE measures in symbolic comparisons and mathematical achievement measures in 6- to 8-year-olds (see Fig. 3).

In a longitudinal study, De Smedt et al. (2009) found that measurement of DE in 6-year-olds predicted their mathematical achievement 1 year later. These findings strengthen the hypothesis that a relationship between basic automatic numerical performance and mathematical achievement is possible and even provide evidence. However, other studies did not find this relationship in older children.

Fig. 3 Correlation between distance effect and calculation ability (Taken from Holloway and Ansari 2008)



Schneider et al. (2009) did not found a relationship between 10 and 11 years old children's understanding of fractions and their DE processing measurements.

Our study (Ben Shalom et al. 2010) also predicted that a relationship would be found between a child's level of number processing and his/her general mathematical abilities. We measured the child's level of automaticity of processing numerical value by using the numerical Stroop paradigm during last year of kindergarten. In addition, all the children were given an arithmetic examination. Only accuracy rate was measured. We employed a test prepared by Manor and colleagues (Manor et al. 2000). Our results found a clear relationship between a child's automatic processing of numerical values and his/her general mathematical abilities. More specifically, components of the SiCE (facilitation and interference; for more details see Henik and Tzelgov 1982) in the physical task (when the numerical value was irrelevant) were correlated with the following three mathematical abilities: (a) Order irrelevance—this subtest tested the child's understanding of the order irrelevance principle in counting. (b) Equivalence principles—this subtest tested the child's understanding of the equivalence principle in number reasoning. When the child understands this principle, he or she realizes that as long as the number of item does not change, attributes of the counted set can be changed (color, size, identity etc.) without having any effect on the quantity. (c) Adding and subtracting one-digit numbers from 5 to 10.

Positive correlations were found between the *congruity* component (incongruent vs. congruent reaction times) and two important principles—counting and quantities reasoning. Those principles are important for the child's comprehension of quantities. We also found a significant positive correlation between the *interference* (incongruent vs. neutral reaction times) and *facilitation* (neutral vs. congruent reaction times) effects and the score of verbal problems in adding and subtracting. This might suggest that the development of the association between numerals and quantities can be related to the development of quantities comprehension.

The growing body of studies trying to predict a child's mathematical abilities is major and crucial for the diagnosis of learning disabilities. Studies found that the child's level of mathematical abilities can be related to executive functions and basic numerical knowledge. Perhaps in the future, we will be able to predict a child's mathematical abilities by using simple and basic numerical tasks. For this goal, clearly more investigation is needed in this field.

4 Summary

Studies have found that even infants can process numerical magnitudes. However, during development and education, children learn to associate between these "inborn" numerical abilities and symbols that culture provides, in order to learn higher mathematical skills.

In examining the development of numerical processing, researches have revealed that children in kindergarten and first grade are already familiar with the association between numerals and quantities and their spatial order on the "mental number line". Moreover, they process these associations automatically, to some degree. This automatization of numerical processing is a relatively new discovery that still needs to be investigated in more populations of kindergartners. However, this might indicate that normally developing children today are more familiar with the "numbers world" at a very young age. Intense education programs that parents and teachers provide children with today can clearly affect their performance in basic numerical tasks and basic numerical knowledge.

Studies that tried to predict individual differences in children's mathematical abilities revealed that basic numerical tasks can be a good predictor for a child's level of mathematical skills in the future. Clearly, more research needs to be done in this field in order to improve those tasks and transform them into more diagnostic tools.

Another important topic in regard to children's numerical processing is their reliance on frontal brain areas at very young ages. Children seem to rely more on frontal brain areas in the beginning of learning, and shift into parietal brain areas as they acquire more experience and maturation. This evidence could indicate that initially, learning mathematics requires more attention, working memory and executive functions from children in this age level.

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Ordinal Processing of Numerical and Non-numerical Information

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1 Introduction

Numerical information requires not only cognitive representations of quantities but also representations of ordinal relationships. It has been shown that the ability to judge and learn the ordinality of a sequence might be innately available to animals (e.g. Brannon and Terrace 1998; Rugani et al. 2007), human infants (e.g. Suanda et al. 2008), toddlers (e.g. Brannon and Van de Walle 2001) and human adults alike (e.g. Fulbright et al. 2003).

Numbers are considered to represent three main concepts; specifically, human beings use numbers (1) to quantify objects, (2) to determine a rank or a position (3) and even to identify objects (the nominal concept) (Nieder 2005). Beyond cardinal meaning, numerical ordinality is considered as the second main numerical concept (Nieder 2005; Zorzi et al. 2010). However, despite the significance of ordinality in numerals, most researchers in the field of numerical cognition focus on quantity processing and much less on ordinal processing.

Specifically, in the last three decades, it had been extensively argued that cognitive foundations of mathematics rest on mental representations that have been developed during the course of evolution. These core representations include a numerical magnitude system that represents the approximate numerical value of a collection of objects (Dehaene 2009), representations of space (Shepard 2001) and representations of continuous quantities such as length and time (Feigenson 2007). Here we want to add an additional core cognitive ability, the ability to represent ordered relations and explore if there are actually two separate core systems (together with others) that lie at the foundations of numerical cognition. Following this line of thought we review cognitive, developmental and neurofunctional studies (see Appendix 1 for an overview of all studies studying order processing

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presented in this chapter) to learn if there are two separate cognitive mental representation: (1) the traditionally accepted numerical magnitude system (Dehaene 2009), but also (2) the ordinal system. This system could be an innately available to human, or, according to Verguts and Fias (2004), might simply be "quickly learnt". Either innately available or quickly leant, we assume here that the ordinal system might be a very basic and initial in cognitive development. As a result, we conclude by suggesting a theoretical (Fig. 2) model that challenges a historical scientific logic which argues that the antecedence of numerical cognition lies only or mainly in the ability to implicitly process quantities. We, together with few others, suggest ordinality as an additional core cognitive system.

2 Ordinal Information: Definition

Buying a ticket to a movie and finding the correct seat in the movie-theater are simple activities that embody the involvement of numerical knowledge in our day-to-day life. Numbers are used to indicate numerical quantities (e.g. two seats), the identity of something (e.g. seat number 5) and the position or rank of an item in a sequence (e.g. the fifth row). The latter involves the ordinal aspect of numbers (Jacob and Nieder 2008; Nieder 2005). Accordingly, numerical knowledge requires representations of both quantities and ordinal relationships (Fias et al. 2007; Nieder 2005). Consequently, numerical operations might be influenced by ordinality and not just quantity (Turconi et al. 2006).

Although there is an agreement that the knowledge and understanding of the ordinal relationship between quantities is a crucial component in numerical knowledge (Fias et al. 2007; Jacob and Nieder 2008; Nieder 2005; Kaufmann et al. 2009), current research in the field of numerical cognition uses different definitions of ordinality rather than one coherent definition.

The most common definition of ordinality, refers to the position or the rank of an item in a sequence, (i.e. ordinality indicate the position of an item in a sequence, e.g. the fifth item) as opposed to "how many?" in the case of quantity processing (e.g. five items, Jacob and Nieder 2008; Kaufmann et al. 2009; Nieder 2005). Similarly, Fias et al. (2007) and Brannon and Van de Walle (2001) refer to ordinality as the relationship between quantities as in the question "what comes before or after?"

Suanda et al. (2008) suggest that at the initial stages of development, the ability to know that two is different from three but not appreciating that three is more than two, represents the cognitive development of quantity representations with no representations of ordinal relationships between these quantities. If this argument is correct, it means that any numerical comparison task (e.g., which one of the two groups of dots has more dots) and its related effect (e.g. the distance effect) are uniquely related to ordinality (i.e., knowing that 3 is more than 2, as in the previous example) rather than quantity discrimination. This example is supported by recent findings showing that numerical comparison tasks (e.g. judging whether 3 is smaller than 7) and ordinal judging tasks (e.g. judging whether 3 comes before 7) are associated with different spatio-temporal courses (Turconi et al. 2004). Therefore, knowing that one quantity is bigger than another is different from knowing if one quantity comes after another. These findings reinforce the view that ordinality and quantity processing are separate and hence, might be based on different mechanism.

Other studies use a more complex definition of ordinality, as for example, in a study by Boysen et al. (1993). They refer to ordinality in terms of inferential reasoning. According to Boysen et al. (1993), judging ordinal relationships between two items, is the result of processing relationships of each of the items with a third one (i.e. transitive inference). In transitive inference tasks, participants are expected to learn the ordinal structure of the sequences. In initial phase, participants are repeatedly presented with sequential pairs of elements from a sequence and learn the internal order of individual pairs. After initial learning of the relationships within these pairs, participants are expected to implement that ordinal knowledge when presented with novel pairs from the same sequence. For example, participants learn the relationships between A–B, B–C and C–D and are expected to conclude that A is smaller than C (Van Opstal et al. 2007). This capacity for processing information transitively is not unique to humans and was also found in primates a (e.g. Boysen et al. 1993).

According to Boysen et al. (1993), inferential reasoning is the ability that stands at the basis of ordinal processing. Accordingly, several studies have investigates the cerebral involvement with ordinal processing by using transitive inference tasks of arbitrary sequences (e.g. Van Opstal et al. 2007, 2009). Van Opstal et al. (2009) found that the left inferior frontal gyrus (left IFG) might be involved with inferential reasoning. In contrast, studies that used comparisons tasks (of both non-numerical and numerical sequences), found mainly the involvement of the IPS in the processing of ordinal information (e.g. Fias et al. 2007; Kaufmann et al. 2009).

The definition of ordinality in numerals has raised the question of exact vs. estimated representation of quantity. Feigenson et al. (2002), found that 10–12 month old infants choose the larger quantity of crackers when presented with sequential quantity pairs up to three (buckets of 1 vs. 2 or 2 vs. 3 crackers). In contrast, infants did not choose the larger quantity when presented with 2 vs. 4, 3 vs. 4 and 3 vs. 6 quantities. Following these results, Brannon and Roitman (2003) suggested that since the numerical ratio did not modulate the infant's performance. It was the ordinality that modulated infants performance and hence, ordinal judgment might be based on an exact representation of quantities as opposed to relative judgment between quantities.

Different definitions of ordinality call for different tasks (see Appendix 1 for summary of all the tasks that are described in this chapter) and, as a result, reveal inconsistent results. For example, judging whether an item comes before or after another item in a sequence (i.e., defining ordinality as the position or the rank of an item in a sequence) reveals a standard distance effect (i.e., greater distance between two items results in faster response – SDE) even when letters are used as stimuli (e.g. Van Opstal et al. 2008). However, judging ordinality ,of numerical sequences that cross a decade (e.g. 17, 19, 21) (Franklin et al. 2009) or sequential number pairs (i.e., deciding whether the pair presented in the ascending or the descending direction; ordinality as the relationship between quantities, Turconi et al. 2006) reveal a reverse distance effect (i.e., greater distance between two items results in slower responses – RDE).

The different ways used to study ordinal processing raise two major questions: (1) Is the process required to solve these tasks are mainly quantity or ordinality based? And (2) Is the ordinal or numerical knowledge, required to solve those tasks, are explicit or implicit?

When using non-numerical ordinal sequences as stimuli (see Appendix 1 for an overview of the tasks described in this chapter) the answers to the two questions are quite simple. Namely, it seems more reasonable to assume that numerical knowledge is not required (since it is not relevant for those non-numerical stimuli) to solve the tasks. Accordingly, and since these tasks are aimed to assess the processing of the ordinal traits of the non-numerical sequence, an explicit ordinal knowledge is in need.

However, in tasks that involve Arabic numerals as stimuli, the answers to these questions are not as clear. Turconi et al. (2004) and Suanda et al. (2008) suggested that knowing that one quantity is bigger than another is different from knowing that one quantity comes after another. Nevertheless, the question remains: are these two cognitive processes disconnected? Can one know that three comes after two without knowing that three is bigger than two? In most of the studies in the field of ordinal processing, participants are presented with pairs of items (e.g., numbers, letters, months etc.) and are asked to decide whether these pairs are presented in an ascending or descending order (e.g., Fias et al. 2007; Turconi et al. 2006) or to decide which of the items appears before or after in a sequence (e.g., Brannon and Terrace 1998; Brannon and Van de Walle 2001). It is reasonable to argue that these tasks require manipulation of quantity, magnitude or semantic information before extracting ordinal information and arriving at a decision. To know, for example, that 4 and 8 are presented in an ascending and not in a descending order, it has to be initially clear that 8 is larger than 4 (i.e., a numerical comparison). Accordingly, in a way, these tasks cannot selectively activate explicit ordinal processing; they require the involvement of several other cognitive processes, among which is quantity processing. Presenting more items (three and more) as in the Kaufmann et al. (2009), Rubinsten and Sury (2011), Franklin and Jonides (2008) and Fulbright et al. (2003) studies might not automatically lead to quantity judging but will probably emphasize the ordinal relationship of a sequence.

Hence, we believe that task that best arouse explicit ordinal knowledge should involve a sequence of three and more items in one stimulus because a task presenting a pair could always be easily solved by pure magnitude discrimination. According to this assumption, we argue that the definition that best suitable to describe ordinality is the set of positions in a sequence that may be driven from the relationships between items.

3 The Development of Ordinal Knowledge

Up to date, only a few studies have dealt with the issue of ordinal processing in early childhood and even fewer have investigated the developmental aspect of ordinal processing. Nevertheless, findings from these studies reinforce the view that ordinality is a basic pre-verbal cognitive ability, similar to quantity processing. For example, Suanda et al.(2008), who implicitly define ordinal processing as the relationship between quantities (i.e. a definition that is implied from the task which they used and the design of their study), found that 11 month-old infants are sensitive to ordinal relationships between three quantities up to a series of 4, 8 and 16 black squares. Nine-month-old infants were also sensitive to these ordinal relationships, but only when presented with multiple converging cues to ordinality (matched quantity, area and size of stimuli). Hence, it is possible that 9-month-old infants are unable to use any of these dimensions in isolation but instead, require a number of corresponding cues in order to process the ordinal relationships between quantities.

Lewkowicz and Berent (2009), who implicitly define ordinality as recognizing the position or rank of a specific item in a sequence, investigated how 4-month-old infants represent sequences. In a series of three experiments, they habituated infants to three different sequences where each sequence included four distinct objects. In their study, all stimulus events (i.e., sequences of four items) were presented as multimedia movies that showed different sequential orderings of four distinct moving objects and their distinct impact sounds. During the habituation phase, the target object's position in the sequence remained fixed while the position of the other three (non-target) objects varied. During the test phase, after habituation, infants were presented with the target object in its original context, either in its original ordinal position or in a novel inconsistent position within the sequence (e.g. A, **B**, C, D vs. A, C, **B**, D). In the second test set infants were presented with the target object in an unfamiliar sequence (novel objects) either in its original ordinal position or in a novel inconsistent position within the sequence (e.g., E, **B**, F, G vs. E, F, **B**, G, while B remains the target object; see Experiments 1 and 2). The infants detected changes in the ordinal position of the target object only when presented within the familiar context. They failed to generalize the object's invariance position to an unfamiliar context. In the third experiment, there was an additional condition: the target object appeared within the novel sequence composed of familiar objects (e.g. infants were habituated to the sequence H, **B**, I, J and then was tested with the sequence D, G, **B**, J. Hence, objects appeared in habituation phase, but the target object was not presented in that context before the test set). Even though presented within the context of familiar objects (but not a familiar sequence) the infants failed to detect ordinal positioning. Lewkowicz and Berent (2009) suggested that infants fail to learn ordinal invariance (the same position even when presented in another context) but rather encode the relationships between the sequence elements (i.e. infants fail to learn that B is always second but do learn that B always comes after A and before C). These findings reinforce the definition of ordinality as not only the position of and items in a sequence but rather a combination between position and relationships between items.

The ability to process ordinality was found not only in human infants but also in animals. For example, Brannon and Terrace (1998) demonstrated that even rhesus monkeys could learn ordinal rule and apply it to novel quantities. Two monkeys were trained to identify the correct sequence of quantities 1–4 (ascending direction) and then succeeded to apply their newly acquired ordinal knowledge to novel sequence of 5–9 quantities. Additionally, Rugani et al. (2007) have shown that even 5 days old chicks can be trained to identify a position in a sequence. Young chicks used ordinality and not distance when required to identify a target by its numerical serial position. Specifically, Chicks learned to identify a specific position in a series of ten identical positions. They walked rather directly to the learnt position even when the stimuli have been rotated by 90° as compared with training session. Rugani et al. suggested that young chicks seemed to use ordinality when required to identify a target by serial position.

These findings, together with those of Lewkowicz and Berent (2009), suggest that ordinal judging is not an 'adult ability' (Kaufmann et al. 2009) but rather a core ability which is pre- verbal and available to humans infants (Suanda et al. 2008) and animals (Brannon and Terrace 1998; Rugani et al. 2007).

Further evidence of ordinal processing in early childhood comes from Brannon and Van de Walle (2001) who trained 2–3 years old children to detect the bigger quantity of paper boxes (either quantities of one or two boxes) that were positions on two separate trays in front of the participants. A sticker was hidden under the tray with the two boxes and was rewarded to the participants whenever they choose the tray with the larger quantity of boxes (i.e., two boxes). After training participants were tested on their ability to detect the bigger quantity from novel pairs including up to six items and succeeded. Brannon and Van de Walle (2001) suggested that children at the age of 2–3 years are able to represent ordinal relationships of quantities that include up to six items. The conclusions of this study are in accordance with Suanda et al.(2008) who suggested that ordinality, beyond quantity discrimination, is the understanding of the relationships between quantities in a sense of "bigger/smaller than" (and not just "different from"). These findings provide clear evidence that ordinal processing might be core ability available to human infants much like quantity processing.

4 Ordinal Processing and Dyscalculia

Little is known about ordinal processing and Developmental Dyscalculia (DD: a deficit in the ability to work with and understand numerical information). To the best of our knowledge, up to date, only two studies have dealt with the issue of ordinal processing in participants with DD. Interestingly; findings from these studies suggest that the core deficits in DD might involve ordinality and not just quantity and hence reinforce the view that ordinality much like quantity is a core ability.

Kaufmann et al. (2009), who explicitly defined ordinality as the position of a numeral in a numerical sequence, conducted a functional Magnetic Resonance Imaging (fMRI) study with children who suffer from DD and with typically developing (control) groups of children. Participants were asked to judge the ordinality of a three items sequence composed of either one-digit number or of shapes that varied in height. In two different tasks, participants had to decide if the three items increased in a linear fashion. Results showed no behavioral differences between groups in judging ordinal relations of both types of sequences (numbers or size/height). However, fMRI results revealed that in children with DD, but not in controls, there was an extension of the brain activity to inferior parietal regions (supramarginal gyrus and IPS).

Rubinsten and Sury (2011) studied the ordinal processing of adults who suffer from DD in compare to typically developing adults. Participants were asked to make an ordinal judging of three non- symbolic quantities that were presented simultaneously (i.e., three groups of dot; Experiments 1) or three symbolic quantities (i.e., three Arabic numbers; Experiment 2). Results showed that contrary to previous finding, DD participants exhibit a typical numerical ratio effect (i.e., faster reaction times for smaller ratios between quantities). However, DD demonstrated a deficit in ordinal judging. While the control group showed faster responses to ordinal sequences, the DD group did not demonstrate such an effect in both symbolic and non-symbolic materials.

These findings (Kaufmann et al. 2009; Rubinsten and Sury 2011) support the claim that the deficit in DD may represent ordinality and not just quantity. These findings may also support the view that ordinality and quantity are separate cognitive representations or systems. This system may be accounted for the numerical deficit in the ability of people with DD to process numbers.

Studies with brain damaged patient, support the idea of the existence of separate cognitive systems for ordinality and quantity processing. For example, Delazer and Butterworth (1997) introduced SE, an acalculic patient with impaired processing of cardinal meaning but a preserved ability to process the ordinal meaning of numbers. Specifically, SE, who suffered from a left frontal infarct, was unable to access the cardinal meaning of numbers (i.e., deficiencies in calculation tasks and an inverse distance effect in number comparison), yet was able to answer correctly “which number comes next?” questions. Turconi and Seron (2002) reported a reverse dissociation. They described a patient with right parietal lesion who was impaired in processing the order of words that denote ordinal information (i.e., numbers, letters, days and months) in various tasks, while showing better performance in processing quantity information. Together, these studies suggest that there are distinct brain and cognitive structures that are responsible for quantity and ordinal processing.

5 The Role of the IPS in Processing Ordinality

Developmental evidence suggest that ordinal judging is not exclusively an adult ability but rather a pre-verbal one, available to animals (Brannon and Terrace 1998; Rugani et al. 2007) and human infants (Suanda et al. 2008). This assumption is reinforced by evidence suggesting that ordinality has a biological base and, hence, might also act as a core system. For example, Jacob and Nieder (2008) suggested that “in terms of neural processing, quantity and rank might just be two sides of the same coin" (p. 8995), based on evidence that ordinality and quantity processing are based on similar neural systems, which are located in the intraparietal sulcus (IPS). This view is sported by varies findings suggesting that the IPS is involved with ordinality by using domain- general cognitive mechanisms, which support ordinal processing of different sequences (e.g. letters or sizes) rather than supporting a specific content, such as number or quantities. Hence, it seems that ordinality is not a specific feature of number processing but also of other sequences. Furthermore, ordinal representation and magnitude representation share a common neural substrate not only in the case of numerals but also for other non- numerical ordinal information. For example, Fias et al. (2007) found high similarity in neural networks located in the horizontal IPS (hIPS) that are activated during comparisons of both numbers and letters. Accordingly, they suggested that the role of the hIPS in number processing might represent ordinality and not just quantity.

Zorzi et al. (2010) reanalyzed the data from Fias et al.'s study (2007) using support vector machines (SVM) which is a fine- grained method of analyzing fMRI data. Results of this re-analysis suggest that ordinal judgments on non-numerical sequences and numerals are supported by different neuron populations within hIPS. Similarly, Fulbright et al. (2003) conducted an fMRI study in which participants were asked to judge whether three stimuli were in order according to their position, using letters, numbers and size (shapes varied in size) as stimuli. Fulbright et al. found an activation of the IPS for numbers, size and letters, supporting the claim that the role of the IPS in number processing might represent ordinality and not just quantity.

Ischebeck et al. (2008) preformed an fMRI study in which participants were asked to silently articulate a canonical or random generation of numbers and month (ordinal sequences) as well as generation of animals' names (non-ordinal material). Word generation of numbers and month activated the IPS more strongly than generations of animal's names. Furthermore, there was no difference between numbers and month in IPS activation. Additionally, Kaufmann et al. (2009) found that the IPS is involved in processing numerical and non-numerical ordinality not only in adults but also in children.

Such findings emphasize the role of intraparietal regions for ordinality and demonstrate the development of ordinality skills. Hence, it is possible that order and quantity processing share similar cerebral basic but with different neural populations.

The role of the IPS in processing ordinal sequences was challenged in a study conducted by Van Opstal et al. (2009) who suggested that ordinal and magnitude representation have different underlying neural and cognitive substrates. In this study, participants learned a sequence of arbitrary figures through exposure and comparison of sequential pairs from of the sequence. Participants were then tested on their ability to discriminate between non-sequential novel pairs (see Van Opstal et al. 2007 for an extended explanation about transitive inference). The learning phase was administered in seven separate sessions (in 7 consecutive days) and participants were scanned in fMRI during the 1st, 2nd, 4th and 7th sessions. Results showed that the hippocampal-angular gyrus activation is initially involved in learning the ordinal sequences but then, with extensive training, extends to the left inferior frontal gyrus (left IFG) but not to the IPS. Activity in the left IFG was also found in the processing of musical sequences (Maess et al. 2001) and the imagery of motion (Binkofski et al. 2000). Therefore, Van Opstal et al. (2009) suggested that the IFG might be involved in processing ordinal information.

Nonetheless, these findings do not necessarily contradict the role of the IPS in processing ordinal numerical information. In their study, Van Opstal et al. (2009), discuss the intensive learning of an arbitrary sequence, which is different from sequences of numbers. It is well established that children, adults, and nonhuman animals share a basic ability to perceive and compare non-symbolic quantities of items even without intensive learning (De Hevia and Spelke 2010; Brannon and Roitman 2003; Nieder 2005). Van Opstal et al. suggest that the location of representation might be determined by the nature of the stimuli rather than its ordinal nature. The IPS involvement with ordinality of numbers as well as letters (Fias et al. 2007) and months (Franklin et al. 2009) might exist because these sequences, like numbers, are extensively learned sequences. Hence, while the IFG might be involved in the learning and internalizing of newly introduces sequences, the IPS may still be involves in the processing of highly familiar materials that are stored in long-term memory.

As was suggested earlier, another possible explanation for the variance between the results of Van Opstal et al. (2009; IFG involvement with processing ordinal information) and other studies that found an IPS involvement in processing ordinal information (e.g. Kaufmann et al. 2009; Fias et al. 2007) is the use of different definitions for ordinality. Van Opstal et al. (2009) use transitive inference as a measure of ordinal processing while others such as Kaufmann et al. (2009) use tasks based on implicitly defining of ordinality as the position or the rank of an item in a sequence or, as the relationship between quantities (e.g. Fias et al. 2007). Measuring ordinality based on transitive inference as definition, requires the involvement of learning a novel sequence and therefore, the involvement of brain regions connected to sequence learning rather than ordinal processing. In contrast, referring to ordinality as the position, rank or the relationships between two items, leads to the use of more familiar stimuli (e.g. letters, height or days of the week).

To summarize, accumulating evidence from neuroimagine (e.g. Fias et al. 2007; Ischebeck et al. 2008; Kaufmann et al. 2009; Zorzi et al. 2010) and neuropsychological (Delazer and Butterworth 1997; Turconi and Seron 2002; Rubinsten and Sury 2011) studies suggest that ordinality has a biological base and support the possibility that the IPS is predisposed to process ordinal information.

6 Ordinality, Direction and Spatial Coding

Evidence show a strong developmental link between ordinal and spatial processes, which might suggest that the typical spatial components that are commonly found in quantity tasks may actually be the result of ordinal related processes. Specifically, mental representation of numbers is assumed to be spatially coded according to quantity, oriented left to right on a mental numbers line (Jacob and Nieder 2008). Important evidence to the number-space association comes from neuropsychological studies with neglect patient. For example, Zorzi et al. (2002) have shown that neglect patient misplace the midpoint of a numbers line (for example, stating that four is halfway between two and eight) as well as in bisecting physical lines. Zorzi et al. (2002) suggested that this resemblance demonstrates the spatial nature of the mental number line. Three scientific effects are considered as underpinning the mental number line. The first effect is the spatial numerical association of response codes (SNARC), where response to large numbers is faster when responding with the right hand side and vice versa for small numbers [e.g. responding to number nine with right hand is typically faster than responding to number one, regardless if the number is relevant to the task or not(Restle 1970; Dehaene et al. 1993). This effect seems to increase with age from childhood to elderly age (Wood et al. 2008)]. The second effect is the standard 'distance effect' (SDE). In numerical comparisons, responding is faster for bigger distances between two numbers in comparison to small numerical distances. The SDE has been documented in multiple studies (e.g., Moyer and Landauer 1967; Vigliocco et al. 2002; Ansari 2008; Dehaene et al. 1993). However, it was also found that the absolute size of the digits matters. Namely, for constant numerical distances, RT is faster when comparing smaller absolute values (e.g., 1 with 3) than when comparing larger absolute values (e.g., 7 with 9) (Buckley and Gillman 1974; Cohen Kadosh et al. 2005; Dehaene 1992; Verguts and Van Opstal 2005; Feigenson et al., 2004). This is the third effect – the size effect. The size effect fits in with the Weber law that states that the discrimination between two stimuli is modulated by the ratio of the intensities rather than their absolute difference. Accordingly, the discrimination between two numbers or quantities is modulated by their numerical ratio (i.e., the ratio effect; for review see Cantlon et al. 2009).

Recent studies have demonstrated that this spatial code indicated by the SNARC and the SDE exist not only in numbers but also in other non-numerical sequences and acutely imply the automatic activation of the spatial component in non-numerical sequences. For example, evidence show that the SNARC effect appears not only when stimuli are numbers but also when participants need to compare months and letters (Gevers et al. 2003). Moreover, the SDE appears also in letter comparison' task (Van Opstal et al. 2008).

In addition, while some studies have found an increase in the SDE with age and development (i.e. adults show bigger and steeper effect then children, e.g. Nuerk et al. 2004) other studies have shown that the SDE decrease with age and development [i.e. adults show smaller and less steeper effect then children; (Duncan and McFarland 1980; Sekuler and Mierkiewicz 1977)]. Holloway and Ansari (2008) found similar developmental patterns during comparisons of non-numerical items as well (brightness and height). Such findings suggest that the spatial components that are associated with the SDE and the SNARC exist in various ordinal sequences including numerals, brightness, letters and months (Gevers et al. 2003; Jacob and Nieder 2008). Indeed in a study involving numbers, month and letters, Gevers et al. (2003) found a response- side effect and a demonstration of spatial code even when ordinal information was irrelevant to the task (i.e. judging whether a specific month ends with the letter R or consonant–vowel classification of letters) . This finding implicates an automatic activation of the spatial components in ordinal sequences, similar to the automatic activation that was found with numerals (i.e. the SNARC effect). Gevers et al. (2003) suggested that the SNARC effect and the SDE which they found when ordinality was irrelevant to task (with the non-numerical ordinal sequences), implies a precise spatial coding of these sequences rather than a crude classification (e.g. the beginning of the sequence in the left and the end of the sequence in the right).

Van Opstal et al. (2008) investigated the SDE and the priming distance effect in numerical and non-numerical sequences. The priming distance effect refers to an effect found in a number-priming experiment in which participants are asked to judge whether a target number is smaller/larger than standard (the target number appears after a prime number). Participants normally respond faster when prime and target number distance is smaller (Dehaene et al. 1998). This effect is explained through the representational overlap of close numerosities; the prime triggers the overlapping or close representation of the target number (Turconi et al. 2006). Van Opstal et al. (2008) found SDE and congruency priming effect (faster response when both the target and prime number are smaller/larger than standard) in numbers and letters, supporting the claim concerning the automatic activation of the spatial components in ordinal sequences.

De Hevia and Spelke (2010) found that even 8-month-old infants form and use relationships between numbers and space. Infants transfer the discrimination of an ordered series of quantities to the discrimination of an ordered series of line lengths. Moreover, infants construct relationships between individual quantities and line lengths when longer lines accompanied greater numbers of dots, but not between numbers and lengths when shorter lines accompanying greater numbers of dots. De Hevia and Spelke's (2010) findings suggest that the human brain is involved with processing quantity and space from infancy during pre-verbal stages of development.

Altogether, these studies may provide evidence for the relationship between ordinality and space. Specifically, the appearance of the spatial component in ordinal sequences such as letters and month (Gevers et al. 2003; Van Opstal et al. 2008); the ability of infants to transfer the discrimination of an ordered series of quantities to the discrimination of an ordered series of line lengths (De Hevia and Spelke 2010) and the sensitivity of 9 month old infants to ordinal relationships when presented with multiple additional spatial cues (Suanda et al. 2008) indicate that there is a strong developmental link between ordinality and spatial processes. If indeed this is the case, a very controversial yet plausible argument would be that the spatial components typically found in quantity tasks (e.g. the SDE and the SNARC effect) may be a mere expression of ordinal related processes rather than pure quantity representations. Future studies will have to test ordinal, spatial and quantity processing separately.

Another relevant issue in the field of ordinality and space is the direction of stimuli in a sequence (e.g., left to right or right to left). In the Franklin et al.'s study (2009), presenting numbers in a descending (from right to left) direction elicited slower response time then the ascending direction (from left to right). Indeed, several studies have pointed out direction as a factor that affects comparisons (Turconi et al. 2006; Paulsen et al. 2010; Conson et al. 2008; Paulsen and Neville 2008). It could be that direction actually embodies a sort of combination between space and order. That is, the second/larger item should appear right to the first smaller item and so on. Therefore, the effect of direction on the processing of numbers should be taken into account when dealing with ordinal processing. For example, Turconi et al. (2006) found that presenting numbers in an ascending (from left to right) order (e.g. 4, 9) reduced the standard distance effect. The authors argued that the reduction in the SDE for ascending pairs might reflect an order related process that is involved in number comparison.

Additionally, Paulsen et al. (2010) conducted an event related potential (ERP) study with a non-symbolic numerical comparison task (different quantity of dots presented one after the other). They found a direction effect between 320 and 440 ms (greater negativity for decreasing direction) compatible with the behavioral results of the task (faster response to numbers presented in the ascending left to right direction). ERP direction effects did not interact with numerical distance, suggesting that the two types of information (distance and direction) are processed independently.

The effect of direction was found not only in adults but also in children. Conson et al. (2008) found that 4 year-old children expected numbers to be ordered from left to right when they count, search for objects in numbered containers and even when they add and subtract.

In Rubinsten and Sury study, When density and surface area of the stimuli were randomized in an ordinal Judging task of non-symbolic sequences (i.e., three groups of dots presented simultaneously), DD participant were able to compare and contrast three quantities based on their ordinal relationships but only with the use of linguistic (or culturally acquired) cues (Rubinsten and Sury 2011). The linguistic (or culturally acquired) cues in that case was the direction of the sequence (i.e., left to right, 2, 4, 7 or right to left 7, 4, 2). Only when sequences were presented in the descending direction (i.e. right to left), DD participants were able to distinguish between ordinal and non-ordinal sequences and demonstrated the same ordinality effect as the control group. To note, participant in Rubinsten and Sury study were Hebrew speakers, the salience of the descending direction fits with the Hebrew writing system, in which words and sentences are written from right to left.

These findings leads Rubinsten and Sury to suggest a three-component model, with quantity, ordinality and language as separate systems (see Fig. 1). The model describes quantity as two cogwheels (representing in this case quantity and ordinality processes) that in some cases need the third wheel (e.g., representing in this case linguistic abilities such as the direction of the writing system) to combine them in order to operate together. Consequently, if ordinality system does not work efficiently (as in the case of DD) cogwheels will not move and the whole system (as represented by the three cogwheels together) does not work (as represented by the sitting person; see Fig. 1b). However when DD participant use language (in this case the direction of the sequence; left to right or right to left) in order

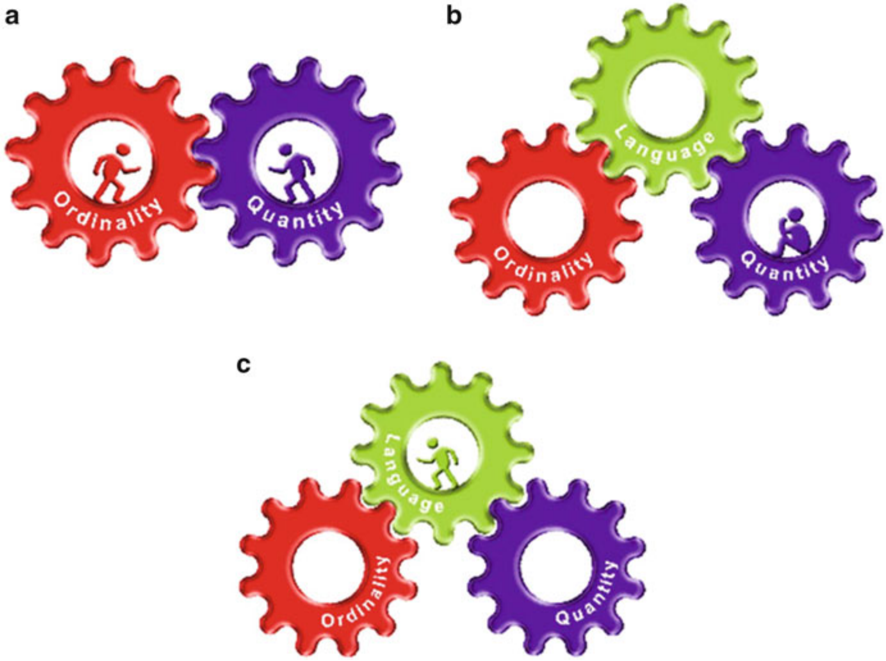

Fig. 1 Three-component model of ordinality as presented in Rubinsten and Sury's (2011) study

to initiate the "movement" of the cogwheel system and actually solve the ordinality task at hand, the intact "language cogwheel" will move the deficient "ordinality cogwheel" and the whole system will work efficiently (see Fig. 1c). Rubinsten and Sury's findings and the cogwheel model bring further support to the hypothesis that the effect of direction in numerical comparisons may reflect an order related process that may be one of the processes underpinning the SDE and the SNARC effect.

7 Ordinal and Quantity Processing: Are They "Two Sides of the Same Coin"?

In contrast with evidence of a strong similarity between processing of ordinality and quantities, there is evidence that ordinality and quantity are processed through different strategies and possibly even different mechanisms. As an example, several studies of ordinal judging describe an interesting phenomena referred to as the reverse distance effect (RDE); as opposed to the SDE, in RDE the smaller the distance between numbers the faster the response (Turconi et al. 2006; Franklin and Jonides 2008; Franklin et al. 2009). However, it should be noted that this effect is not as consistent as the SDE and in different studies, it appears in varying ways.

Turconi et al. (2006), for example, compared the results from a number comparison task (4, 9; which is bigger) to an ordinal judging task (4, 9; ascending or descending order?) and found a RDE in the ordinal task only when presenting participants with sequential number pairs but not when presented with non-sequential pairs. Turconi et al. suggested that the reverse SDE might reflect specific ordinal related processing such as serial search or direct recognition of ordinality in sequential numbers. Franklin and Jonides (2008; Franklin et al. 2009) also found a RDE in an ordinal judging task. In Franklin et al. study (2009) participants were presented with three double-digit numbers and were required to indicate whether the sequence was in the correct order (see Experiments 1 and 2). In the third experiment, participants were asked to indicate whether the three numbers were ordered in a forward, backward or mixed direction. Franklin et al. also manipulated the distances between the items within the sequence items, resulting in some sequences in which the numbers crossed a decade (e.g. in the sequence 28, 29, 31 there is a cross of a decade from the twentieth to the thirtieth decade). Findings show that only when numbers crossed a decade there was a RDE. Similar results were found when participants were presented with names of months. That is, a RDE appeared when there was a cross of boundaries in the sequence [e.g. in the three items sequence; October, December, February there is a cross of boundaries as a result of "jumping" from the end of the sequence (December) to its beginning (February)].

In an fMRI study, Franklin and Jonides (2008) found that the RDE is consistent with brain activity in the IPS and different from the activity seen during the numerical comparison task. Additionally, they found activation in the cerebellar vermis during the ordinal task. Franklin et al. argued that this activity implicates the involvement of the vermis in the processing of ordinal information since several studies have connected the cerebellum to sequential operations. For example, lesions to the cerebellar vermis are associated with reading errors largely due to the transposition of letters (Moretti et al. 2002)

These differences in brain activity between ordinal judging and numerical comparisons tasks are supported by Turconi et al. (2004) ERP study. They found that despite a similar behavioral effect, ordinality and quantity were associated with different spatio-temporal courses in parietal and prefrontal cortices. Specifically, in an ERP study, participants preformed numerical comparison task (judging whether a number is larger or smaller then a target number) and an ordinal task on the same stimuli (judging whether a number comes before or after the target number). Despite similar behavioral results indicating a SDE in both tasks, electrophysiological evidence reveals significant differences. The SDE related activity appeared earlier and with greater intensity in the left hemisphere for quantity processing, while in ordinal processing the activity was delayed and bilateral. SDE related activity was also observed in parietal areas where the activity was more intense on prefrontal areas for the ordinal judgment. These findings support previous studies with brain-damaged patients (Delazer and Butterworth 1997) and suggest, in contrast to other arguments, that ordinal and quantity processing dissociate at both the behavioral and biological levels.

To summarize, it seems that ordinality relies on a partially different mechanism than quantity processing. Even though they both stimulate activation of the IPS, these activation patterns are somewhat different (e.g. Turconi et al. 2004). Furthermore ordinal tasks stimulate areas different from those stimulated by quantity tasks and sometimes even show different behavioral results (e.g. Franklin and Jonides 2008, 2009; Turconi et al. 2006; Kaufmann et al. 2009) suggesting that quantity and ordinality may not necessarily be different sides of the **same** coin.

8 Conclusions

In this chapter, we reviewed scientific work that deals with processing of numerical and non-numerical ordinal information. We started with defining the term ordinal knowledge and continued with describing developmental pattern and related brain activities. Finally, we reviewed studies that dealt with the relationships between ordinality and apace and their implication on the well-known phenomena such as the SNARC and the SDE.

This chapter assembled empirical evidence that, quite directly leads to the suggestion that ordinality and not only quantity is a core cognitive and biological system, which stands as an important foundation of numerical cognition.

The data which we presented here together with a recent study of ours (Rubinsten and Sury 2011) has led us to construct a theoretical model describing the different and separate cognitive representations which are required to fully process numerical information (see Fig. 2). We wish to emphasize that this is a purely theoretical model but we believe that it can contribute an important framework for the new scientific field of ordinal processing. The model describes representations which are involved (circled at the top of the figure) in processing ordinal numerical information and the developmental and cognitive aspects (horizontally presented below the circles) of it. As can be seen in the figure, three separate cognitive representations are involved with processing numerical information. The first representation includes ordinal estimation. Specifically, estimation of numbers relates to the strategy employed when a stimulus configuration is comprised of a large number of items and is presented briefly (Pavese and Umiltà 1998). It is an intuition available to humans regardless of language and education and, hence, estimation is considered to be **part of the core numerical system** (Dehaene 2009) that is available to preverbal infants and to non-humans animals (Cantlon et al. 2009). However, can we estimate order as well? Is it an additional core cognitive system? Our review chapter and previous work (Rubinsten and Sury 2011) suggest that it is. We show here that processing ordinal information is an ability which appears early in human development. For example, Suanda et al. (2008) showed that 9 month old infants are able to estimate ordinality and Lewkowicz and Berent (2009) study suggests that even 4 month old infants are able to encode the relationships between the sequence elements. Furthermore, the ability to process ordinality was found even in animals. For example, Rugani

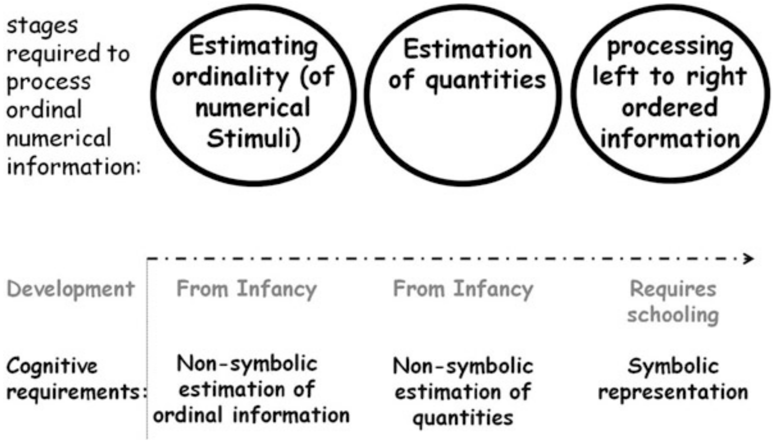

Fig. 2 A suggested theoretical model for the stages required to process ordinal numerical information

and colleagues have shown that young chicks use ordinality and not distance when required to identify a target by its numerical serial position. Accordingly, the ability to estimate ordinality seems to appear side by side with the ability to estimate quantity and it is probably an additional and possibly a separate core ability that appears early in development (Cantlon et al. 2009). The third representation embodies the effect of culture and schooling, in which ordinal information is represented from left to right or top to bottom. As mentioned earlier, this stage is subjected to schooling and therefore will appear later in development and will require acquisition of symbolic representation.

In conclusion, further research is necessary in order to develop a deeper understanding of the relationships between ordinality, quantity and space. In addition, a developmental point of view can help in understanding the role of ordinality in DD. However, we believe that dealing with ordinality as core ability may lead to more accurate scientific and clinical directions.

Appendix 1: Overview of All Ordinality Studies Which Presented in This Chapter

Authors	Title	Type of study	Participants	Stimuli	General task description
Brannon and Van de Walle (2001)	The development of ordinal numerical competence in young children.	Behavioral	2–3 years-old children	Quantity (Stimuli consisted of two trays, each containing a different number of boxes. In Experiment 1, box size was constant. In Experiment 2, box size varied so that cumulative surface area did not correspond with the quantity of boxes.)	Children were trained to compare 1 vs. 2 boxes and then tested on novel numerosities.
Brannon and Terrace (1998)	Ordering of the numerosities 1–9 by monkeys.	Behavioral	2 rhesus monkeys	Quantity (stimuli size, shape, and color were varied).	Monkeys were trained to respond to quantities 1–4 in an ascending order (e.g. 1 vs. 3, 2 vs. 3 and 3 vs. 4) and then tested on their ability to order pairs composed of the novel quantities 5–9.
Conson et al. (2008)	A common processing system for duration, order and spatial information: Evidence from a time estimation task	Behavioral	Typically developing adults	Tones changed in duration , duration ranged from 1,000 to 3,000 ms	Judging whether the first or second tone presented was shorter.
Delazer and Butterworth (1997)	A dissociation of number meanings.	Neuropsychological	An adult patient who suffered from a left frontal infarct	Numbers	Number comparison, calculation, and number processing were assessed.

(continued)

(continued)

Authors	Title	Type of study	Participants	Stimuli	General task description
Gevers et al. (2003)	The mental representation of ordinal sequences is spatially organized.	Behavioral	Typically developing adults	Month and letters.	Two tasks: (1) order relevant task: judging the position of the months/letter as coming before or after July/the letter O. (2) order irrelevant task: judging whether the presented month ended with the letter ‘R’ or a (consonant–vowel classification of letters).
Fias et al. (2007)	Processing of abstract ordinal knowledge in the horizontal segment of the intraparietal sulcus.	Neuroimagine	Typically developing adults	Numbers, letters and saturation levels.	Two tasks: (1) comparison task and (2) detection of the dimmed stimuli task.
Franklin and Jonides (2008)	Order and magnitude share a common representation in parietal cortex.	Neuroimagine	Typically developing adults	Double digit numbers.	Two tasks: (1) a comparison task (comparison of a target to a fixed number) and (2) ordinal judging of a three double-digit numbers.
Franklin et al. (2009)	Processing of order information for numbers and months	Behavioral	Typically developing adults	Double digits numbers and months of the year. *Manipulation on Distance and cross of decade.	Judging whether the three Numbers/month are in the correct order (i.e., in the forward direction) or not.
Fulbright et al. (2003)	Quantity determination and the distance effect with letters, numbers, and shapes: a functional MR imaging study of number processing.	Neuroimagine	Typically developing adults	Numbers, letters and shaped that varied in size.	Judging whether three stimuli were in order according to their position.

Ischebeck et al. (2008)	Are numbers special? Comparing the generation of verbal materials from ordered categories (months) to numbers and other categories (animals) in an fMRI study	Neuroimagine	Typically developing adults	Months, numbers and animals.	Word generation of numbers, months (non- numerical ordinal material) and animals (non-ordinal category).
Kaufmann et al. (2009)	Numerical and non-numerical ordinality processing in children with and without developmental dyscalculia: Evidence from fMRI.	Neuroimagine	Children with and without DD.	Numbers and figures varied in height.	Ordinal judging of a three item sequence of numbers or figures height (i.e. judging whether a sequence presented increases in a linear fashion).
Lewkowicz and Berent (2009)	Sequence learning in 4-month-old infants: do infants represent ordinal information?	Behavioral	4-month-old infants	Arbitrary sequence of moving and sounding elements.	Infants were habituated to four elements sequences, three of the elements varied in their position while the position of 1 target element remained constant (e.g., A**B**CD, C**B**DA) and then were tested for the detection of changes in the target's position.
Rubinsten and Sury (2011)	Processing ordinality and quantity: the case of developmental dyscalculia	Behavioral	Adults with and without DD.	Symbolic (numbers) and non-symbolic (groups of dotes) quantities (in the non symbolic task, stimuli were presented in three conditions: fixes area, fixed density and randomized).	Ordinal judging of a three item sequence of numbers or quantities (i.e. judging whether a sequence presented in an ordinal fusion or not).

(continued)

(continued)

Authors	Title	Type of study	Participants	Stimuli	General task description
Rugani et al. (2007)	Rudimental numerical competence in 5-day-old domestic chicks (Gallus gallus): identification of ordinal position.	Behavioral	5 day old domestic chicks	Holes with chick crumbs.	Chicks were trained and tested on their ability to peck a specific position in a series of 10 identical ones.
Suanda et al. (2008)	Changes in the ability to detect ordinal numerical relationships between 9 and 11 months of age.	Behavioral	9 and 11 month old infants	Different quantities of rainbow squares in random configurations appearing one after the other.	Infants were habituated to ascending or descending sequences of three quantities and then tested with both ascending and descending sequences containing novel numerical values. * the differences in experiment 1–5 are in time of stimuli presentation and the low visual features of the stimuli.
Turconi and Seron (2002)	Dissociation between order and quantity meaning in a patient with Gerstmann syndrome	Neuropsychological	An adult patient with Gerstmann syndrome	Symbolic and non- symbolic numbers.	Numerical comparison, Positioning a number on an analogue scale and arranging non-adjacent numerals in increasing order.
Turconi et al. (2006)	Numerical order and quantity processing in number comparison.	Neuroimagine	Typically developing adults	Numbers	Two tasks: (1) comparison task and (2) an order judgment task (e.g. 2 5; ascending or descending order?).

Van Opstal et al. (2007)	Hippocampal-parietal network for learning an ordered sequence.	Neuroimagine	Typically developing adults	A sequence of arbitrary figures	A transitive inference task: participants learned a sequence of arbitrary figures through exposure to sequential pairs of the sequence and were then tested on their ability to discriminate between non-sequential novel pairs.
Van Opstal et al. (2008)	Dissecting the symbolic distance effect: Comparison and priming effects in numerical and non-numerical orders.	Behavioral	Typically developing adults	Numbers and letters	A priming task: the task was to compare a target letter or number to a fixed standard.
Van Opstal et al. (2009)	The neural representation of extensively trained ordered sequences.	Neuroimagine	Typically developing adults	Sequences of arbitrary figures	Participants learned a sequence of arbitrary figures through exposure to sequential pairs of the sequence and were then tested on their ability to discriminate between non-sequential novel pairs. The learning occurred for seven sessions in 7 consecutive days.
Zorzi et al. (2010)	Distinct representations of numerical and non-numerical order in the human intraparietal sulcus revealed by multivariate pattern recognition.	Neuroimagine	Typically developing adults	Numbers, letters and saturation levels.	Two tasks: (1) comparison task and (2) detection of the dimmed stimuli task.

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Diagnostics and Intervention in Developmental Dyscalculia: Current Issues and Novel Perspectives

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1 Introduction

When trying to explain developmental dyscalculia, a probable and reasonable way may be to specify it as a developmental learning disorder comparable to developmental dyslexia. The major difference is that dyscalculia does not manifest itself in an impaired processing of written words or text, but of numbers and arithmetic. While noticeably profiting from the fact that most people already know – or at least believe to know – what developmental dyslexia stands for, it is still discouraging to find that knowledge about developmental dyscalculia is much less established. Interestingly, this does not hold for public advertence by parents, teacher, and educational authorities only, but also for research interest dedicated to the issue. A convenient example for the severity of the difference in these two learning disorders' popularity is to compare the hits the two produce in online search engines. We entered the search terms *dyslexia* and *dyscalculia* into the search engine *Web of Knowledge*, on November 3rd, 2010. Our searches yielded a total of 10,880 hits for *dyslexia*, but only 599 hits for *dyscalculia* (see Fig. 1 for a comparison of the increase in publications on the two topics over the last 20 years).

These results impressively demonstrate how little dyscalculia has thus far been researched in comparison to its famous counterpart dyslexia. Ever since the first attempts at defining its symptoms (U.S. Office of Education 1977), dyslexia has

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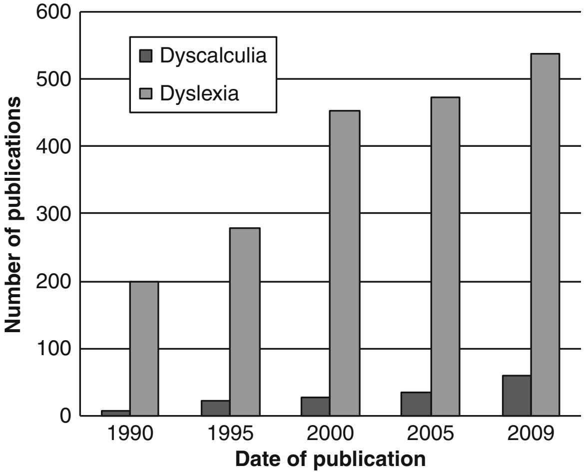

Fig. 1 Overview of the number of publications in the last 20 years as found on the ISI Web of Knowledge for entering the topics ‘Dyscalculia’ and ‘Dyslexia’. Please note that for reasons of readability a 5-year interval has been chosen which perfectly reflects the overall trend

been profusely researched, diagnostic instruments and intervention programmes have been developed, and children with dyslexia are conceded extraordinary assessment regulations in schools in many countries. These regulations may consist of being granted more time for the completion of written tests, the possibility to take exams orally instead of in written form, or the grading of written tests without consideration of spelling errors (even in language classes). So far, no such systematic international regulations have been implemented for children with dyscalculia whose impairments in several areas of academic achievement may be just as severe as those of children with dyslexia. In fact, poor numeracy was found to be even more detrimental to an individual’s job opportunities and promotion than poor literacy (Bynner and Parsons 1997; Parsons and Bynner 2005) and a major cost for nations (Gross 2009).

Quite a few possible reasons have been proposed as to why dyscalculia was discovered and accepted as a learning disability much later than dyslexia. One reason might be that the investigation of its neural substrates took longer and was more complex. Another possible explanation may be that the large number of different processes involved in mastery of mathematics complicated a diagnostic definition and a consensus about the aetiology of dyscalculia. There is also the possibility that measures of intelligence had a part in the later discovery, since many of them contain subtests that require arithmetic knowledge and might thereby have lead to a judgment of dyscalculic children as altogether less intelligent. Such a misinterpretation seems comprehensible when taking into account that Thurstone (1938) considered number facility to be one of his seven primary mental abilities. And even today, most of the broadly used intelligence tests incorporate subtests assessing numerical capabilities [e.g., WAIS-IV (Wechsler 2008) and IST 2000-R (Amthauer et al. 2001) for adults and K-ABC (Kaufman and Kaufman 1983) and WISC-IV (Wechsler 2003) for children].

So, we need to discuss why dyscalculia has been studied less. What is certain, however, is that due to this delay, the investigation and treatment development of dyscalculia is still in its infancy. Encouragingly, due to the growing attention mathematical learning disabilities receive in research as well as clinical settings our knowledge is accumulating. While the term *dyscalculia* is still a foreign word to many, it is beside other reasons the high prevalence that has lead to severe growth in its publicity over recent years. It seems as though finally, the failure of certain children to reach age-adequate proficiency in mathematics is no longer being attributed to a lack in motivation or intelligence, but is recognized as a distinct learning disability that needs to be diagnosed and treated accordingly.

Fortunately, developmental dyscalculia attracts more and more attention of researchers, but also parents, teachers, and educational authorities. Against this background, the present chapter discusses four basic but nevertheless very important aspects regarding this developmental disorder: First, we will describe and evaluate the ongoing debate about the origins and causes of developmental dyscalculia. After having illustrated current theoretical accounts, we will then in a second section elaborate on whether and if so, how the diagnostics of dyscalculia should consider different conceptualizations regarding its underlying deficits. Third, the case of comorbidity between developmental dyscalculia and other developmental disorders such as dyslexia will be addressed. In particular, we will recapitulate the issue of estimating comorbidity rates from empirical data and thus helping to evaluate whether observed comorbidity rates are disproportionally higher than expected by chance. Finally, we will briefly review recent remediation programmes for dyscalculia and suggest criteria that such programmes should fulfill to be effective.

2 Theoretical Underpinnings of Developmental Dyscalculia

2.1 The Core Deficit Hypothesis

Generally, neuroscientific research investigating developmental dyscalculia is still in its infancy and our current understanding of developmental dyscalculia – and thus our diagnostic and treatment methods (see below) – is very limited. Nevertheless, neurocognitive research suggests developmental dyscalculia to be a brain-based disorder. The syndrome-defining cognitive impairment (i.e., deficient numerical capabilities) is supposedly linked to neural abnormality of brain regions in and around the intraparietal sulcus (IPS; Butterworth 2005). Furthermore, there is accumulating evidence for IPS anomalies being associated with numerical deficits on both the structural (i.e., Isaacs et al. 2001; Molko et al. 2003; Rotzer et al. 2008; Rykhlevskaia et al. 2009) and the functional level (i.e., neural activation pattern; developmental dyscalculia in children: Kaufmann et al. 2009b; Kucian et al. 2008; Mussolin et al. 2010a; Price et al. 2007; dyscalculia in adults: Cohen Kadosh et al. 2007). The IPS is generally agreed to be a key structure when it comes to the processing of numerical and in particular number magnitude information (e.g., Pinel et al. 1999; see Dehaene et al. 2003 and Hubbard et al. 2005 for reviews). Thus, recent neuro-imaging data corroborates the notion of developmental dyscalculia being caused by deficient processing of very basic numerical concepts such as quantity, magnitude, numerosity, etc. associated with the IPS. This explanatory approach is usually referred to as the *core deficit hypothesis* of developmental dyscalculia (e.g., Gersten and Chard 1999; Robinson et al. 2002). Therein, it is proposed that all numerical deficits observed in developmental dyscalculia are caused by this central deficit in the processing of number magnitude information, also termed a deficient *number module* (Butterworth 1999, 2005; Landerl et al. 2004) or a deficient *number sense* (Dehaene 1997; Wilson et al. 2006a).

However, the existent developmental literature on developmental dyscalculia is inconclusive and inconsistent as regards evidence corroborating the core deficit hypothesis. In line with the hypothesis of a deficient number sense, Mussolin et al. (2010b; see also Landerl and Kölle 2009) observed children with dyscalculia to be impaired in the processing of symbolic but also non-symbolic quantities. However, there is also evidence suggesting that the deficiencies of children with dyscalculia are specific to the format of numerical input. For example, Rousselle and Noël (2007) found deficits in the processing of symbolic but not non-symbolic stimuli in dyscalculic children. Furthermore, also results within symbolic/nonsymbolic deficits are inconsistent. For non-symbolic number processing (i.e., comparing the numerosity of dot patterns), both group differences between children with and without developmental dyscalculia (Price et al. 2007) but also the absence of group differences (Kucian et al. 2006) were reported. Likewise, for the case of symbolic number processing (i.e., processing of Arabic digits), group differences emerged on number comparison (Mussolin et al. 2010b) and approximate – but not on exact – arithmetic (Kucian et al. 2006). Notably, all of the latter studies were targeted at identifying the neural correlates of deficient quantity/numerosity processing, which to date seems to be the most thoroughly validated core deficit of developmental dyscalculia (Wilson and Dehaene 2007).

2.2 Subtypes of Dyscalculia Due to Domain General Processes

Nonetheless, as already implied above, the core deficit approach may not be sufficient to account for the complex and often heterogeneous clinical picture of developmental dyscalculia (Kaufmann and Nuerk 2005; Rubinsten and Henik 2009). A first conceptualization of subtypes was proposed by Rourke and colleagues (see Rourke and Conway 1997 for a review). Due to differential performance of children with mathematical disabilities on visuo-spatial and verbal tests (e.g., Rourke and Finlayson 1978), they suggested a visuo-spatial and a verbal subtype associated with either right- or left-hemispheric impairments, respectively. Since then, other subtypes have been proposed. For instance, Geary (1993, 2004) posits three subtypes associated with (i) deficits in verbal working memory assumed to be essential to acquire arithmetic procedures, (ii) deficits in long-term memory as required in building up and retrieving arithmetical facts, and (iii) deficits in processing visuo-spatial information. Another attempt at subtyping dyscalculia was made by Temple (1991), who presented a double dissociation of impaired arithmetic fact knowledge (i.e., deficient multiplication) and impaired arithmetic procedures (i.e., procedural calculation as in subtraction and division). From this, Temple concluded that arithmetic facts and arithmetical procedures develop semi-independently, meaning that neither one seems to be a precursor of the other; a notion hard to reconcile with the hypothesis of a core deficit. In line with this, most of the above described studies suggesting possible subtypes of developmental dyscalculia build upon impaired processes which are not in themselves numerical. Rather, they propose domain general processes of cognitive functioning such as working memory or attention.

2.3 Subtypes Due to Domain-Specific Numerical Deficits

When reasoning about subtypes of developmental dyscalculia, one might also be interested in whether there are subtypes defined by specific deficits in particular numerical competencies such as arithmetic fact knowledge (which has initially been proposed by Temple 1991). A first step towards such a conceptualization was suggested by Wilson and Dehaene (2007) based on the differentiation of numerical representations postulated by the Triple Code model of number processing (Dehaene and Cohen 1995, 1997; Dehaene et al. 2003; Dehaene 2009). The Triple Code model discriminates between three different numerical representations: (i) an analogue numerical quantity representation reflecting the semantic magnitude information, (ii) a visuo-spatial numerical representation associated with mental number line representations attentional shifting along this number line, and (iii) an auditory-verbally representation of arithmetic fact knowledge such as multiplication tables. Inspired by this differentiation, the authors proposed three theoretical subtypes of developmental dyscalculia, and even derived neuro-anatomical predictions from the Triple Code model. A first subtype could be a kind of number sense (core deficit) dyscalculia linked to dysfunctions of brain areas around the IPS (Kaufmann et al. 2011; Kucian et al. 2008; Mussolin et al. 2010a; Price et al. 2007) that subserve magnitude processing. As a second potential developmental dyscalculia subtype, they proposed a spatial attention subtype (characterized by difficulties to solve number tasks requiring spatial skills such as locating numbers on a number line), possibly supported by the posterior superior parietal lobule (PSPL). Finally, the verbal subtype (characterized by deficient number fact retrieval, among others) may be linked to anomalous functioning of angular gyrus (AG) and perisylvian areas. Importantly, this conceptualization of developmental dyscalculia (Wilson and Dehaene 2007) represents a hypothetical model and so far lacks empirical confirmation. Nevertheless, it fuels the debate about possible subtypes of developmental dyscalculia no longer motivated primarily by impairments in rather general cognitive processes such as left-/right-hemispheric processing (cf. Rourke 1993) or (working) memory (cf. Geary 1993, 2004). Such different views were recently formalized by Rubinsten and Henik (2009) in different frameworks suggesting abnormalities in different but specific brain areas to underlie specific associated numerical processing deficits.

Moreover, Rubinsten and Henik (2009) even took one step further and proposed possible frameworks conceptualizing comorbidities of developmental dyscalculia with either ADHD or dyslexia. However, in line with above argument on dyscalculia subtypes we would suggest these subtypes to be associated with impairments of specific basic numerical representations and processes instead of rather general processing characteristics.

In sum, there have been a number of different suggestions which subtypes may be dissociated. While there is certain agreement in the literature on certain subtypes that may be particularly important (e.g., verbal subtype, spatial-attentional subtype), there is still little agreement on *how many* and *which* subtypes should be considered. This is probably due to a lack of large-scale multivariate studies (Q-factor analyses, cluster analyses etc.) dissociating different subtypes of dyscalculia. Thus, while there is a large number of single-case descriptions (e.g., Temple 1991) from which hypotheses for subtyping can be generated, there are no large-scale multivariate data on whether all dyscalculics can be sufficiently categorized by any subtyping system.

However, for any personality trait a person-oriented and a variable-oriented approach can be dissociated (Eye and Bogat 2006; Stern 1911). While the person-oriented approach describes different persons according to their individual profiles (in our case dyscalculia subtypes), the variable-oriented approach describes different persons according to their performance on variables of interest (in our case different number representations). In dyscalculia, one or more of these representations may be impaired leading to numerical and/or arithmetic deficits. In the following, this variable-oriented view will be further specified with respect to numerical processing by suggesting a differentiation between six basic numerical representations and associated deficiencies in dyscalculia.

2.4 Numerical Representations and Consequences of Their Specific Impairments

Over decades of research on numerical cognition, a multitude of representational components has been suggested. The basic numerical components posited and described in the next paragraphs follow the classification of Nuerk et al. (2006; see also Claros-Salinas et al. 2009; Moeller et al. 2009a). Basically, the Nuerk et al. (2006) classification extends and specifies the representations postulated by the Triple Code model (Dehaene and Cohen 1995, 1997; Dehaene et al. 2003). In addition to the visual Arabic, the auditory verbal, and the analogue magnitude code proposed by the Triple Code model, Nuerk et al. (2006, see also Moeller et al. 2009a) suggest three more basic representations: a spatial representation of number magnitude, a representation of the place-value structure of the Arabic number system and finally, a representation of procedural, strategic and conceptual numerical knowledge. These six basic numerical representations will be described in greater detail in the following.[1]

2.4.1 Visual Number Form

Comparable to the case of reading and writing, the most basic precondition for any understanding and correct application of a symbolic number system is the successful recognition, representation, and mastery of the number symbols. In our Arabic number system, these basic number symbols are the ten digits (i.e., 1, 2, 3, 4, 5, 6, 7, 8, 9, and 0). As any multi-digit number can be composed of these ten digits, their understanding is a vital corner stone of any development of mathematical/arithmetic capabilities. For instance, the digit 5 needs to be recognized as a digit (as opposed to a letter) and be discriminated from other digits such as 6. Difficulties at this most basic level should be indicated amongst others by problems in number naming and/or writing (also referred to as *transcoding*). At the same time, understanding of non-symbolic quantities such as dot patterns should be preserved. It follows that a pure form of visual number form dyscalculia should result in clear-cut symptoms in the processing of symbolic numerical information that do not generalize to non-symbolic quantity processing such as reading symbolic number aloud. Temple (1989) termed a respective disorder as digit dyslexia (see also Cohen and Dehaene 2000; Dehaene and Cohen 1995, for patient data). In most diagnostic tests of numerical abilities, the correct understanding of the visual number form is not assessed explicitly. This is because this component is preserved in most children suffering from dyscalculia. Nevertheless, for any kind of remediation programme it is essential to evaluate whether the observed numerical impairments originate from this very basic representation of visual number forms. Training of more advanced numerical capabilities can only be successful when a child is able to recognize and discriminate between the used symbols.

2.4.2 Semantic Representation of Numerical Magnitude

There is accumulating evidence suggesting that both children and adults automatically activate at least an approximate quantity representation (e.g., Dehaene et al. 1993; Rubinsten and Henik 2005; Gebuis et al. 2009, for children data) when

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[1] It is important to note that this differentiation into six basic representations is open to the discussion whether these representations are domain-general, domain-specific, or an interaction of both. For instance, the verbal representation of numbers (e.g., arithmetic facts) may be impaired as a consequence of a deficit in a specific numerical domain or as a domain-general deficit (impaired verbal retrieval of any semantic facts). While this issue is important, it is not the main focus of the present section, in which we want to argue that numerical competence relies on certain underlying basic representations, but do not wish to make assumptions about where an eventual deficits stems from.

confronted with either symbolic (e.g., Arabic digits) or non-symbolic (e.g., dot patterns) magnitudes. Thereby, numerical magnitude information becomes instantaneously available and may allow for a primary estimation/evaluation of possible results in any kind of numerical tasks (e.g., $2 + 4 = 9$). This is possible even before explicit magnitude manipulations are conducted to calculate the actual result. As this magnitude representation reflects the primary semantic information conveyed by numbers and/or numerosities, its impairment results in severe deficits on all numerical tasks involving the processing of magnitude information in any form. These tasks include magnitude comparisons, but also number bisection tasks or arithmetical operations like subtraction. Additionally, because magnitude information is the semantic key property of any number, an impairment of this magnitude representation represents a deficit right at the heart of any numerical understanding. In accordance with above considerations on a core deficit underlying developmental dyscalculia, an impairment of this basic numerical representation may be the best candidate to cause such a core deficit of the number sense (cf. Wilson & Dehaene 2007). However, within the present conceptualization, an impaired magnitude representation may be a sufficient cause for developmental dyscalculia, but not a necessary one. Nevertheless, there is ample empirical evidence that children diagnosed with developmental dyscalculia often exhibit an impairment of their number magnitude representation (Ashkenazi et al. 2008; Holloway and Ansari 2009; Rousselle and Noël 2007; Kaufmann and Nuerk 2008; Moeller et al. 2009b).

2.4.3 Verbal Numerical Representations

Subsumed under the term of verbal numerical representations there are at least two important but at a first view very different numerical concepts. On the one hand, auditory-verbal representations of number words such as “seven” but also more complex ones like “one hundred eighty four” are denoted by this term. Often the acquisition of counting sequences and thus the first number words represents an initial step in the development of numerical cognition. However, in this context it should be noted that the composition of number words is not consistent across languages but shows great inter-language variability. Apart from specific number words (e.g., Eighty in French “quatre-vingt” can be translated literally as “4 times twenty”) one of the most important differences concerns the inversion of the order of tens and units in two-digit number words of some languages. For instance, in German (but also in Maltese, Arabic, etc.) 47 is spoken as “siebenundvierzig” (literally “seven-and-forty”) and thus the order of tens and units is reversed in number words as compared to symbolic digital notation. This seems to influence numerical development even later on, as it is assumed that typically developing children but also adults verbally recode digitally presented numbers while e.g., performing calculations to keep track of partial results and the calculation procedure (see Helmreich et al. 2011; Pixner et al. 2011, for influences of different verbal number word systems on non-verbal numerical cognition in children; Nuerk et al. 2005 for adult data; Nuerk et al. 2011 for a review).

Despite the straightforward involvement of verbal number words, the second important aspect of verbal numerical representations are the so-called arithmetic facts which are assumed to be stored in an auditory-verbal manner (cf. Dehaene and Cohen 1997; Dehaene et al. 2003). For instance, after multiplication tables are highly overlearned during primary school, it is widely agreed that single-digit multiplications do not have to be actively calculated any more (e.g., Ashcraft 1987; Campbell 1995; McCloskey and Lindemann 1992; Rickard 2005; Siegler 1988, see Delazer et al. 2003, 2005; Ischebeck et al. 2006 for fMRI data on multiplication learning). Instead, it is assumed that multiplication (but also small addition) problems together with their results have become long-term memory entries of a verbally mediated network. In the case of an impaired verbal representation the most noticeable symptom should be a severe lack of arithmetical fact knowledge. For instance, children suffering from arithmetic fact dyscalculia should resort to more time-consuming back-up strategies in multiplication, such as computing each result through repeated addition instead. As already noted above, there is empirical evidence corroborating the existence of such specific deficits in arithmetic facts retrieval (also termed number fact dyscalculia, Temple 1991; or long term memory subtype, Geary 1993).

2.4.4 Spatial Representation of Numerical Magnitude

Since the seminal work by Galton (1880) back in the nineteenth century, a representational association of numbers and space has become widely accepted. Often, the spatial numerical representation is described by the metaphor of a mental number line along which numbers are represented in ascending order with respect to their magnitude (cf. Restle 1970; Dehaene and Cohen 1995). Initially, Berch et al. (1999) observed that typically developing children exhibit such spatial numeric representations by the end of primary school. However, more recent studies suggest a spatial numerical representation as early as grade one (van Galen and Reitsma 2008) or even earlier (e.g., de Hevia and Spelke 2009, 2010; McCrink and Wynn 2009; Opfer and Furlong 2011; Opfer and Thompson 2006). Additionally, it was found that a good spatial representation of number magnitude (as for instance assessed by the number line task, in which children have to estimate a numbers position on a hypothetical number line) is not only correlated with actual arithmetic achievement but is also a reliable predictor for the successful learning of new arithmetical problems (Booth and Siegler 2008). This indicates that an educated spatial representation of numerical magnitude seems to be beneficial for the general representation, understanding, and application of number magnitude information. Moreover, empirical evidence suggests an interrelation of more general visuo-spatial deficits and numerical performance. In this context, Bachot et al. (2005) found that the prevalence of mathematical difficulties was significantly higher for children with deficits in the general processing of visuo-spatial information (see also Rourke and Finlayson 1978 for a corresponding subtype of developmental dyscalculia).

However, concerning multi-digit numbers another influence of spatial-numerical representations has to be acknowledged: the impact of the place-value structure of the Arabic number system (see above). It has been observed repeatedly (e.g., Siegler and Booth 2004; Moeller et al. 2009c; Helmreich et al. 2011) that children initially do not adhere to the equidistance relation between numbers as indicated by the base-10 property of the Arabic number system (i.e., the distance between 0 and 60 is exactly 10 times the distance between 0 and 6). In the view of the interrelation between numbers and space, these findings suggest specific influences of spatial information on multi-digit number processing even in children. This conclusion can be drawn because the differentiation between the stack slots complying with the place-value structure of the Arabic number system is actually based on spatial information. Consequently, a related specific dyscalculic deficit may present with specific problems transcoding multi-digit numbers due to inefficient integration of the spatially coded stack information. Additionally, these children should be specifically impaired in tasks such as the number line estimation task which require an externalization of the spatial representation of numerical magnitude.

2.4.5 Representation of the Place-Value Structure of the Arabic Number System

Besides representations of the visual number form of digits and their semantic magnitude information there is another specific numerical representation which is inevitably necessary to correctly represent and use multi-digit numbers in particular – a representation of the place-value base-10 structure of the Arabic number system. Whenever confronted with multi-digit numbers, one needs to assign each individual digit its place-value stack information to correctly derive the number's overall magnitude. Throughout development, children need to learn how to identify units, tens, hundreds, etc. correctly to become aware of the fact that although 28 and 82 are composed of the same digits, they differ considerably in their magnitudes. According to their different places within the digit string, the digits are assigned different stack values (e.g., 2 at the tens, i.e., 28 vs. at the units' position, i.e., 82). The necessity of understanding the place-value structure to master basic numerical tasks such as magnitude comparison but also arithmetic implies specific effects of such place-value integration processes on arithmetic performance. And in fact, Nuerk and colleagues observed reliable effects of place-value integration in magnitude comparison for both children and adults (Nuerk et al. 2001, 2004a, b, 2005; see Mann et al. 2011 and Pixner et al. 2009 for children data; see also Macizo and Herrera 2010; Ganor-Stern et al. 2009; Zhou et al. 2008; see Nuerk et al. 2011, for a review). When separate comparisons of tens and units yielded compatible decision biases (e.g., 32_57, $3 < 5$ and $2 < 7$), the larger of two numbers was identified faster than when these comparisons yielded incompatible biases (e.g., 37_62, $3 < 6$ but $7 > 2$, see Nuerk and Willmes 2005 for a review). Additionally, there is now first evidence that the carry effect in addition may also be interpreted as a specific effect of place-value integration as tens and units are processed differentially (Klein et al. 2010; Moeller et al. 2011a, b). Furthermore, recent studies suggest that the structure of the number word system of a language (with/without inversion) may have particular influences on the successful acquisition and application of place-value information (Helmreich et al. 2011; Pixner et al. 2011). Generally, children whose number word system is inconsistent with the Arabic notation (i.e., because of an inversion of tens and units as e.g., in German number words; 64 → four and sixty) are at a disadvantage for acquiring the place-value structure of the Arabic number system successfully (e.g., Miura et al. 1993, 1994; Towse and Saxton 1998). In line with these findings, developmental dyscalculia caused by an impaired place-value representation should manifest itself for instance by an increased carry effect in addition.

2.4.6 Strategic, Conceptual and Procedural Components

Compared to the former numerical representations that reflect more or less very basic components of numerical cognition this last conceptualization addresses representational aspects primarily involved in/required for the solution of more complex numerical/arithmetic tasks and problems. As a consequence, the specific components subsumed under this last headword are less unitary than those described above and may be further differentiated by future research. However, for the purpose of the current chapter it is sufficient to illustrate that apart from the very basic representations serving as a building block for the development of higher numerical cognition there are of course arithmetical strategies, numerical concepts and procedures that may involve more than just one of the above described representations. For instance, the carry effect in addition may serve as an example of how different representations are recruited and applied in an arithmetic procedure to solve the task at hand. Consider the problem $27 + 48 = 75$. First, the individual digits need to be identified correctly. Then, following the standard algorithm the sum of the unit digits has to be computed first by either manipulation of semantic magnitude representations or fact retrieval of single-digit addition facts. As the sum of the unit digits is larger than 10, its decade digit needs to be carried to the tens stack of the place-value structure of the Arabic number system, which requires place-value knowledge. All these single steps together may then represent the procedural rule for correctly solving a carry addition problem. For both children and adults it is known that carry addition problems take more time and are more error prone than comparable non-carry problems. Therefore, these have to be trained specifically during primary school. The latter may be of particular importance as there is accumulating evidence for the suggestion that the neural correlates of procedural components are localized differently as compared to basic numerical representations such as number magnitude knowledge. On the one hand, it is widely agreed that processing of number magnitude information is subserved by (intra)parietal cortex sites (Wood et al. 2008; Dehaene et al. 2003; Dehaene 2009). On the other hand, procedural, conceptual, and strategic processes as well as related processes of cognitive control and working memory have been associated repeatedly with (pre)frontal cortex (e.g., Burbaud et al. 2000; Delazer et al. 2005; Miller 2000). With regard to specific deficiencies in developmental dyscalculia, we posit that there may be children who suffer from deficient procedural processing (cf. Geary 1993; Temple 1991), even though they successfully acquired all of the above described representations. In such a case, an affected child should show no specific impairment on any of the individual representations. Instead, the child should experience an extraordinarily increased difficulty of task and/or problems that require the correct application of procedural arithmetic rules (e.g., specific problems executing carry and/or borrowing operations in addition/subtraction), choices of solution strategies, or the application of conceptual knowledge (i.e., $0 \times X$ is always 0).

Before turning to the next point on the diagnostics of developmental dyscalculia, one important note has to be made. Above, following the description of each basic numerical representation, we made suggestions about how an isolated deficit in any of the specific representations could manifest itself in numerical or arithmetic difficulties. However, these descriptions should only be seen as suggestions to illustrate the multi-componential variable-oriented view on numerical cognition we wish to advocate. We are confident that the described basic representations will prevail as an important foundation of numerical cognition. There is, however, a number of issues that have to be considered concerning the above description.

First, the postulated representations may not be exhaustive. For instance, the representation of strategic, conceptual and procedural processes may need to be further differentiated. Moreover, recent findings suggest that embodied representations of numerical representations that are based on finger counting processes may also play an important role in numerical or arithmetic functioning (Domahs et al. 2008, 2010; Fischer 2008; Lindemann et al. 2011). Complementing these findings, another line of research has found evidence that finger gnosis might be important for numerical development (e.g., Gracia-Bafalluy & Noël 2008). Therefore, future descriptions might incorporate an embodied representation of finger counting, finger gnosis, or finger quantity.

Second, we do not wish to rule out the possibility that any of the described deficits might also induce problems in areas of cognitive processing other than the numerical domain. For instance, it is well conceivable that a fact retrieval deficit may not be restricted to numerical facts, but may also involve other less circumscribed deficits such as impaired retrieval of any kind of semantic information, such as a general (verbal) memory deficit that also extends to numerical information. In the above description of the six basic numerical representations, we only aimed at illustrating the importance of a verbal representation of numbers for numerical and arithmetic functioning and that its impairment may be detrimental for numerical performance. However, whether the causal reason for an observed impairment is a domain-general or a domain-specific deficit is still a matter of debate. Quite possibly, there may not even be a general answer to this issue, as recent data indicate that variation in numerical cognition is also subject to individual differences (e.g., Grabner et al. 2007; Ischebeck et al. 2009; see Dowker 2005 for implications on numerical development and education) . In our view, such individual differences might also be found in children. Consequently, impaired arithmetic fact retrieval might be a result of a domain-specific deficit in one child while in another child it might be the result of a broader, domain-general deficit of semantic fact retrieval also extending to arithmetic facts. However, these considerations are not limited to the verbal representation of numbers. For instance, also deficits in procedural and strategic processing could be domain-specific but might as well be domain-general and generalize to other domains of cognitive processing such as reading and writing. In any case, we postulate that such elementary processes underlie complex numerical cognition and thus have to be functioning so that complex arithmetic tasks can be mastered.

Third, and finally, identifying basic numerical dimensions in a variable-oriented approach does not preclude the possibility that there are different profiles (e.g. certain combinations of impairments) manifesting themselves in different dyscalculia subtypes. While we favour a variable-oriented approach to describe dyscalculic dysfunctioning, the current data do not preclude the validity of a person-oriented profile approach (i.e., subtyping). In our view, to date this issue is still debatable because of the lack of large-scale multivariate data (e.g., Q-factor analyses, cluster analyses, discriminance analyses) testing large samples of children with dyscalculia over a broad range of variables that index different numerical and non-numerical representations. Such analyses could reveal whether certain profiles of dyscalculic deficiencies (i.e., subtypes) can be reliably clustered. Obviously, such large-scale studies on dyscalculia are difficult to conduct because of the immense research effort. However, we suggest that this kind of study is exactly what is needed to progress in understanding reliable differences within dyscalculia regarding both the grouping of variables (numerical representations) and/or persons (profiles of dyscalculia subtypes).

3 Diagnostics of Developmental Dyscalculia

A necessary prerequisite for any reliable diagnosis is a consensual definition of the to-be-diagnosed impairment or disorder. Only when it is explicitly specified which criteria must or should be met, a valid diagnosis can be made. However, while this has been more or less accomplished in the case of dyslexia (Consensus project 2002), there is as of yet no universally accepted definition of developmental dyscalculia. In fact, in our view, we are in urgent need of a similar Consensus Project for dyscalculia. Nevertheless, as a working base the two prominent classification systems ICD-10 (World Health Organization 1992, Version 2007) and DSM-IV-TR (American Psychiatric Association 2000) can be used that now include disorders of arithmetical/mathematical skills, even though the term developmental dyscalculia is not used explicitly.

3.1 Diagnostic Criteria and Prevalence Rates: The Inconsistency Problem

According to ICD-10 a Specific Disorder of arithmetic skills (code F81.2) is described as a specific impairment of arithmetic skills not entirely attributable to general mental retardation or inadequate schooling. Additionally, the deficit has to primarily involve the mastery of basic computational competencies such as the basic arithmetic operations rather than impairments in more abstract mathematical domains such as algebra or calculus.

On the other hand, DSM-IV-TR criteria for a Mathematics Disorder (code 315.1) include a mathematical ability [. . .] that falls substantially below the arithmetical/mathematical capabilities of a child as expected on the basis of the individual's chronological age, her/his measured intelligence, and/or age-appropriate education. Furthermore, the deficient mathematics abilities have to interfere significantly with everyday life but also with academic achievement.

Taken together, it is evident that even the criteria of these two definitions do not match entirely. In fact, both imply a discrepancy criterion as regards mathematics abilities and general intelligence. However, while the DSM-IV-TR standards also include discrepancy diagnosis with respect to chronological age and-age appropriate education, ICD-10 does not explicitly refer to these criteria. Accordingly, the discrepancy criterion is used in research on developmental dyscalculia (e.g., Kosc 1974; Lewis et al. 1994; Fuchs et al. 2005; but see Fletcher et al. 1998; Siegel and Ryan 1989, for critical discussions of the reliance upon the discrepancy criterion, see also Weber et al. 2002, for results suggesting no difference of intervention effects for children either fulfilling the discrepancy criterion for dyslexia or not). Nevertheless, the discrepancy necessary for a diagnosis of dyscalculia varies from study to study (e.g., 2 years between chronological age and actual achievement level as used by Shalev 2004; Shalev et al. 2000; Shalev and Gross-Tsur 2001; e.g., discrepancy >15 points between standardized IQ and mathematics achievement test scores, Mazzocco and Myers 2003). Interestingly, these are not the only (and maybe not even the most widely used) diagnostic criteria/definitions of developmental dyscalculia in dyscalculia research. More often than the discrepancy criterion a simpler – and often more convenient – cut-off criterion is applied. However, as in the case of the discrepancy criterion there is currently no generally agreed cut-off for a dyscalculia diagnosis. In the literature, different cut-off criteria are either reported as percentiles (e.g., percentiles <35 e.g., Geary et al. 2000; Jordan et al. 2002; percentiles <25, e.g., Koontz and Berch 1996; McLean and Hitch 1999; percentiles <15, e.g., Geary et al. 2008; percentiles <10, e.g., Geary et al. 2007; Mazzocco and Myers 2003; Murphy et al. 2007), deviations from the population mean in SD (i.e., 1.5 SD, e.g., von Aster et al. 2007; 2.0 SD, e.g., Piazza et al. 2010; Ashkenazi and Henik 2010; 3.0 SD, e.g., Landerl et al. 2004) or ranges of standard scores such as for instance the bottom 2 stanines (Butterworth 2003). Obviously, it is not satisfactory that each diagnostic classification system and what is more even each research group applies their own preferred definition of developmental dyscalculia or math impairments. Consequently, the question arises which one of these diagnostic criteria provides the best assessment of developmental dyscalculia.

Mazzocco and Myers (2003) addressed this important issue by directly comparing the application of discrepancy and cut-off based criteria in a longitudinal study on 210 children from kindergarten to grade three. Generally, the authors observed that a cut-off based diagnosis of dyscalculia was more reliable than a diagnosis based on the discrepancy between IQ and mathematics achievement score (see also Marx et al. 2001; Weber et al. 2002 for similar results suggesting no difference for children with dyslexia either fulfilling the discrepancy criterion or not). Furthermore, they found that the two diagnostic criteria did not overlap much. Hence, the majority of children diagnosed to suffer from dyscalculia by their mathematics achievement falling below the 11th percentile did not meet the discrepancy criterion and vice versa. However, the superiority of the cut-off based diagnosis became particularly evident when the longitudinal design of the study was taken into consideration. Concerning the longitudinal validity of the diagnosis, the authors reported that out of all children who ever met the cut-off criterion, 63% exhibited persistent impairments (i.e., performance <11th percentile over two or more years). In contrast, persistency was considerably lower (i.e., 18%) when the discrepancy based criterion was applied.

In summary, these data argue for the superiority of the cut-off based over the discrepancy based diagnosis of dyscalculia and call for a revision of the diagnostic classification systems. However, these data do not suggest that IQ assessment in general is no longer useful – they only demonstrate that the absence of a discrepancy between IQ and mathematics achievement does not preclude the occurrence of developmental dyscalculia. Thereby, the discrepancy criterion may provide considerable specificity for detection of dyscalculia but may lack sufficient sensitivity to identify all children affected by dyscalculia (see also Mazzocco and Myers 2003 for a more detailed discussion of this point). Moreover, the results of Mazzocco and Myers (2003) indicate that a single time assessment of numerical/mathematical capabilities using only one single test may not be sufficient to warrant a reliable diagnosis of dyscalculia. Instead, due to incidence figures varying both at one given point in time as well as over the course of time, the relevant numerical/mathematical abilities should be assessed several times using different tests. This would make it possible to assess another criterion which has been suggested in recent years as an alternative to discrepancy or cut-off based diagnostics. Based on findings that dyscalculic children still struggle with retrieving basic arithmetic facts even after extensive training (e.g., Howell et al. 1987), Geary (2004) argues that such treatment resistance in itself may also be a valid diagnostic criterion of dyscalculia (see also Mazzocco and Myers 2003 for a similar rationale).

In a nutshell, because of these inconsistencies in dyscalculia definitions as well as diagnostic standards, it is not surprising to learn that the reported prevalence rates differ from study to study. Nevertheless, across different countries and continents, similar prevalence rates between about 3% and 10% of the overall population suffering from developmental dyscalculia have been observed (Kosc 1974; Badian 1983; Klauer 1992; Lewis et al. 1994; von Aster 1994; Gross-Tsur et al. 1996; Ostad 1998; Shalev et al. 2000; Shalev and Gross-Tsur 2001; Ramaa and Gowramma 2002; Mazzocco and Myers 2003; Koumoula et al. 2004; von Aster et al. 2007)

Taken together, the above literature denotes that the absence of a universally agreed definition of developmental dyscalculia together with non-uniform diagnostic criteria caused great heterogeneity in existing dyscalculia diagnostics, since cut-offs and discrepancy measures are picked more or less arbitrarily. As a consequence, prevalence rates observed on the basis of these differing diagnostic criteria differ as well, and primarily serve as educated guesses, rather than elaborated estimations of the actual prevalence rates of dyscalculia. Therefore, we would like to offer a unifying approach on diagnostic criteria of developmental dyscalculia by taking into account the above considerations on specific basic numerical competencies and related dyscalculic deficiencies.

3.2 Towards a More Specific Diagnosis of Developmental Dyscalculia

Apart from the psychometric and methodological shortcomings and limitations, the definition of the ICD-10 Specific disorder of arithmetical skills and of the DSM-IV Mathematics Disorder also provide links to the above described reasoning on actually impaired competencies and subtyping. For instance, in ICD-10 one can find further specifications as regards the kind of impairments observed in developmental dyscalculia. In line with our considerations, primary impairments of rather basic numerical abilities are suggested even though these are not described at the representational level but at the level of basic arithmetical operations. Interestingly, this approach is corroborated by a recent review of dyscalculia interventions and remediation programs currently in use in the UK (Dowker 2009). Dowker argued that training of rather basic numerical competencies seems to be most beneficial for dyscalculic children. Therefore, it is only plausible to address basic numerical capabilities in dyscalculia diagnostics to narrow down the specific origin of the deficits individually – rather than adopting a more or less broad label of deficient numeracy. At the moment, such specific information about children's differential performance on particular tasks and/or subtests is often not fully exploited. In this vein, Geary (2004, p. 5) remarks that "Standardized achievement tests sample a broad range of arithmetical and mathematical topics, whereas children with MLD often have severe deficits in some of these areas and average or better competencies in others". Thus, the use of sometimes quite liberal cut-offs for the diagnosis of dyscalculia (e.g., <26th percentile, cf. Koontz and Berch 1996; McLean and Hitch 1999) may be due to the fact that no specific and differential evaluation of the basic numerical competencies has been conducted. Instead, the 25% cut-off may have been chosen to compensate for the averaging across items assessing different competencies. Therefore, to overcome the shortcoming that such results indicate "a level of performance (e.g., at the 20th percentile) that overestimates the competencies of children with MLD in some areas and underestimates them in others" (Geary 2004), we recommend to diagnose dyscalculia by combining general task performance measures with performance measures for individual subtests.

Table 1 Overview of suggested cut-offs for dyscalculia diagnostics

Percentile	Suggested diagnosis
Overall performance above 25th percentile	No indication of developmental dyscalculia
Between 25th and 11th percentile	At risk for developmental dyscalculia
≤10th percentile	Developmental dyscalculia
Specific subtests ≤5th percentile	Specific developmental dyscalculia (indicative of specific deficiencies in specific numerical processes)

First of all, we suggest classifying all individuals scoring ≤ the 25th percentile on a standardized test as being *at risk* for dyscalculia. Furthermore, individuals whose general performance was ≤10th percentile should be diagnosed with developmental dyscalculia (see also TEDI-MATH, Kaufmann et al. 2009a). Alternatively, a specific dyscalculia deficit diagnosis should be warranted if the individual scores ≤5th percentile on at least an a priori defined number of subtests – the latter indicating specific impairments of the particular competencies addressed by these subtests. Thereby, under the precondition of existing tests being standardized at the subtest level, such a proceeding should allow for a reliable diagnosis of developmental dyscalculia in general. In addition, it allows for direct assessment of certain deficits by examination of critical differences between subtests. Additionally, very specific dyscalculic deficits (such as postulated above) can be identified by taking into account those subtests in which a person performs ≤5th percentile, and be diagnosed even when general performance is still above the 10th percentile (see Table 1 for an overview).

To better illustrate how such a differential dyscalculia diagnosis could be achieved, we will describe the German version of the TEDI-MATH (Kaufmann et al. 2009a) as an example. This test was designed specifically for the diagnosis of developmental dyscalculia and therefore differentiates best in the range of low performance. Beside a total score, the individual subtest scores can be integrated into two subscale scores: *Numerical Processing* (subtests including, for example, *Counting Principles*, *Arabic Digit Comparison*, and *Numerical Transcoding*) and *Calculation* (for example *Addition*, *Subtraction*, *Word Problems,* and *Knowledge of Arithmetic Concepts*). As the TEDI-MATH was standardized on the subscale level, it should be possible to base a diagnosis on specific performance dissociations between some of the subtests. For instance, one of the basic numerical representations we introduced above, the Verbal Numerical Representation (consisting of both the knowledge of spoken number words and verbally stored arithmetic facts), is addressed by several subtests of the TEDI-MATH (Kaufmann et al. 2009a): the subtests *Recognition of Number Words, Transcoding,* and *Multiplication*. These subtests measure how well children can discern number words from non-numerical verbal stimuli, whether children can correctly read and write numbers, and how well children can retrieve verbally stored multiplication tables, respectively. The standardized norms for each subtest of the TEDI-MATH make it possible to determine whether a child performs ≤5th percentile on these subtests. If this is the case, we suggest that a diagnosis of a *verbal* dyscalculia deficit should be warranted even if the child performs in the average range on all other subtests and even though its total score may lie above the 10th percentile (see e.g., Temple 1991 for a dissociation of number fact and procedural dyscalculia).

This approach on subtyping seems particularly important regarding the differentiation of basic numerical competencies but also the latest DSM-IV-TR definition of Mathematics Disorder. Here, one can read that "a number of different skills may be impaired in Mathematics Disorder, including "linguistic" skills (e.g., understanding or naming mathematical terms, operations, or concepts, and decoding written problems into mathematical symbols), "perceptual" skills (e.g., recognizing or reading numerical symbols or arithmetic signs, and clustering objects into groups), "attention" skills (e.g., copying numbers or figures correctly, remembering to add in "carried" numbers, and observing operational signs), and "mathematical" skills (e.g., following sequences of mathematical steps, counting objects, and learning multiplication tables)". As these different "skills" can be easily associated with above described basic numerical representations (e.g., linguistic skills → verbal numerical representations; mathematical skills → procedures, concepts, and strategies), this definition emphasizes the importance of a reliable diagnosing of the *specific* impairments in developmental dyscalculia.

Admittedly, to fully exploit the potential of such a multi-componential differential diagnosis of dyscalculia, further research and psychometric development is necessary to provide the required standardized tests. To date, only a very limited number of tests has been standardized at the subtest level [e.g., CMAT (Hresko et al. 2003; TEMA-3 (Ginsburg and Baroody 2003); TOMA-2 (Brown et al. 1994); ZAREKI-R (von Aster et al. 2006); TEDI-MATH (Kaufmann et al. 2009a, b)].

In this context, it is necessary to investigate in which way the postulated basic numerical representations are interrelated and influence one another (e.g., Wood et al. 2008; Nuerk et al. 2002). Additionally, there is still a lack of understanding how far basic numerical representations are influenced by surface formats such as numerical notation (i.e., possible differing representations of symbolic or non-symbolic magnitude). Finally, when aiming at studying developmental dyscalculia transculturally, the development of appropriate dyscalculia tests should be coordinated across cultures and nations – thereby, enhancing the comparability of international studies on developmental dyscalculia. Otherwise, even when relying on agreed criteria, different children might be selected still when using different tests with different subcomponents.

To sum up, in line with our proposition of possible dyscalculia diagnoses (see Table 1) being associated with specific impairments of basic numerical representations, we suggest multi-componential differential diagnostics for developmental dyscalculia. In our opinion, this would not only allow for a better understanding of the actual individual impairment(s), but would also pave the way for more tailored intervention programmes adapted to the needs of each individual with dyscalculia. From a practical point of view we have to admit that the prerequisite for such elaborate in-depth diagnostics is still in its fledgling stages with only few appropriate tests. These few tests, however, provide the required differentiation and thus a first step towards more comprehensive understanding of developmental dyscalculia as well as its causes, deficiencies and remediation.

As regards a comprehensive understanding of developmental dyscalculia, it is important to not only concentrate on issues of theoretical underpinnings and diagnostics but also to consider its comorbidities with other developmental disorders such as dyslexia and/or ADHD. In the following paragraphs this issue will be pursued.

4 Developmental Dyscalculia and Comorbid Developmental Disorders

Generally, a so-called comorbidity is given by the presence of coexisting or additional diseases with reference to an initial diagnosis or to the index condition that is the subject of study (i.e., developmental dyscalculia in the present case). As for other (developmental) cognitive disorders it is an important point to know or to at least have a reliable estimate of the rate at which developmental dyscalculia co-occurs with other cognitive impairments such as dyslexia. Often, it is a multimorbid pathology that is recognized by either teachers or parents, and background knowledge about the interrelation of co-occurring developmental disorders should be mandatory for a differential diagnosis and the later decision on remediation. At this point, we would like to once again emphasize the importance of a differential diagnosis of developmental dyscalculia. Of course, arithmetic difficulties can also arise not as a primary impairment of numerical competencies but also as the secondary result of a different (developmental) cognitive disorder, such as, for instance, ADHD. In this case, treatment of the primary impairment should be the main focus of intervention. Such a secondary symptomatology, however, does per definition not qualify as a comorbidity or co-occurrence in the narrower sense and will therefore not be elaborated on in this section (see e.g. Rubinsten 2009; Rubinsten et al. 2008; Kaufmann and Nuerk 2008 for numerical impairments in children with ADHD). However, it is important to note that general developmental cognitive disorders can exert an influence on numerical processing as well as on other cognitive domains, which, when not considered as a mediating variable, may lead to an overestimation of co-morbidity.

4.1 Comorbidity Rates

In this context, the comorbidity rate is one important index reflecting the percentage or proportion of children suffering from developmental dyscalculia that also exhibit considerable symptoms of, for instance, dyslexia.

As we have few data on comorbidity of dyscalculia to date, a look on the much better studied impairment of dyslexia might be helpful. For the case of dyslexia the comorbidity rates reported in the literature vary considerably between 17% and 70% of children with dyscalculia also showing reading problems and 11–56% of children with dyslexia also suffering from dyscalculia (Badian 1983; Barbaresi et al. 2005; Dirks et al. 2008; Gross-Tsur et al. 1996; Lewis et al. 1994; von Aster et al. 2007). The enormous variation in this comorbidity estimates clearly suggest that the criteria defining developmental dyscalculia differ between studies (see also above) and do not yet provide reliable comorbidity estimates. Therefore, it is necessary to take a closer look on this methods before reporting any conclusive numbers.

4.1.1 Empirical Comorbidity Rates and Cut-off Criteria

In a recent article, Landerl and Moll (2010) argue that there are several reasons for this high variability in comorbidity rates in contrast to the rather stable prevalence estimates. On the one hand, the authors point out that academic achievement tests of e.g., arithmetic, often comprise word problems that children with reading difficulties have troubles solving even when they are not dyscalculic. Therefore, the overall achievement score derived by most arithmetic achievement tests might be confounded because not only the capabilities of interest are assessed. Instead, successful mastery of the arithmetic problems depends on other capabilities such as reading ability that are not explicitly assessed. This reasoning further corroborates our recommendation of a thorough differential diagnostic of the actually impaired numerical representations/competencies to avoid such confounding.

Moreover, Landerl and Moll (2010) suggest that comorbidity rates may be inflated not only by the use of averaged general achievement scores (instead of performance profiles), but by the selection criteria applied for diagnosing either dyscalculia or any other disorder. Accordingly, comorbidity increases with more liberal selection criteria. In this context, Dirks et al. (2008) were able to show that the comorbidity rate for dyscalculia and dyslexia declined from 7.6% to about 1.0% when employing a selection criterion of performance ≤10th percentile as compared to ≤25th percentile. Interestingly, this reduced comorbidity rate of 1.0% reflects exactly the rate of co-occurrence expected by chance when assuming two unrelated disorders. More light is shed on this interrelation by the results of Landerl and Moll (2010). These authors assessed comorbidity rates of dyscalculia and dyslexia in a population based sample as well as in a subsample with learning disorder(s). In line with the results of Dirks et al. (2008), Landerl and Moll (2010) observed that comorbidity rates between these two disorders decreased when applying a more stringent cut-off. Additionally, they found that comorbidity rates for the learning disabled sample were generally higher (and particularly so for the stricter cut-off) than those observed for the population based sample. Thus, liberal selection criteria as well as the examination of preselected populations such as children with learning disorders seem to increase comorbidity rates. In general, more liberal selection criteria are assumed to lead to less homogeneous and thus probably more multi-morbid deficit groups. When then evaluating the comorbidity rate of any two developmental disorders, it is very likely to find these rate being inflated by the preselection of the sample. This skepticism regarding the reported comorbidity rates is also corroborated by a recent study on dyscalculia by Auerbach et al. (2008). The authors assessed behavioral problems in a sample of adolescents with persistent dyscalculia. Interestingly, they observed only few and rather unsystematic evidence suggesting more attentional and/or externalizing problems in adolescents with dyscalculia.

4.1.2 A More Theoretical View on Comorbidity Rates

Despite the fact that above rationale suggests decreasing comorbidity rates with more stringent cut-off criteria, there is also evidence suggesting that comorbidity increases with the severity of one developmental disorder (e.g., Landerl and Moll 2010). Thus, contrary to what has been described above this means that a child should exhibit more co-occurring conditions the more severe the primary disorder (e.g., Jordan and Montani 1997; Kaplan et al. 2006). For any combination of developmental disorders, such phenomena are often interpreted as suggesting a common neuro-biological basis of the two disorders at hand (in terms of pleiotropy, e.g., Pennington 2006) or complex downstream effects in brain development (e.g., Kaplan et al. 2006).

To illustrate this argument, consider the case of attentional and arithmetic deficits. For both cognitive functions, there is ample evidence associating its neural correlates with parietal cortex sites in and around the intraparietal sulcus (e.g., Simon et al. 2002). Accordingly, when impaired arithmetic skills are attributed to dysfunctional neural processing at these cortical sites that overlap with those involved in attentional processes, then attentional deficits should get more pronounced the more neural processing of numerical information is impaired. Following this rationale, comorbidity rates should increase, rather than decrease, for more stringent selection criteria; reflecting the common neural underpinnings of the comorbid disorders. However, most of the empirical evidence suggests that comorbidity rates increase with more liberal cut-off criteria. Nevertheless, there is also contrasting evidence indicating increasing comorbidity rates with more stringent cut-off criteria (e.g., Landerl and Moll 2010). The latter findings are of particularly relevance when taking into account the notion of common neural bases of the comorbid disorders. And indeed, in such a case, differential evaluation of comorbidity rates for diverse developmental disorders may offer the possibility to gain further insights into the connectivity of the human brain and its differential contribution to seemingly distinct cognitive functions.

For instance, assuming that comorbidity of disorders A and B *decreases* for more liberal cut-offs while the co-occurrence of disorders A and C *increases*, this would indicate a closer relationship (in terms of neural correlates) of disorders A and B compared to A and C. Importantly, Landerl and Moll (2010) found such a dissociation for the comorbidity of arithmetic and spelling v.s. arithmetic and reading deficits. While the rate of co-occurrence for arithmetic and reading deficits decreased when stricter selection criteria were applied, the comorbidity rate of arithmetic and spelling deficits did not. The authors interpret this data pattern to suggest a more pronounced biological mediation of the comorbidity between arithmetic and spelling disorders. Thereby, Landerl and Moll (2010) provide a first account of how to not only interpret but make use of the inconsistent empirical evidence as regards the interrelation of comorbidity rates and cut-off criteria selection. Bridging the gap between the two assumptions on comorbidity and selection criteria, Landerl and Moll (2010) conclude that comorbidities are the result of a complex interplay between both general and disorder-specific aetiological factors. In this context, two disorders sharing disorder-specific factors (e.g., neural abnormalities in IPS, see above) would be reflected by increasing comorbidity rates with more stringent criteria, whereas two disorders both involving more general factors (e.g., intelligence) should manifest in decreasing comorbidity rates with more stringent cut-offs. Basically, such a conclusion was conceptualized in the work by Rubinsten and Henik (2009) and will be discussed in greater detail in the following.

4.2 Different Origins of Comorbidity

In their theoretical article Rubinsten and Henik (2009) proposed three different frameworks within which dyscalculia and its comorbidities with other developmental disorders can be conceptualized. The first framework assumes a unique pathophysiology in the IPS to underlie developmental dyscalculia – a notion similar to that described above as the core deficit hypothesis. In the second framework, different symptomatologies at the cognitive level are attributed to different pathophysiologies, depicting a more multi-componential view of numerical cognition with the possibility of more specific impairments as advocated above. Finally, in their third framework, comorbidity is addressed. As already reflected by the differences between the first two frameworks, Rubinsten and Henik (2009) suggest both the possibility of comorbidities being caused by a single pathophysiology as well as being attributable to differing underlying pathologies (see Rubinsten and Henik 2009, Figure 2, p. 95). These conceptualizations of comorbidities with developmental dyscalculia are corroborated by the findings of Landerl and Moll (2010), as the latter provide first evidence that comorbidities may have different origins.

In this context, it is also important to note that the discussion about the origins and the conceptualization of comorbidities is not limited to developmental dyscalculia. Rather, there is currently an ongoing debate questioning the prevailing view of comorbidity representing the correlation of two latent variables (i.e., the co-occurring developmental disorders). As an alternative approach, Cramer et al. (2010, p. 137) suggest to conceptualize comorbidity as a network in which comorbidity is assumed to “arise from direct relations between symptoms of multiple disorders”. Thereby, the co-occurrence of two or more disorders is not qualified by the correlation of latent variables defined by different observed variables which vary across studies (as employed tests or experimental set-ups vary). Instead, comorbidity arises at the level of the observed variables as overlapping and thereby directly related symptoms. Following this approach, it should be possible to differentiate between symptoms that are related to both comorbid disorders – thereby establishing their co-occurrence – and other symptoms, which are primarily related to only one of the disorders. While the former is less relevant for diagnostic purposes, identification of the latter would be extremely beneficial for the improvement of diagnostic validity and reliability.

However, research employing this rationale is only in its infancy and we are still lacking a universally agreed definition of developmental dyscalculia as well as standards for diagnosing it. With regard to comorbidities, this means that their evaluation should take into account variables such as selection criteria, preselection of samples, but also differences in the theoretical conceptualization of comorbidity. In this context, knowledge on whether an observed comorbidity rate is higher than expected by chance – on the basis of the prevalence of the single disorders– provides the researcher as well as the diagnostician with important additional information for evaluating its relevance. Therefore, we chose to recapitulate in the following on the issue of how co-occurrence rate expected by chance can be estimated.

4.3 Comorbidity or Only Random Co-occurrence?

Generally, estimating the comorbidity of two independent disorders as expected by chance is a rather simple matter of probability calculus. For instance, consider the prevalence of developmental dyscalculia to be about 8% of the population (see above) and that of developmental dyslexia to be about 10% (e.g., Lindergren et al. 1985; Lyytinen et al. 2004; Lam et al. 2008). Under the presupposition that the two disorders are independent of each other, that is, that suffering from one of these two does not influence the probability of suffering from the other one, the comorbidity expected by chance can be computed by multiplying the prevalence rates of the two disorders:

$$p_{\text{comorbid}} = p(\text{Disorder 1})^{*}p(\text{Disorder 2}) = p(\text{Disorder 1}|\text{Disorder 2})$$

Thereby, for above given prevalence rates of developmental dyscalculia and dyslexia a random comorbidity rate of .08 * .10 = .008 or 0.8% can be expected. Any association between these two disorders observed to be higher than this should consequently be considered to indicate epidemiological comorbidity in the sense that the two disorders are not statistically independent but seem to co-occur more frequently than expected by chance. This way, the product of the prevalence rates of two disorders always indicates the lower boundary of epidemiological comorbidity.

Only when the co-occurrence of two disorders is more probable than expected by chance, it should be taken as evidence for an association of these two disorders.

However, as above introduced formula is based on the prevalence rates of the disorders of interest, estimating the random comorbidity of two disorders of which one is developmental dyscalculia is subject to problems already discussed above. As there is no generally agreed diagnostic criterion of developmental dyscalculia prevalence rates are highly dependent on the cut-off criteria used to diagnose dyscalculia. In turn, also the estimated random comorbidity changes with different cut-off criteria. For instance, when a cut-off criterion indexing the lower 5% of the population to suffer from dyscalculia is used, basically, a prevalence rate of 5% is assumed. Following above described formula the random comorbidity of dyscalculia and dyslexia would be $.05 * .10 = .005$ or 0.5% when relying on a prevalence rate of 10% for dyslexia as has been reported in the literature. Nevertheless, often much more liberal criteria are used for diagnosing both developmental dyscalculia as well as dyslexia, for instance cut-off criteria assuming all children falling $\leq$25th percentile to be either dyscalculic or dyslexic (see above). Taking into account the resulting prevalence rates of 25% for both disorders the comorbidity as estimated by chance raises to $.25 * .25 = .0625$ or 6.25%. And only if the actual comorbidity estimate is higher than this estimation, it is valid to assume a common underlying origin. Please note that this problem of inflated random comorbidity is even more aggravated when relying on selected samples such as samples from special schools or special education centers. For example Norman and Zigmond (1980) reported that in a sample of children diagnosed and served as learning disabled up to 62% of the children diagnosed with developmental dyscalculia also fulfilled the criteria for dyslexia. With a prevalence rate of 21% for developmental dyscalculia and 36% for dyslexia random comorbidity in this sample would be as high as 7.6%. To further illustrate this point imagine a special education centre in which 70% of the children suffer from developmental dyscalculia and 80% suffer from developmental dyslexia in this case a comorbidity rate of 56% should be observed by chance. Taken together, we suggest that, as already argued above, it is important to take into account issues of selection criteria, sample preselection, and random comorbidity when interested in epidemiological comorbidity rates of developmental disorders. Preferentially, estimates of epidemiological comorbidity should be based on diagnoses following generally agreed criteria, evaluating performance in an unselected sample and testing against random comorbidity of the two disorders.

Nevertheless, research over the last years has not only led to the development of diagnostic criteria and diagnostic instruments as discussed above but also to a growing number of intervention approaches for dyscalculia. While all of these still need to be evaluated and optimized, they represent a first step towards providing children with dyscalculia with the support they need and deserve. Upon considering that neuroscience-based dyscalculia research is in its infancy, it is not surprising to learn that neuro-cognitively based intervention studies on developmental dyscalculia are extremely scarce. As regards behavioural/cognitive intervention, recent studies showed the effectiveness of intervention programmes targeted at the core deficit of numerical quantity processing (Kaufmann et al. 2003, 2005; Krajewski et al. 2008). Moreover, a recent meta-analysis of different intervention programmes (primarily targeted at more general mathematics learning disabilities) provided first hints that training in the domain of basic skills seemed to be most effective (Dowker 2001; Kroesbergen and van Luit 2003). However, intervention studies targeted at developmental dyscalculia deficiencies other than the numerical quantity subtype are still very rare. In the following section, existing intervention studies and their implications will be discussed and evaluated.

5 Interventions for Dyscalculia: Up to Now

Dyscalculia has proven to be a rather stable impairment (Shalev et al. 2005), having implications into adulthood and possibly all of an affected person's life (cf. Parsons and Bynner 2005). In the course of this realization, a variety of treatment approaches for developmental dyscalculia has been developed: prevention programmes that aim at compensating arithmetic difficulties before they aggravate into dyscalculia; and intervention programmes that tackle the difficulties of children who suffer from developmental dyscalculia. Furthermore, some approaches have been designed that so far have only been tested on typically developing children and do not yet fit into either of the above two categories. In the following, these approaches will be referred to as trainings. To a certain degree, dyscalculic children can profit from prevention programmes (Fuchs and Fuchs 2001). However, the different deficiencies that can underlie dyscalculia call for a tailored intervention programme that can effectively be adapted to children with specific arithmetic difficulties as regards the basic numerical competencies described above. This was also emphasized by Dowker (2004), who recommended that intervention should be individualised and furthermore, should take place relatively early in development.

In this section, we will give an overview over some contemporary treatment approaches, focussing on those addressing children in kindergarten or elementary school (see Table 2). We would like to emphasize, however, that this overview does not claim to be exhaustive and should thus not be taken as a review of all existing literature.

To evaluate these approaches, we propose three important criteria that an intervention/prevention programme should meet to successfully lead to long-lasting improvements in children with dyscalculia: First, because we assume that there are different deficiencies in dyscalculia based on impairments in different areas of basic numerical processing (see above), it would have to be multi-componential. It would thus have to involve different modules covering as many of the potentially impaired areas of basic numerical competencies as possible. Second, these modules should be applicable independently from one another, so that the training can be adapted to a child's specific needs and challenges. Thereby, redundant training of competencies that a child has already mastered can be avoided. The final criterion is for an intervention/prevention to be evaluated regarding its effectiveness for

Table 2 Information about treatment approaches evaluated in this chapter (sorted alphabetically by author)

Authors	Title	Target children	Age group	Type of approach	Range of tasks	Domain of knowledge	Intervention material	Treatment setting	Evaluation
Butterworth and Laurillard (2010)	Basic numeracy games	Children with special educational needs	?	Intervention	Multi-componential	Basic numerical competencies	Electronic	Individual	In progress
Sarama and Clements (2002, 2004)	Building Blocks software	Children without dyscalculia	Pre-kindergarten to grade 6	Prevention/training	Multi-componential	Basic numerical competencies	Electronic	Individual	Whole program
Dowker (2001)	Numeracy Recovery Programme	Children with dyscalculia	Age 6–7 years	Intervention	Multi-componential	Basic numerical competencies	Tangible	Individual	Whole program, no control group
Fischer et al. (2011)	Dance mat training	Children without dyscalculia	Kindergarten	Training	Magnitude comparison task	Basic numerical competencies	Electronic	Individual	By task
Griffin et al. (1994), Griffin (2003)	Number Worlds Curriculum	Children with/without dyscalculia	Pre-kindergarten to grade 6	Prevention and Intervention	Multi-componential	Basic numerical competencies and higher arithmetic	Electronic and tangible	Classroom, small-group or individual	Whole program
Kaufmann et al. (2003)	Numeracy Intervention Programme	Children with dyscalculia	Third grade	Intervention	Multi-componential	Basic numerical competencies	Tangible	Individual	Whole program
Metzenleitner (2007)	Multi-Componential Training Approach	Children with dyscalculia	Third grade	Intervention	Multi-componential	Basic numerical competencies	Tangible	Small-group	Whole program
Siegler and Ramani (2009), Booth and Siegler (2008)	Linear number board games	Children from low-income background	Kindergarten	Intervention	Linear board game	Basic numerical competencies	Tangible	Individual	By task
Wilson et al. (2006a, b)	Number race game	Children with dyscalculia	Age 5–8 years	Intervention	Comparison tasks	Basic numerical competencies	Electronic	Individual	By task
Wright et al. (2000, 2002)	Mathematics Recovery Programme	Children with dyscalculia	Age 6–7 years	Intervention	Multi-componential	Higher arithmetic	Tangible	Individual	Whole program

improving numerical performance of children with dyscalculia. Up to now, no treatment approach has been developed that fully meets all three of these criteria. Nevertheless, we would like to discuss a few promising approaches which have received growing interest over the last years.

Contemporary approaches at treating dyscalculia differ on several dimensions, such as the range of applied tasks, the domain of knowledge considered, intervention material, and whether they are designed for groups or individuals (see also Table 2 for an overview of the evaluated approaches and their characteristics). Accordingly, in the following section we will evaluate existent intervention/ prevention approaches with respect to these dimensions. In a concluding remark, we will then elaborate on what has so far been learned about the effectiveness of certain types of treatments.

5.1 Range of Tasks: Multi-componential vs. Specific Approaches

The majority of existing intervention approaches trains more than just one domain of numerical competence. Examples for multi-componential approaches are the *Mathematics Recovery Programme* by Wright and colleagues (Wright et al. 2000, 2002), which is based on a sequential model of numerical development; the *Numeracy Recovery Programme* by Dowker (2001) that trains numerous components of basic numerical processing; a *Numeracy Intervention Programme* by Kaufmann et al. (2003) focusing on basic numerical knowledge and conceptual knowledge; a *Multi-Componential Training Approach* for children with dyscalculia developed by the research group of Nuerk (e.g., Metzenleitner 2007; see also Müller 2010; Pircher 2007); the *Building Blocks* software (Sarama and Clements 2002, 2004), which provides an online-accessible mathematics curriculum and is based on research in a Logo programming environment (Clements 2002; see also *Turtle Math*; Clements and Meredith 1994); a new series of electronic *Basic Numeracy Games* (Butterworth and Laurillard 2010); and the probably most popular prevention and intervention programme for mathematics, the *Number Worlds Curriculum* by Griffin and colleagues (Griffin et al. 1994; Griffin 2003). These intervention programmes try to convey a large range of numerical competencies and knowledge so that children at a certain age level can improve in all age-relevant areas of arithmetic knowledge.

In contrast, some other programmes focus on training just one single competence which is then supposed to invoke improvement on other numerical capabilities and tasks as well. One such approach was developed by Siegler and colleagues (Siegler and Ramani 2009; Booth and Siegler 2008), who claim that improvement of children's mental number line accuracy (i.e., the accuracy of children's spatial representation of number magnitude, see above) induced by repeated playing of linear number board games should corroborate children's performance in tasks measuring other basic numerical competencies. Likewise, Fischer et al. (2011) tried to improve children's mental number line accuracy by training on a digital dance mat that enabled a bodily experience of the number line orientation. They found that the effects of this physical number line training generalized to transfer measures such as counting; thus speaking for a transfer of number line improvement onto other domains of numerical competence.

Considering the multi-componential vs. specific differentiation, the Number Race game by Wilson et al. (2006a, b) falls somewhere between the extremes as it was designed to train the number sense, which the authors describe as a basic understanding of quantities. However, although the number sense can be interpreted as one area of arithmetic proficiency, it involves several relevant components. Therefore, the game trains a number of different numerical comparison tasks, such as comparison of two non-symbolic magnitudes or comparison of the results of two simple addition problems. Again, this rather specific training impacted on other areas of arithmetic performance that were not explicitly trained (e.g., subtraction).

Taken together, there are advantages to both multi-componential as well as specific intervention programmes. To make an intervention programme interesting and beneficial for a wide range of audiences, multi-componential approaches have the advantage of being capable of specifically addressing different problems. However, a common drawback of multi-componential programmes is that to date most of them are only evaluated as a whole. Thereby, no conclusions can be drawn about whether the single elements of a programme are effective by themselves. In contrast, specific intervention approaches allow for a more accurate evaluation of their effectiveness. Additionally, when the trained task is actually essential for numerical proficiency in general, transfer effects into other domains of numerical abilities may be attained. Unfortunately, by means of such specific intervention programmes it is not possible to adapt the intervention to a certain child's needs covering all her/his specific problematic areas. However, such an adaptation would become necessary when – as we proposed – there are different deficiencies in dyscalculia (see Sect. 2 of this chapter) that call for different types of intervention.

5.2 Domain of Knowledge: Basic Numerical Competencies vs. Arithmetic Procedures

Considering the domain of numerical competencies trained there are important differences between intervention programmes. They either train basic numerical competencies or arithmetic procedures and tasks that are often based on curricular requirements. Some multi-componential approaches incorporate elements and tasks tapping both domains of knowledge (such as the Number Worlds Curriculum, the Building Blocks software, the Mathematics Recovery Programme, and the Numeracy Recovery Programme), while others address a range of basic numerical processing tasks (e.g., Butterworth and Laurillard 2010; Kaufmann et al. 2003; Metzenleitner 2007; and Wilson et al. 2006a, b). Approaches training only one specific area of arithmetic proficiency mainly focus on basic numerical competencies, because these are most likely to impact further arithmetic development and lead to significant improvements in other numerical domains. This is true for the above mentioned approaches by Siegler and Ramani (2009) as well as Fischer et al. (2011).

As we will elaborate on later in this section, basic numerical competencies are assumed to have to be mastered before a training of more elaborate arithmetic procedures can bring about lasting effects. Therefore, based on an extensive diagnostic examination, it seems usually advisable to start an intervention on the level of basic knowledge before administering training on more complex procedures. However, since children with mathematical difficulties often already lag behind their peers in school mathematics, topics currently discussed in class should also be addressed during intervention to avoid an increase of this performance gap and a resulting decrease in motivation. In sum, the everyday challenge in setting up the most appropriate intervention is to keep the balance between improving underlying basic numerical competencies and keeping track with school demands.

5.3 Intervention Material: Tangible Games vs. Electronic Games

For the most part, current intervention programmes attempt to impart numerical knowledge in a game-like and game-based fashion. This way, not only children's motivation is enhanced, but by visualizing concepts and making them accessible for children's own experience, greater learning effects can be achieved. For example, Metzenleitner (2007), Kaufmann and coworkers (2003, 2005), as well as Siegler and colleagues (Siegler and Ramani 2009; Booth and Siegler 2008) implemented tangible game material to improve children's performance, such as board and card games. Additionally, a lot of recent approaches utilize computers as an up-to-date, flexible, and motivating medium for interventions. The Number Race game (Wilson et al. 2006a, b), the Basic Numeracy Games (Butterworth and Laurillard 2010), the Building Blocks software (Sarama and Clements 2002, 2004), and the sensori-motor training by Fischer et al. (2011) convey numerical knowledge in an electronic game format. The Number Race game (Wilson et al. 2006a, b), the Basic Numeracy Games and the Building Blocks software (Sarama and Clements 2002, 2004) are also available online for download.

The benefits of computer-assisted intervention lie not only in their high motivational appeal but also the possibility to use multimedia (Mayer 1999, 2001), thereby allowing for a combination and integration of different presentational formats (i.e., text, graphics, animations, etc.). Additionally, computerized intervention can flexibly adapt to an individual learner's needs and skills, so that mainly tasks which need to be trained are presented. Due to these aspects, computer-assisted trainings can be very effective (Christensen and Gerber 1990; Räsänen et al. 2009). Nevertheless, when designed appropriately, tangible games also provide important benefits: They allow the use of haptic experience for children's knowledge acquisition. In this vein, children can manipulate objects in a real environment with their own hands, which has also been shown to improve performance through self-experience (Jonassen and Rohrer-Murphy 1999). A symbiosis of the two types of intervention material is attempted in the Number Worlds Curriculum (Griffin et al. 1994; Griffin 2003) that combines study workbooks, board games and other tangible intervention material with online games and a CD-Rom containing supporting material.

Another approach at a combination of technological elements with self-experience was attempted by Fischer et al. (2011). Their training required children to respond physically – with a full body movement on a digital dance mat – to a visually presented magnitude comparison task. These two approaches provide examples of how the benefits of the two types of intervention material can be joined – the high motivational appeal of electronic games and the physical self-experience of tangible games.

5.4 Treatment Target: Groups vs. Individuals

As regards the frequency of intervention programmes targeted at either individuals or groups, a clear gradient is observable. Of the approaches reviewed in this chapter, the majority is applied to individuals, only two to small groups (Kaufmann et al. 2003; Metzenleitner 2007), and only one was developed to be run in classroom settings (Griffin et al. 1994). Of course, *interventions* for developmental dyscalculia in classroom settings are hardly advisable. Children with average and high arithmetic proficiency would most probably be unchallenged, whereas the specific difficulties of children with dyscalculia could not be addressed appropriately (Kaufmann and Nuerk 2006). In such a setting, it is not possible to assure that all children understand a certain topic (Kroesbergen and Van Luit 2003), and some children with dyscalculia seem to be unresponsive to such forms of treatment (Fuchs and Fuchs 2001). However, *prevention* programmes (e.g., the prevention portion of the Number Worlds curriculum by Griffin and colleagues; Building Blocks, Sarama and Clements 2002, 2004) that comprise exercises at a medium level of difficulty can be administered successfully in classroom settings (Fuchs and Fuchs 2001). Thereby, the respective elements and tasks should not be too boring for good students but should at the same time prevent students with lower than average achievement from developing more serious math problems. Prevention programmes are, however, not sufficient to remedy difficulties of students already struggling with mathematics or exhibiting clear signs of developmental dyscalculia (Fuchs and Fuchs 2001). These children are much better cared for in individual interventions (Kaufmann and Nuerk 2006; Dowker 2004, 2009). Furthermore, an intervention tailored to a child's specific needs is also realized best in an individual setting where individual difficulties can be properly addressed and sessions can be adapted to the child's speed of progress (Kroesbergen and Van Luit 2003; Kaufmann and Nuerk 2006; Metzenleitner 2007).

Alternatively, interventions in small groups have advantages as well, mainly because they allow for social interaction. Be it a competitive or collaborative setting – working in a group can increase motivation drastically (Beirne-Smith 1991; Bientzle et al. 2009; Johnson and Johnson 1987; Slavin 1983; Webb 1989). Yet, what has to be considered in such a setting is how well children in a certain group fit together. Generally, members of a small group should start intervention at approximately the same level of proficiency, so that social comparison does not generate feelings of inferiority in individual children (Webb 1989).

5.5 The Bottom Line on Existing Intervention Programmes

Because of the huge diversity of existing intervention approaches, it is necessary to evaluate which types of trainings are most effective for which cohort of children. So far, one of the few meta-analyses on this topic was conducted by Kroesbergen and Van Luit (2003). They analyzed a total of 58 studies in which interventions were performed on kindergarten and elementary school children that were affected by what they termed mathematical difficulties. The authors defined an intervention as ‘a specific instruction for a certain period to teach a particular (sub)domain of the mathematics curriculum’. In their analysis, Kroesbergen and van Luit (2003) distinguished between three domains of mathematical knowledge that are mastered at different levels of development. Their first and most basic domain is *preparatory mathematics*, which they described as the skill set that Dehaene (1997, 2001) termed the *number sense*. We suggest that despite slight differences in definition this domain also corresponds to the set of *basic numerical competencies* that we proposed in the first section of this chapter. The second domain, *basic math skills* (not to be confused with the above basic numerical competencies), builds upon these preparatory skills. Basic math skills involve the acquisition as well as automatization of the four basic mathematical operations (i.e., addition, subtraction, multiplication, and division). Finally, Kroesbergen and van Luit termed the third domain *mathematical problem-solving skills*. These are thought to play an important role in the solving of problems by applying previously acquired information. According to Kroesbergen and Van Luit (2003), the majority of intervention studies trained basic mathematical skills (e.g., multiplication), and training of these skills produced higher effect sizes than training of the other two domains (preparatory and problem solving skills). Furthermore, their analysis revealed that effect sizes increased with the age of the trained children. Surprisingly, duration of intervention and total intervention time correlated negatively with effect sizes. As a possible explanation, they hypothesized that short interventions might only train one very specific area of mathematics that is thus taught and learned more thoroughly.

From their meta-analysis, Kroesbergen and Van Luit (2003) drew a number of conclusions. First of all, they emphasized once again the choice of the most appropriate teaching method for a particular intervention. For example, interventions using direct instruction proved to be most effective when training basic math skills. Second, their analysis revealed that, while the use of computer-assisted instruction might be helpful to motivate students, it does not alone suffice to remediate children’s basic difficulties. The full potential of computer-assisted instruction is only unfolded when combined with direct instructions from a teacher. Finally, it seems that children with special needs do not particularly benefit from peer tutoring. Those children depend on instruction by an adult teacher who can better perceive and react to their individual needs.

In our opinion, the meta-analysis by Kroesbergen and Van Luit (2003) highlights a fairly prominent problem of current intervention programmes: Most of them set out at a level that, while termed by the authors as *basic math skills*, is in fact far from what would be called basic taking into account evidence from neuropsychological research (see Sect. 2 of the current chapter). At the bottom of mathematics proficiency is what they refer to as *preparatory mathematics*, which are in our view not just *preparatory*, but essential for any type of numerical and mathematical knowledge acquisition. We thus prefer the terminology we introduced earlier in the chapter, naming them *basic numerical competencies*. Because recent neurocognitive research suggests deficits of dyscalculic children in such basic numerical competencies (see above), we propose that they should receive more attention in future intervention programmes.

Certainly, the meta-analysis of Kroesbergen and Van Luit (2003) provides pointers as to what a successful *intervention* for dyscalculia should or should not encompass. We would like to emphasize, however, that prior to any intervention, *appropriate diagnostics* are required to not only identify children with dyscalculia as such, but also describe their specific impairments properly to allow for a tailored intervention. Furthermore, awareness of the existence of this learning disorder should be increased in teaching professionals as well as parents, so that children with dyscalculia are no longer stigmatized and can receive appropriate support to help them take on their mathematical difficulties. An exemplary step in this direction has been taken in the UK, where the *Every Child a Chance* charity in partnership with the government has begun to develop the *Every Child Counts* programme (see Dowker 2009, for a description). This programme aims to support children with mathematical difficulties all over the country by trained teachers that apply an intervention approach called *Numbers Count*. This intervention approach covers a wide range of areas of number processing and mathematics, and therefore seems particularly promising at prevention and remediation of developmental dyscalculia. The programme is currently in its first year of implementation and its progress can be followed at http://www.edgehill.ac.uk/everychildcounts/. In our opinion, the Every Child Counts programme proves that intervention for dyscalculia can be provided and implemented nation-wide, thereby raising awareness and nurturing research on the topic.

Recapitulating the body of work we considered in this section, we have not yet come upon an existing intervention that meets all three of the criteria we proposed above (see introduction to Sect. 5): (i) an intervention programme should be multicomponential, (ii) adaptable to a child's special needs, and (iii) evaluated regarding its effectiveness for improving arithmetic performance of children with dyscalculia. Currently, there is a large number of broad approaches that, while often covering several areas of mathematical knowledge, were only evaluated as a whole, with no information provided on how efficient single modules are or why they were included in the first place. Moreover, when looking at the tasks involved in most intervention programmes, it seems that results from neurocognitive research are often more or less neglected. The great majority of interventions focuses on training arithmetic operations, with training content being based on curricular requirements. However, a long line of research indicates now that to understand arithmetic operations and successfully manipulate numbers, it is inevitably necessary to have a proper basic numerical foundation to build on (see above; e.g., Dehaene 2009; Holloway and Ansari 2009). Even the most basic arithmetic operations build on even more basic numerical representations and competencies such as the ones introduced above (e.g., McCrink and Spelke 2010; McCrink and Wynn 2004, 2007). Thus, a tailored, theory-grounded training programme should first of all examine how well such basic numerical competencies are developed in a dyscalculic child before training arithmetic operations and facts that build on them, thereby ensuring that children can master and understand complex arithmetic in their later educational career.

To sum up the current section on existing interventions, we claim that there is still the need for a thoroughly evaluated, neuropsychologically grounded multi-componential intervention programme fulfilling all three of the above criteria. However, a couple of interesting trainings have already been developed that could viably contribute to such a programme.

6 Conclusion

In this chapter, we discussed a number of issues regarding developmental dyscalculia that we find particularly important. We thereby went from a definition of its symptoms to diagnostic measures and possible comorbidities and finally, to intervention and training approaches. As a starting point, we emphasized that for a reliable diagnosis of dyscalculia, the distinction between different dyscalculia deficiencies may be beneficial. Such an identification of specific numerical deficits can be helpful for the design and choice of intervention measures. To identify specific deficits we argue that it is necessary to apply diagnostic measures that enable a distinction between them. This, however, is not the only challenge in diagnosing dyscalculia. As there is still no general consensus as to what criteria should be met for a diagnosis, we proposed a solution to this issue that should work for an initial diagnosis as well as the choice of specific intervention (see Table 1). By applying these cut-off criteria, the sensitivity of diagnostic measures may be improved and an individualized intervention can thereby be provided to all children in need of it.

In the course of diagnostics, it is also important to consider possible comorbidities. Although a lot of research has been dedicated to the co-occurrence of dyscalculia with other developmental disorders, this research has not yet provided consistent results. The problem of increasing comorbidity rates for more liberal as well as for stricter cut-off criteria and the problem of participant selection in such studies are only some of the future challenges. Additionally, we emphasized that it is important to consider the percentage of comorbidity of two developmental disorders expected by chance, especially when working with preselected samples.

Finally, once a diagnosis is made, it is important to choose an intervention. We gave an overview of existing remediation approaches for developmental dyscalculia and/or mathematics learning disabilities. Although we may have criticised all of them in one regard or the other, this is not to say that one should not apply them. Indeed, all of the approaches we reviewed train important numerical competencies and may therefore be beneficial for children with dyscalculia. Of course, one has to be careful in choosing the right intervention for a certain child, so as to adapt to its individual needs and challenges.

Coming back to the introduction of this chapter, we would like to emphasize that research interest on dyscalculia is slowly, but nevertheless steadily, growing (see Fig. 1). This is encouraging in several ways as it might induce that (i) diagnostic as well as intervention measures are developed, evaluated, and improved continuously; and (ii) that awareness is raised so that we now know a lot more about developmental dyscalculia than we did just 20 years ago. Even though extensive support for children with developmental dyscalculia is indeed needed, we are on a promising way, as indicated by the example of the Every Child Counts programme in the UK. Generally, we agree with Butterworth and Laurillard (2010) that both the research and teaching community need to work hand in hand to provide successful intervention for every child affected by mathematical difficulties. Furthermore, we are confident that this may be an attainable goal that we are on the right track to achieving.

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New Approaches to Teaching Early Number Skills and to Remediate Number Fact Dyscalculia

Liane Kaufmann and Silvia Pixner

1 Introduction

Good calculation skills are important in Western cultures and pervade both academic careers and every-day-life situations. Beyond being crucial for monetary activities such as settling one's bank and shopping affairs, intact number processing and arithmetic skills are prerequisites to compare quantities, to grasp soccer rankings and to estimate whether the size of your new desk fits into your lab, among others. While in many individuals the acquisition of numerical skills follow a flawless trajectory, around 5% of the general elementary school population is known to experience difficulties in acquiring basic number skills (e.g., Shalev and Gross-Tsur 2001). Importantly, if untreated arithmetic difficulties tend to persist into adolescence and adulthood (Shalev et al. 2005). Severe arithmetic difficulties that already manifest in elementary school are coined as developmental dyscalculia (DD). DD is a recognized developmental disorder that is – according to international disease classification systems – not primarily caused by deficient intellectual abilities and/or poor schooling (American Psychiatric Association 1994). Unlike dyslexia (i.e., reading disorder) dyscalculia rarely manifests as isolated disorder. Rather, affected individuals frequently experience comorbid problems such as attentional, visual-spatial or reading deficiencies. Furthermore, quite often children suffering from DD develop secondary emotional problems that may require them to seek psychiatric support (e.g., von Aster and Shalev 2007). Importantly, DD is not a unitary disease but rather may manifest with quite different performance profiles which led some authors to postulate the existence of DD subtypes (e.g., Geary 2000; Kaufmann and Nuerk 2005; Temple 1991). Beyond deficient numerosity[1] processing (which to the present is the empirically best validated subtype

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[1] The term numerosity denotes the number of a set and thus, represents semantic number knowledge (Butterworth 2005).

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of DD; e.g., Landerl et al. 2004; Rubinsten and Henik 2009; Wilson and Dehaene 2007), other potential core deficits such as deficient fact retrieval (Geary 2000; Kaufmann et al. 2004; Temple 1991) and deficient executive functions (e.g., Kaufmann 2002; Kaufmann et al. 2004; Kroesbergen et al. 2009; Passolunghi and Cornoldi 2008) have been discussed.

The scientific interest in DD increased considerably during the past years which is not surprising given the high prevalence rate of DD (equaling the prevalence rate of dyslexia) and it's persistence into adulthood if untreated. There is converging evidence that even in proficient adults arithmetic skills are complex and require the integrity and flawless interplay of various neurocognitive processes and mechanisms (e.g., Dehaene and Cohen 1995; McCloskey et al. 1985). Nonetheless, it is important to acknowledge that findings derived from adult data may not be applicable to children because children's brains are immature with respect to both structure and function (Karmiloff-Smith 1997). Hence, in order to fully acknowledge the differences between mature and developing brain systems, we need to go beyond adult models by formulating and empirically testing true developmental calculation models (Kaufmann and Nuerk 2005; Rubinsten and Henik 2009).

Overall, the scientific study of DD remains an interesting and challenging field as many open questions regarding the neurocognitive foundations of DD as well as regarding effective remediation programs for DD need to be answered yet.

2 Development of Early Number Skills

A breakthrough finding was that the acquisition of number skills is not restricted to school age. Rather, typically developing preschool children acquire basic number concepts and counting knowledge during every-day-life activities and even toddlers and infants demonstrate rudimentary number skills (for respective overviews, see Butterworth 2005; Kaufmann and Nuerk 2005). Importantly, already infants have been shown to be sensitive to numerosity (e.g., Wynn 1992; Xu 2003). However, infants' numerical understanding is clearly influenced by physical stimulus characteristics such as density, luminosity or physical object size (e.g., Mix et al. 2002). With increasing age and schooling, children grasp the abstract meaning of quantity and learn that object size is irrelevant for the set number (e.g., five oranges are numerically equivalent to five cherries; even non-physical things like holidays are countable etc.).

Another insight from recent findings is that numerosity understanding itself seems to be rather independent from language processing (Brannon 2005; Gelman and Butterworth 2005). The above described evidence showing that rudimentary number skills (e.g., numerical discrimination abilities) are detectable in preverbal infants and non-linguistic primates alike led some researchers to suggest that there is a neurobiological basis for basic numerical competence (Nieder 2005). Nonetheless, other aspects of number processing and arithmetic are clearly language-dependent.

Influence of non-numerical skills on the acquisition of arithmetic. Counting skills emerge with *language* development whereby in the early stages of language acquisition, children use count words without referring to their numerosity meanings. Later on, during kindergarten time, children learn that every number word is linked to a specific numerosity and that the last number word in an increasing number sequence determines the set size (cardinality meaning of number words, Gelman and Gallistel 1978; see also Fuson 1988). Another example for language-dependency is the encoding and retrieval of simple mental calculations (i.e., arithmetic facts). In most Western societies simple one-digit additions and multiplications (e.g., $2 + 5$; 2×5) are learned via phonological repetition and accordingly, are retrieved phonologically from long term memory like other semantic contents. Thus, proficient calculators generally don't solve simple calculations by procedural strategies but rather retrieve them phonologically from long-term memory like any other semantic knowledge (e.g., Imbo and Vandierendonck 2007; Lemaire and Siegler 1995; Siegler 1988).

Beyond language, also executive functions and visual-spatial skills are known to influence the acquisition of number skills. As regards executive functions, it is not very surprising that *monitoring, updating and working memory* that have been suggested to be key aspects of executive functions (Miyake et al. 2000) are important for solving complex multi-digit arithmetic problems and arithmetic word problems (e.g., Bull and Scerif 2001; Passolunghi and Cornoldi 2008). A somewhat more intriguing finding is that also arithmetic fact retrieval (e.g., $3 \times 5 = 15$) requires intact working memory (Lemaire et al. 1996; see also Kaufmann 2002; Kaufmann et al. 2004). This is so because incorrect, but semantically related results ($3 \times 5 = 18$) interfere with the correct answer. Obviously, interference is stronger in non-proficient individuals and children who are less fluent in retrieving previously learnt number facts from long-term memory (Geary 2000; Siegler 1988). Indeed, executive functions have been shown to be a good predictor for counting skills in kindergarten children (Kroesbergen et al. 2009).

Likewise, there is accumulating evidence for the impact of *visual-spatial abilities* on number skills. According to the findings of a recent review of adult neurocognitive studies, Hubbard and collaborators (2005) postulate a close interlink between spatial and numerical competencies (for respective developmental aspects, see Dowker 1996; Kaufmann and Nuerk 2005). Hubbard and colleagues (2005) report findings disclosing neighboring (and even overlapping) brain regions in parietal cortex that support both spatial and numerical processing (see also Walsh 2003). Further evidence for a link between space and number comes from the behavioral experimental literature: Robust reaction time effects like the spatial numerical association of response codes (SNARC) and the numerical distance effect (NDE) support the assumption of spatially oriented mental number representations (small numbers being located on the left, large numbers on the right). The SNARC effect reveals that individuals generally are faster to respond to small numbers with their left hand and to large numbers with their right hand (even if numerical magnitude is task-irrelevant as in parity judgment tasks). The repeatedly reported link between response code and number magnitude is thought to reflect the spatial nature of mental number representations (i.e., small numbers supposed to be located on the left side of the mental number line and large numbers supposed to be located on the right side of the mental number line; Gevers et al. 2010; Treccani and Umiltá 2011). The NDE reflects a negative correlation between reaction time and numerical distance of two to-be-compared numbers: Adults and children alike are quicker to classify the larger number upon viewing 2 and 6 (large numerical distance) than upon being presented with 2 and 3 (small numerical distance; Moyer and Landauer 1967). Generally, the NDE decreases with increasing age and schooling (e.g., Holloway and Ansari 2009; Sekuler and Mierkiewicz 1977). A popular explanation for the NDE is that neighboring numbers on the mental number line impose more interference (resulting in longer response latencies and more errors) than numerically distant numbers. With increasing age and schooling mental number representations become more precise and likewise, interference from neighboring numbers decreases.

3 Remediation of DD

Noteworthy, the term DD is utilized differently by various authors. While some researchers as well as international systems for disease classification (American Psychiatric Association 1994) suggest that DD is a severe and possibly circumscribed form of math learning difficulty (manifesting as a discrepancy between average intellectual abilities and sub-average arithmetic skills), the term mathematical learning disability (MLD) is utilized by others to denote the lower end of the performance distribution on a standardized math test (whereby the lower end is defined rather arbitrarily between 5% and 35% of the distribution, according to sensitivity/specificity issues of the respective study). Though DD and MLD might be distinguishable, for the sake of simplicity we will utilize the term DD only in the remainder of the text.

Another important issue for remediation planning pertains to the fact that unlike dyslexia, dyscalculia rarely manifests as isolated disorder but rather is frequently associated with comorbid disorders (such as attention deficits, dyslexia and socio-emotional problems; Shalev and Gross-Tsur 2001) that need to be considered in treatment planning (see Fig. 1).

Precursor skills for arithmetic ability and disability. There is accumulating research supporting the notion that precursor skills of arithmetic may be reliably detected already in kindergarten children. Even more so, longitudinal studies have shown that specific precursor skills are useful predictors for arithmetic skills acquired later in elementary school. For instance, basic number skills such as number conservation, number comparison, reading of one-digit Arabic numbers and simple addition with concrete objects have been identified to be reliable predictors for later MLD (Mazzocco and Thompson 2005). The study of Mazzocco and Thompson (2005) included 226 children that were examined every year from kindergarten through third grade. Importantly, in this study neither intellectual ability (IQ) nor IQ profiles were found to be predictive for arithmetic abilities.

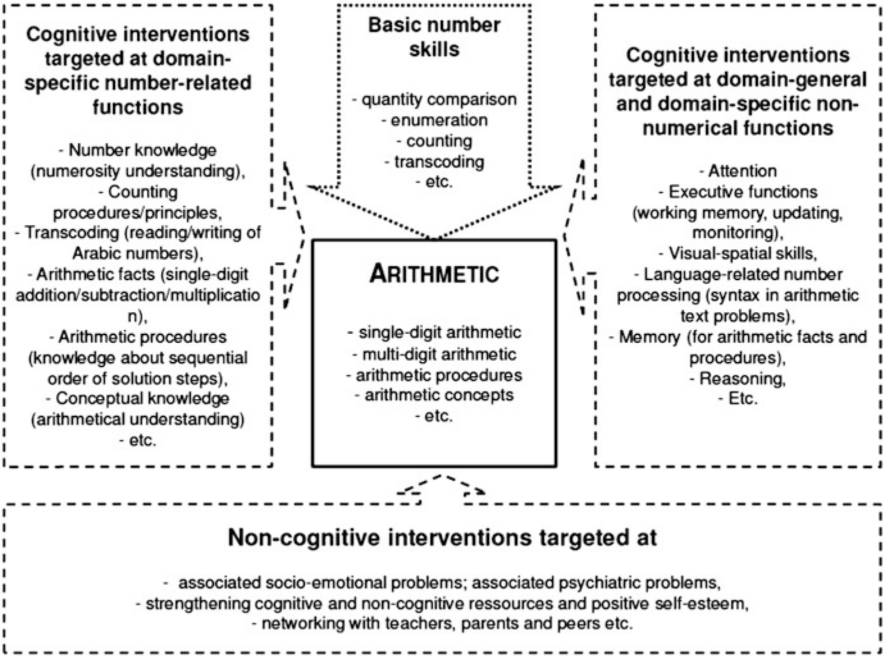

Fig. 1 Schematic representation of key areas for remediation of developmental dyscalculia

The notion of a reliable link between good preschool mastery of quantities and numbers and the flawless acquisition of later arithmetic skills is supported by other longitudinal studies. For instance, Krajewski and Schneider (2009) investigated whether the influence of preschool quantity knowledge is specific and goes beyond the impact of non-numerical skills such as phonological awareness and visual-spatial working memory. In their longitudinal study, 91 children were repeatedly assessed from preschool to grade 3. Findings disclosed that (1) early quantity knowledge was a good predictor of later arithmetic skills and that (2) phonological awareness had no direct influence on later math achievement. Though phonological awareness was found to be related to one subset of early quantity knowledge (i.e., number word sequence) it was found to be unrelated to another subset of early number skills (i.e., mapping of number words to the respective quantities). The latter finding is according to expectation since it is long known in the literature that, among others, the recitation of number words (counting) is tightly linked to language development (Butterworth 2005; Fuson 1988).

The influential work of Siegler and collaborators showed that children's mental number representations become more precise with increasing schooling and hence increasing exposure to formal math (Opfer and Siegler 2007; for similar findings see Moeller et al. 2009). The so-called number line task requires children to estimate the position of a given number on an empty number line (number lines ranging from zero to 10 or from zero to 100 or 1,000). According to Opfer and Siegler (2007), the developmental shift from (immature) logarithmic to (mature) linear number representations denotes a representational change in children's mental number line representations taking place between grades 2 and 4 and that may be important for the further flawless acquisition of complex mathematical skills.

Importantly, the findings of Holloway and Ansari (2009) further corroborate the tight link between early quantity knowledge and later math achievement. In this study, the authors asked participating children to solve both a symbolic and a non-symbolic number comparison task (i.e., to classify the larger of two simultaneously presented Arabic one-digit numbers). Response latencies were then used to calculate the NDE for each participating child. Subsequent correlation analysis revealed that individual differences in the symbolic NDE at first grade were highly predictive of math achievement in third grade. Noteworthy, no correlation was found between (1) the symbolic NDE and reading achievement and (2) between non-symbolic NDE (comparing dot patterns) and math achievement (Holloway and Ansari 2009). Consequently, the latter authors propose that low-level skills (i.e., number processing) might be important for and even predictive of later arithmetic achievement. However, this prediction becomes only evident if the low-level task requires the manipulation of Arabic symbols (but not of dot patterns etc.). Furthermore, the predictive utility of low-level skills emerges solely upon utilizing response latencies but not if considering response accuracies (since even young children generally commit very few to nil errors on this quite easy task).

Early detection and remediation of DD. As already mentioned above, DD tends to persist if untreated. Thus, early identification of DD is of utmost importance. Only if DD is recognized as a learning disability effective remediation plans may be offered to affected individuals. Nonetheless, the majority of existing standardized calculation tests is targeted at elementary school children. Thus, DD frequently is diagnosed in second grade or thereafter because in first grade potential learning difficulties frequently are mistakenly attributed to adaptation difficulties (i.e., switching from the playful kindergarten to the more demanding school environment). If elementary school children experience learning difficulties at early numeracy levels (that are not taught anymore in regular school classes), the knowledge gap between the actual skill level and the required grade-equivalent mastery steadily increases. Beyond seriously hampering the child's learning motivation, the continuous experience of failure in math classes frequently results in secondary behavioral and emotional problems (that not rarely require professional psychological/psychiatric care; Shalev and Gross-Tsur 2001).

Upon acknowledging the importance of early diagnosis (and intervention), diagnostic tools for the identification of young children being at risk for developing DD were developed recently. For instance, the German-language version of the multi-componential dyscalculia test TEDI-MATH (Kaufmann et al. 2009) is targeted at children aged 4–9 (i.e., second last grade of kindergarten to third grade) and provides norms per semester. Furthermore, the TEDI-MATH distinguishes between a so-called number processing and a calculation component (each of which consists of several subtests) that might be differentially affected.

Hence, it is possible to tailor the remediation plan to the diagnostic outcome. Overall, the TEDI-MATH complies with the plea for a comprehensive and detailed diagnosis of DD (or being at risk to develop DD) by enabling the examiner to systematically assess various aspects of number processing and calculation that are crucial for the establishment of effective and economic dyscalculia remediation plans.

Targets of DD remediation. Most researchers and practitioners agree that effective remediation of DD needs to be targeted at the areas of difficulties or in other words, need to focus on the remediation of domain-specific skills (e.g., Dowker 2007; Kaufmann et al. 2003). We wish to stress that though there is accumulating evidence that domain-general abilities such as working memory impact upon the acquisition of number skills in typically developing children (e.g., Kroesbergen et al. 2009; Passolunghi et al. 2008), there is no evidence to date that training of domain-general abilities will have beneficial effects on number processing and calculation skills in children diagnosed with DD (or MLD).

Interestingly, school children experiencing difficulties in mathematics frequently exhibit deficiencies in basic numerical skills which are supposed to be already mastered by that level of schooling (e.g., Dowker 2007; Kaufmann 2002; Kaufmann et al. 2003). If indeed DD manifests as primary deficit in basic number skills (e.g., difficulties to make numerical classifications or estimations) the remediation plan needs to be targeted at the identified areas of difficulties rather than aiming at mimicking the mathematics curriculum. As already mentioned above, children may also exhibit learning impairments in other areas of mathematics (e.g., fact retrieval, procedural arithmetic knowledge, arithmetic concepts).

Taking into account the variability in patterns of difficulty, it becomes apparent that DD is not a unitary disorder but rather may manifest in quite heterogeneous performance profiles (Dowker 2007). Hence, it is not far-fetched to propose the existence of DD subtypes (e.g., Geary 2000; Temple 1991). Nonetheless, empirical evidence delineating the neurocognitive foundations of potential DD subtypes and their implications for the development of remediation programs targeted at addressing potential core deficits remain scarce to date (Kaufmann and Nuerk 2005; Wilson and Dehaene 2007).

4 Empirical Evidence Supporting the Link Between Numerical and Spatial Cognition

In the following, we will report the main results of a preschool intervention study that is described in detail in a German-language journal (Handl and Kaufmann 2008). The main aim of this study was to systematically evaluate intervention effects in typically developing preschool children. For this purpose, we developed two training programs that aimed at fostering either basic numerical or spatial skills.[2] Basic numerical training was targeted, among others, at establishing counting procedures and principles as well as arithmetic understanding for simple additions and subtractions (using visual displays and non-symbolic referents such as tokens). The contents of the spatial training were kept non-numerical and focused on the establishment of visual-spatial skills and directional knowledge (left/right, above/below etc.). Each program consisted of games to be played in small-group settings. Games increased in levels of difficulty and were administered by kindergarten teachers who were carefully instructed and closely supervised by the researchers throughout the duration of the training study. Overall, the training was offered during a semester and was conducted two to three times per week for 30 or 20 min each (respectively). In addition to the two experimental groups (numerical training: n = 24; spatial training: n = 23) a control group (receiving regular preschool training: n = 27) was included in the study. Groups were matched according to age (median age ranging from 5.6 to 5.7 years), sex (almost equal distribution in all groups) and intelligence (median IQ ranging from 94 to 97.5 as measured by the German version of the Culture Fair Test 1/CFT 1, Weiß and Osterland 1997). Furthermore, verbal comprehension and spatial abilities were psychometrically assessed and if deficient, considered as exclusion criteria. Pre-and post-intervention assessment comprised a standardized test tapping early number knowledge (Osnabrücker Test zur Zahlbegriffsentwicklung/OTZ: Van Luit et al. 2001), among others. Importantly, the contents of the basic numerical training did not contain any items belonging to the OTZ tapping early number knowledge.

As depicted in Fig. 2, number skills of both experimental groups improved significantly as a result of the training. Interestingly, group differences were highly significant as regards the following subtests of the early number knowledge test (OTZ): ‘one-to-one correspondence’ ($\chi^2(2, 68) = 10.91$, $p = .004$), ‘use of counting words’ ($\chi^2(2, 68) = 12.39$, $p = .002$) and ‘resultative counting’ ($\chi^2(2, 68) = 10.06$, $p = .007$). Furthermore, performance differences between groups were marginally significant on the subtest ‘application of counting knowledge’ ($\chi^2(2, 68) = 5.82$, $p = .055$).

Pair wise comparisons disclosed that compared with controls, both experimental groups exhibited significant training effects on the subtests ‘use of counting words’ (basic numerical training group: $Z = -2.82$, $p = .005$; spatial training group: $Z = -3.15$, $p = .002$) and ‘resultative counting’ (basic numerical training group: $Z = -2.36$, $p = .018$; spatial training group: $Z = -2.93$, $p = .003$). Thus, both numerical and spatial training proved to be beneficial for the establishment of counting skills. While the subtest ‘use of counting words’ mainly taps procedural counting knowledge, the subtest ‘resultative counting’ captures cardinality knowledge which has been denoted to be a key counting principle (Butterworth 2005; Gelman and Gallistel 1978; Fuson 1988).

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[2] Handl and Kaufmann (2008) reported data from an additional experimental group being subjected to a combined numerical and spatial training. However, due to space limitations only data from the main experimental groups (i.e., those receiving either numerical or spatial training) will be presented here.

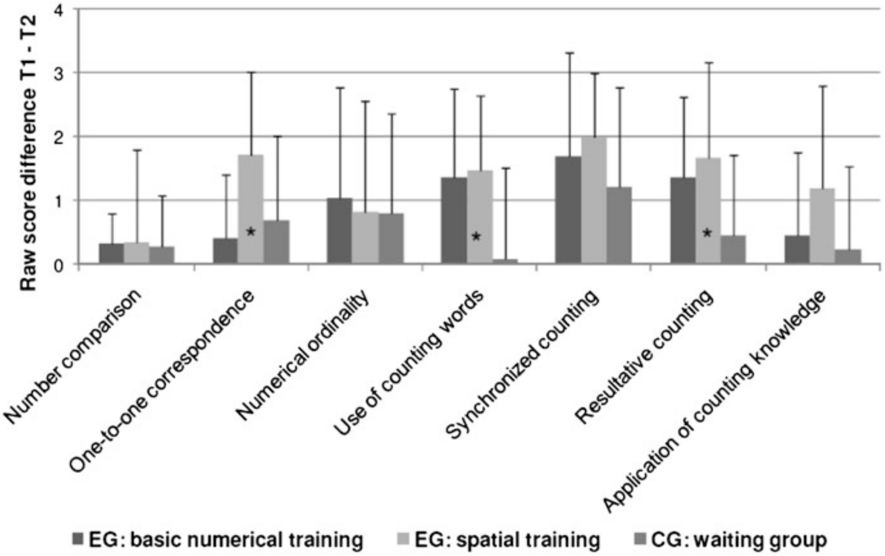

Fig. 2 Training induced performance increases of the three study groups on the subtests of an early number knowledge test (OTZ: Van Luit et al. 2001). Please note that due to participants' characteristics non-parametric statistical procedures were used (Kruskal-Wallis tests for multi-group comparisons; Mann–Whitney-U-Tests for pair wise comparisons)

The only subtest on which training induced performance increases were significantly different between the two experimental groups was the subtest 'one-to-one correspondence' ($Z = -3.17$, $p = .002$), while performance differences approached significance on the subtest 'application of counting knowledge' ($Z = -1.83, p = .055$). In both subtests, performance increases were considerably larger in the spatial training group than in the basic numerical training group (see Fig. 2). Thus, it seems that the ability to correctly assign number words to arrangements of tokens or object sets is clearly influenced by spatial skills. Upon considering that to-be-counted items are laid out in spatial arrangements (either linear/regular or irregular patterns) the impact of (visual-)spatial skills on counting activities comes to no surprise. Rather, the latter findings extend the notion of a close interlink between (visual-)spatial and numerical skills as observed in children's correlational and cross-sectional studies (Dowker 1996; Kaufmann and Nuerk 2005) to intervention studies.

Though our findings clearly show that beyond basic numerical training also spatial training might have beneficial effects on the development of number skills, we would like to stress that our results are derived from typically developing children. Upon acknowledging the crucial differences between typical and atypical developmental trajectories (both with respect to brain structure and function) we strongly doubt that the same results could be obtained in children diagnosed with DD. Finally, it would be desirable to replicate the present findings with a larger sample.

5 New Approaches to Remediating Number Fact Knowledge: Evidence from Multisensory Training

As mentioned already above arithmetic facts (also called number facts; e.g., 3 + 5, 3 × 5) are extensively trained in elementary school and skilled children and adults retrieve arithmetic facts from long-term memory like any other semantic contents (Imbo and Vandierendonck 2007; Lemaire and Siegler 1995; Siegler 1988; see also Ashcraft 1992). In most Western cultures, arithmetic facts are learned by verbal repetition and thus, are encoded and retrieved phonologically. Many children diagnosed with DD experience severe difficulties to memorize and/or to retrieve number facts (e.g., Geary 2000; Temple 1991; Kaufmann 2002; Kaufmann et al. 2004) despite good non-numerical memory. Thus, the development and evaluation of effective programs to remediate fact knowledge is of utmost importance.

As regards remediation of number fact knowledge, the adult literature on acquired calculation disorders reports beneficial effects of drill training (Girelli et al. 1996). The term drill training refers to a training method that emphasizes repetition and aims at re-establishing lost number fact knowledge by pure repetition of problem-answer associations. However, a severe limitation of this learning approach is that after termination of the drill training performance increases (gained during training) are rapidly lost. A plausible explanation for the latter findings is that drill training without simultaneous establishment of arithmetic concepts that underlie the to-be-trained fact knowledge will fail to provide stable intervention effects.

A new and promising approach to remediate arithmetic facts aims at combining number fact training with multimodal (i.e., multisensory) training. There is converging evidence from other research domains that multimodal stimulation or training indeed is superior to training targeted at one modality solely (e.g., Alais et al. 2010; Fairhall and Macaluso 2009).

In the realm of numerical cognition, a first attempt to systematically investigate the effectiveness of multimodal training was a remediation study that aimed to re-teach number fact knowledge in a neurological patient with acquired calculation disorder by linking multiplication problems with color (Domahs et al. 2004). In particular, multiplications were presented in different colors, each color being associated to the unit digit of the respective problem. Thus, the problems 4 × 3, 6 × 2, 8 × 4 were presented in yellow because the unit digit of their solutions (i.e., 12, 12, 32, respectively) is 2 which in turn was associated with yellow. Training encompassed 20 sessions and was offered three times per week. Results revealed that colored presentation of multiplication problems proved to be a valuable cue in facilitating the patient's performance. Interestingly, though training effects generalized to the non-trained operand order (e.g., training the problem 4 × 6 was beneficial for solving 6 × 4) as well as to non-trained problems and non-trained output modality (i.e., training a keyboard response proved to facilitate also verbal production), the learning transfer was restricted to multiplications (i.e., did not generalize to addition, subtraction or division problems; Domahs et al. 2004).

Based on the findings of Domahs et al. (2004) we aimed to develop a comparable training program suitable for elementary school children. In a first pilot study, children were offered an intensive training period that lasted about 8 weeks (one training session per week). Similar to Domahs et al. (2004), numbers were associated with colors, the same color being linked to the same number during the training period (e.g., orange denoting 2). Multiplication facts were presented visually, each constituting number being printed in its respective color. Upon visualizing the results of multiplication facts (that are mostly two-digit numbers) only the unit digits were colored. This procedure is based on the assumption that it might be sufficient to cue the unit-digit which – due to the intransparency between the spoken and written number word system inherent in the German language (inversion) – is first spoken. Thus, we assumed that cueing the unit digit might be sufficient to facilitate children's fact retrieval. For instance, upon being faced with the problem 4 × 3 the color-cue orange might suffice to retrieve the problems solution (i.e., 12). Training was structured into units with specific learning aims (see Table 1).

In order to evaluate intervention effects, third and fourth graders were subjected to a standardized arithmetic test (Heidelberger Rechentest/HRT 1–4; Haffner et al. 2005) before and after training as well as 8 weeks after termination of the training. The follow-up examination aimed at investigating whether potential training effects are stable over time. Furthermore, children were asked to rate on a 5-step scale (mimicking school grades, ranging from very much ["1"] to not at all ["5"]) eight questions tapping the self-perceived utility of the training program (e.g., do you think (a) that colors were helpful cues to learn multiplication facts; (b) that the training improved your multiplication fact knowledge; (c) that the color-training was fun). Overall, 22 children participated in this pilot study (Pixner et al. unpublished). Twelve children comprised the experimental group (EG; receiving color-cue training of multiplication facts) and 10 children constituted a control group (CG). The CG was subjected to a training focusing on attention and memory (comparable as regards number and duration of sessions). Groups were matched on age (EG: *M* 9.53, *SD* .68 versus CG: *M* 9.45, *SD* .52; $t(20) = .31$, *n.s.*) and intellectual ability (as measured by two subtests of the Wechsler intelligence scale for children[3]; EG: *M* scaled score 8.63, *SD* 1.71 versus CG: *M* scaled score 8.25, *SD* 2.44; $t(20) = .42$, *n.s.*).

Results disclosed significant training-induced performance increases on the standardized calculation test HRT. In particular, children of both groups displayed improved performance after termination of training. As regards the scale 'arithmetic operations' the one-tailed results of a 2 (time: before and after training) x 2 (group: EG vs. CG) ANOVA revealed a significant main effect of time

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[3] The two subtests were similarities (indexing children's verbal intelligence) and block design (indexing non-verbal intelligence). As for the current German-language version of the Wechsler intelligence tests used in this study (HAWIK-IV, Petermann and Petermann 2008) no prorating formula exists that allows to prorate a full intelligence quotient from a limited number of subtests, we chose to report mean scaled scores as an estimate of children's intellectual abilities.

Table 1 Conceptual framework of the color-cue training developed by Pixner et al. (unpublished)

Training contents and aims	Activities/games (exemplary)
Associating colors to numbers	(i) Children are requested to produce a collection of learning cards; each card contains a number on one side and a colored cloud on the other side; children are presented with a color (i.e., cloud) and are asked to name the respective number; upon turning the card around the child may check whether the answer was correct or not
Learning multiplication tables (one multiplication table per session) by grasping the multiplication procedure (i.e., repeated addition)	(i) Children are asked to complete a sheet of paper containing an increasing number of two-dimensional pictures of dices (e.g., dices contained 2 dots only in the session targeted at learning the multiplication table of 2); thus, in the first row one dice [with 2 dots] was presented, in the second row two dices [2 dots each] were presented, in the third row three dices [2 dots each] etc.); children are requested to write down the multiplication problem plus answer (e.g., $1 \times 2 = 2$; $2 \times 2 = 4$; $3 \times 2 = 6$ etc.); on this sheet it becomes obvious that multiplication can be solved by repeated addition; (ii) On subsequent sheets children are presented with irregular arrangements of varying number of dices (e.g., all dices containing the same quantity; e.g., 2 dots); again, children are requested to write down the multiplication problem plus answer; here, children are encouraged to quickly enumerate canonical quantities and to calculate the respective result; (iii) Children are presented with pictures of concrete objects (e.g., 2 is represented by a pair of cherries; 3 by three scoops of ice-cream; 4 by four tires of a car); again, children are requested to write down the respective results
Automatization of multiplication fact knowledge (one multiplication table per session)	(i) Children are asked to process a series of cards, each of which containing a problem pertaining to the same multiplication table (e.g., 1×2, 2×2, 3×2) as well as a colored cloud on one side and the result printed with the color cue (only the unit digit being colored) on the other side; (ii) In one session (i.e., aiming at memorizing one multiplication table) all problems of one table are repeated in two series, each of which consists of four trials (once in sequential order starting from the beginning, once in the reverse order, than again in correct order and finally, in randomized order); (iii) Rows of clouds are printed on a paper sheet and children are asked to complete them (enabling them to check whether they still know the color-number associations) (iv) Memory game consisting of pairs of cards (please note that for each multiplication table a separate memory game was constructed): one of which contains the multiplication problem and the other the respective result;

(continued)

Table 1 (continued)

Training contents and aims	Activities/games (exemplary)
	(v) Board game (for each multiplication table a separate game): on each playing field a multiplication problem without result is presented, the background being colored in the matching cue-color (e.g., 3 × 4; background color being orange because 2 is associated with orange)
Motivational aspect of training	(i) At the beginning of the training children receive a training calendar containing empty boxes for each training session; children are encouraged to put stickers into the box denoting the respective training session whenever they mastered the respective training session

Overall, the training consists of eight sessions, each of which incorporates specific training aims and is targeted at establishing one (and in some instances two) multiplication tables

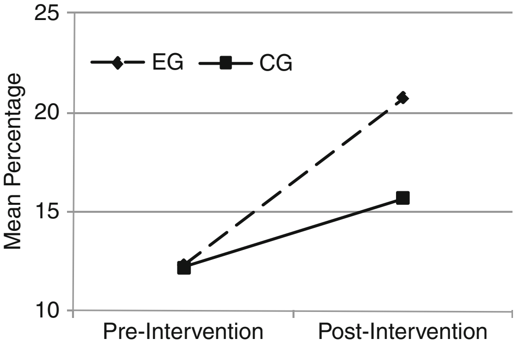
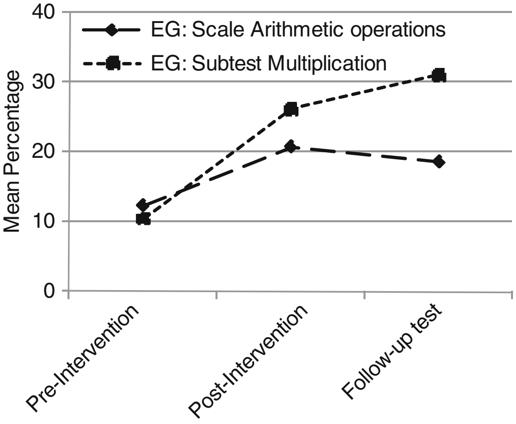


Fig. 3 Training induced performance increases on the scale 'Arithmetic Operations' of the HRT (Haffner et al. 2005). *Abbreviations: CG* control group, *EG* experimental group

($F(1,\ 20) = 3.55$, $p = .037$). However, neither the main effect of group ($F(1, 20) > 1$, *n.s.*) nor the interaction between time and group ($F(1, 20) < 1$, *n.s.*) were significant. Similar results emerged as regards the HRT subtest 'multiplication': the main effect of time was significant ($F(1, 20) = 11.93$, $p = .003$), while the main effect of group and the interaction time x group were non-significant (each $F(1, 20) < 1$, *n.s.*). Nonetheless, as depicted in Fig. 3, children comprising the EG displayed a considerably higher performance increase compared with controls.

There are several potential explanations for our failure to find a significant interaction. First, our sample was rather small. Considering that our results clearly went in the expected direction (i.e., experimental training being more beneficial than control training) it is possible that with larger sample sizes the observed and rather considerable group differences (see Fig. 3) would become significant. Second, the training duration was rather short (i.e., eight sessions, one session per week). It could be assumed that a longer training period would yield larger and possibly also significant performance increases. Finally, the control training was a very strict one since it was targeted at improving attention and memory, both of which are also crucial for learning multiplication facts (e.g., Kaufmann and Nuerk 2005).

Fig. 4 Training induced performance increases and performance stability over time (i.e., 8 weeks after termination of the training). *Abbreviation: EG* experimental group



In order to examine whether training effects observed in children comprising the EG remained stable over time, children's performance after termination of the training program was compared with performance levels 8 week later (*t*-test for dependent samples). Results revealed that performance differences were non-significant as regards performance accuracy (i.e., percentage correct) on the subtest 'multiplication' of the standardized calculation test HRT ($t(20) = -.97$, *n.s.*) as well as regards the scale 'arithmetic operations' ($t(20) = .82$, *n.s.*; see Fig. 4).

As regards the self-perceived utility of the training, results were very promising. For instance, all 12 participating children stated that colors were useful cues to learn multiplication facts (ten children gave the highest rank "1", two children gave a neutral rank of "3"). Eight children thought the training improved their fact knowledge (seven children marking the "1" and one child the "2", three children a neutral "3"). Most importantly, 11 children reported the color-training to be fun (six children rating it as high fun "1"; five children as fun "2"; one child provided a neutral rank "3").

Taken together, the pilot intervention study yielded promising results which encourage future studies aiming at incorporating larger samples and possibly, other types of control groups. Upon considering that our CG received training that surely is beneficial for multiplication training, our control condition was a very stringent one and might have led to an underestimation of the effectiveness of our novel training method targeted at establishing and automatizing multiplication fact knowledge.

6 Discussion and Concluding Remarks

In the present chapter current topics on numerical development and dyscalculia remediation are briefly summarized. An important insight from the current literature is that typical pathways of numerical cognition are influenced by both domain-specific and domain-general abilities. Nonetheless, it remains an open question whether the mutual influence of domain-specific and domain-general abilities remains the same in atypically developing children. In the realm of cognitive (neuro)psychology, systematic and empirically driven evaluations of dyscalculia remediation programs are scarce. What is urgently needed are (1) a true developmental model of number processing and calculation; (2) empirically validated subtype models of DD; and (3) theoretically driven and empirically validated DD remediation programs.

To the present, there is a paucity of studies that systematically investigate the neurocognitive underpinnings of typical and atypical trajectories of numerical cognition and as a consequence, there is a lack of theory-driven and systematic brain imaging guided assessment and intervention studies for DD. However, novel intervention methods incorporating the new media (i.e., smart-tables, smart-boards) and embodiment (i.e., embodied cognition) in addition to targeted cognitive intervention are now being used in pedagogical contexts, and may be promising in the establishment and remediation of numerical skills. The term embodied cognition has been coined to denote the close link between body and mind (i.e., cognition) (Anderson 2003). An early representative of an embodied cognition view is the developmental psychology of Jean Piaget proposing that the emergence of cognitive abilities (including arithmetical skills) is crucially shaped by specific sensorimotor functions. Please note that the latter view is quite different from other stances of cognitive (neuro)science suggesting that cognition is the outcome of abstract information processing mechanisms that are more or less independent of bodily and/or environmental influences (Fodor 1983). In the domain of numerical processing, examples for embodied cognition include finger-based representations of numbers in children and adults (Kaufmann et al. 2008; Lakoff and Nunez 2000). Clearly, future research endeavors are urgently needed to empirically evaluate the effectiveness as well as the specificity of different approaches for DD remediation (e.g., domain-specific vs. domain-general, with and without embodiment).

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Number Sense in Low-Performing Kindergarten Children: Effects of a Working Memory and an Early Math Training

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1 Introduction

Number sense is one of the most important precursors of later math development (Van de Rijt and Van Luit 1998). Recently, much attention is given to the role of working memory in the development of math skills (e.g. Kroesbergen et al. 2009; Passolunghi et al. 2008). However, few studies have taken this into account when investigating possibilities for early screening and intervention (Gersten et al. 2005). In this chapter, the focus is on the role of number sense and working memory in math development, which will be illustrated by two studies that investigated the effects of interventions in children at risk for mathematical learning difficulties.

Children begin to develop mathematical skills already before they receive formal mathematics education in elementary school (Jordan et al. 2006; Van de Rijt and Van Luit 1999). These preparatory mathematical skills are often called number sense. The concept of number sense includes different aspects and is thought to lay the foundation for learning formal math. Dehaene (2001) has defined number sense as the ability to quickly understand and estimate numerical quantities. Other researchers include more preparatory mathematical skills in their definition of number sense. An example of such a definition is given by Van de Rijt and Van Luit (1999), who state that number sense consists of 'Piagetian' aspects (i.e. conservation, classification, correspondation and seriation) and counting skills. Von Aster and Shalev (2007) describe a developmental path of different number sense components: from subitizing through verbal counting and the understanding of digits to the use of a mental number line. Other researchers mention both counting and quantity discrimination as the most important elements of number sense (e.g. Aunio et al. 2005; Bryant 2005; Gersten et al. 2005), which is supported by the empirical study of Jordan et al. (2006).

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In this chapter, we include counting, quantity discrimination and the use of a mental number line in the concept of number sense. Counting consists of several aspects, namely ‘use of number words’ (counting forwards and backwards, using cardinal and ordinal numbers), ‘structured counting’ (counting while pointing to objects), and ‘resultative counting’ (understanding and applying the cardinal principle of counting; Van de Rijt and Van Luit 1999). Quantity discrimination refers to the ability to discriminate between quantities and to compare quantities (Aunio et al. 2005). Around the age of 6, numbers are mapped on numerical quantities (Ansari 2008) and a mental number line develops. These number representations become more accurate over time (Laski and Siegler 2007; Ramani and Siegler 2008; Siegler and Ramani 2008) and enable children to compare numerical magnitudes and to understand the concept of the number line (Laski and Siegler 2007; Ramani and Siegler 2008; Siegler and Ramani 2008).

According to Kalchman et al. (2001), good number sense has certain characteristics which are necessary in formal math: (a) fluency in estimating and judging magnitudes, (b) ability to recognize unreasonable results, (c) flexibility when mentally computing, (d) ability to move among different representations and to use the most appropriate representation. Therefore, good number sense will enhance mathematics learning. In kindergarten, the number sense components counting and quantity discrimination are not well linked, but they seem to be important precursors of later math (dis)abilities. The counting component is related to simple computation, while quantity discrimination is linked to the use of mental number lines. The ability to use a mental number line appears to be dependent on a potentially inherent magnitude representational system (Laski and Siegler 2007). The ability to count and to use counting to determine exact quantities is considered to be another fundamental numerical ability (Gallistel and Gelman 1992).

Number sense trajectories have indeed been found to predict math achievement in first grade fairly well (Jordan et al. 2007; Locuniak and Jordan 2008). In a longitudinal study Jordan et al. (2007) studied the development of skills related to number sense from the beginning of kindergarten through the middle of grade 1. The tasks used involved abilities related to counting, number patterns, magnitude comparisons, estimating, and number transformations. They found that number sense in kindergarten and number sense growth predicts mathematical performance in first grade. More precisely, number sense and number sense growth explain 66% of the variance in mathematical performance in first grade. Locuniak and Jordan (2008) conducted a similar study, but they used number sense to predict mathematical ability in second grade. They concluded that number sense also predicts mathematical ability in second grade. Kavkler et al. (2003) found that number sense, among which were counting skills, at the age of 5 even could predict mathematical performance at the age of 10. Children who performed very low at number sense in preschool, showed significantly lower math scores 5 years later than the children who performed high in kindergarten. In accordance with this, Geary et al. (1999) found that children, who score low on a counting task, also score low on later mathematics. Booth and Siegler (2006) state that being able to accurately and linearly estimate the place of numbers on a number line has a positive effect on the development of children's mathematical skills. Good number sense is a requirement for success in mathematics (Aunio et al. 2005), comparable with phonological awareness being a requirement for success in reading (Gersten and Chard 1999). Therefore, it is important to intervene when children have insufficient number sense skills.

Former research has shown that number sense can be trained, both in typically developing children and in children at-risk (e.g. Van de Rijt and Van Luit 1998). However, the transfer effects to later formal math skills are in general small, especially in children at-risk for math learning disabilities. Recent research has shown promising results in improving number sense by playing numerical games (Ramani and Siegler 2008; Siegler and Ramani 2008; Whyte and Bull 2008). Siegler and Ramani (2008) conducted an experiment to find out whether playing a numerical board game improves the number sense of 4 year-old low-income children. They assessed number sense by the children's number line estimates. The children were assigned to two groups and individually attended four 15 min sessions in 2 weeks. One group had to play a linear board game with squares labelled from 1 to 10. The other group had to play a board game in which the squares represented colors instead of numbers. It was found that the children who had played the linear numerical board game performed better on the number line estimation task at the post test than the children who had played the color board game (Siegler and Ramani 2008). Ramani and Siegler (2008) replicated these findings in a second experiment. They did not only assess number line estimation, but also counting, numerical magnitude comparison and numeral identification. It was found that the children who had played a linear numerical board game showed improvement in these additional tasks too (Ramani and Siegler 2008). In an experiment of Whyte and Bull (2008) a third condition was added, besides the linear numerical board game and the linear color game. In this third condition, the children had to play a non-linear numerical game. Number sense of the children was assessed by counting ability, number comprehension (naming and magnitude understanding) and numerical estimation skills (number line estimates). The results indicated that the children in the two numerical groups performed better on counting ability and number comprehension than the color group. The children who had played the linear numerical game performed better on numerical estimation than the children in the linear color group and the non-linear numerical group. It was also found that the children in the linear numerical group performed better on number naming than the children in the non-linear numerical group. However, this could be due to the range of numbers tested and used in the games. The range of tested numbers was 1–9. In the linear numerical game a range of 1–40 was used, whereas in the non-linear numerical game a range of 1–100 was used (Whyte and Bull 2008).

In summary, it can be concluded that it is important to intervene when children have low number sense, because number sense seems to be a prerequisite for doing well in mathematics. Playing numerical games seems to be a promising method to improve number sense. Low number sense can be caused by a lack of experience with numbers and number related activities, which is supported by research on the mathematical abilities of children from low-income families. In higher income classes, children usually have more opportunities to participate in number related activities (Tudge and Doucet 2004). This leads to children from higher income classes having higher number sense than children from lower income classes (Siegler and Ramani 2008; Tudge and Doucet 2004). However, lack of experience is not the only cause of low number sense in children and low number sense is not the only cause of mathematical difficulties. Cognitive abilities, especially working memory, play an important role in number sense and later mathematics as well. Several studies have pointed out that working memory is related to number sense (Locuniak and Jordan 2008) and mathematical abilities (Bull and Scerif 2001; Gathercole and Pickering 2000; Geary et al. 1999; Locuniak and Jordan 2008; Swanson and Beebe-Frankenberger 2004). Therefore, this study will explore the enhancement of number sense in relation to the enhancement of working memory skills.

Within the working memory model of Baddeley (1996) a storage and a processing component can be distinguished. Although both components are closely related, especially the processing component is very important in academic learning. It is responsible for the monitoring and manipulating of incoming information. This means that the information that the incoming information is memorized and constantly updated with new information. Old information is replaced by new information or the new information is added to the old information and remains activated together (Passolunghi and Pazzaglia 2005).

Working memory is essential in the performance on tasks related to number sense. It plays an important role in counting, because children have to keep track of the counting row, while naming the different numbers and pointing to objects. It is therefore expected that children with better working memory skills, are better able to develop their number sense. And, as a consequence, children who perform relatively bad on working memory tasks will perform accordingly on number sense tasks. Support for this hypothesis was found in a study by Kolkman et al. (2012), who found that in preschool working memory was related to three distinct, though related foundational numerical skills, namely visual/symbolic number line estimation, number categorization, and number comparison. Working memory contributes also to the improvement in number line performance in young children (Geary et al. 2008; Krajewski and Schneider 2009).

Bull et al. (2008) showed that working memory is also related to mathematical performance in first and third grade. This result is supported by several other studies (e.g., Passolunghi and Pazzaglia 2005; Swanson and Beebe-Frankenberger 2004). Rasmussen and Bisanz (2005) found that in preschool children working memory was related to the performance on both verbal math tasks and nonverbal math tasks with irrelevant information. In grade 1 children, working memory was related only to verbal mathematical tasks with and without irrelevant information (Rasmussen and Bisanz 2005). Geary et al. (2007) found that working memory predicted performance on counting tasks, number representation and retrieval when solving addition problems. Furthermore, children with mathematical learning difficulties in general show deficits in working memory (Geary et al. 1999); they have more difficulty with working memory tasks than their peers (Swanson and Beebe-Frankenberger 2004; Van der Sluis et al. 2007) and perform significantly below average on working memory tasks (Passolunghi and Siegel 2003; Swanson and

Beebe-Frankenberger 2004). More specifically, children with mathematical learning difficulties have more difficulty with the storage and at the same time processing of information (Geary et al. 1999). The relation between working memory and math performance continues into adulthood (Wilson and Swanson 2001). Moreover, working memory is related to (later) math abilities independently from general IQ level (Alloway 2009; Alloway and Alloway 2010). Although working memory and IQ are moderately correlated both at kindergarten age and late elementary school age and both variables explain a unique part of the variance in math abilities, working memory at age 5 years is a better predictor of math abilities at age 11 years than either verbal or nonverbal IQ (Alloway and Alloway 2010).

If working memory skills are necessary prerequisites of math ability, it is assumed that improving working memory will lead to better math performance of children. There is not much known about the training of working memory, although some studies have shown that various working memory functions can be improved through training (Dowsett and Livesey 2000; Thorell et al. 2009). Witt (2007) studied the effects of a working memory training on the math skills of 9- and 10-year-old children. The training showed a significant effect on mathematics. The results suggest that improving working memory results in improved mathematical ability. Holmes et al. (2009) demonstrated positive effects of a working memory training on verbal and visual working memory in 10-year olds. Moreover, they found a significant gain in mathematical reasoning skills 6 months after the training was completed. However, until now, little of this research has studied the possibilities of improving working memory skills in young children. However, because working memory training in older children, including children with mild intellectual disabilities shows significant effects, even at a delayed post test (e.g. Van der Molen 2009), it is assumed that working memory is also trainable in younger children.

This chapter will address the question whether working memory can be trained in kindergarten children and whether this adds to the improvement of number sense. Two studies will be reported in which the children received a math (counting or number sense) training and/or a working memory training. The math interventions were aimed at improving the number sense skills of the children, by giving practice in counting and/or playing games which create familiarity with numbers, the number line and quantity discrimination. These activities are assumed to improve number sense based on previous studies which demonstrated that (a) practicing counting skills is very important in the development of number sense (Gersten et al. 2005); (b) estimation of numbers on a number line can be improved by creating familiarity with numbers (Ebersbach et al. 2008) and (c) by playing linear board games (Ramani and Siegler 2008; Siegler and Ramani 2008; Whyte and Bull 2008); (d) playing linear board games also improves the counting skills and quantity discrimination of children (Ramani and Siegler 2008; Siegler and Ramani 2008; Whyte and Bull 2008); (e) classifying and sorting numbers and quantities also has a positive effect on the development of good number sense skills (Laski and Siegler 2007); (f) magnitude understanding of children can be improved by comparing magnitudes and relating these magnitudes to digits (Whyte and Bull 2008).

The working memory interventions were aimed at improving working memory and through this improving number sense skills. All the activities concentrated on working memory, in that they required the children to memorize, process and activate information simultaneously, which is in line with the definition of working memory as given by various researchers (e.g., Kroesbergen et al. 2009; Passolunghi and Pazzaglia 2005). It was assumed that playing games that concentrate on working memory, is useful in enhancing working memory skills, as it has been shown that using (computerized) activities related to the processing and memorization of information are effective in improving working memory (Holmes et al. 2009; Klingberg et al. 2005; Thorell et al. 2009).

2 Method

Two studies with an experimental design are reported. Two experimental conditions were compared in order to examine the influence of the different types of training children received. To be sure that the effect was not caused by maturation, the experimental conditions were also compared to a control condition in which the children received no training. A pre test was used to measure the children's number sense and working memory skills before the training. After the training a post test was used to measure the children's improvement. In the first study, the children received either a counting training or a counting + working memory training. Because the former group was primarily trained on counting skills and the latter group received twice as much instruction time, a second study was conducted in which broader number sense was trained and the number sense and working memory intervention were combined in a training that could be given in the same amount of time as the number sense only training, by adding a number sense content to the working memory training, instead of training working memory and number sense separately.

2.1 Participants

A total of 75 Dutch children from the second year of Kindergarten participated, 30 children in the first study and 45 children in the second study (see Table 1). The mean age of the children was 5.47 years ($SD = 0.30$). For both studies, five schools in the Netherlands were selected. Children at risk for math difficulties were selected on the base of a national preparatory math test (including counting and Piagetian skills). In the first study, a cut-off criterion of below the 25th percentile was used. In the second a cut-off criterion of below the 50th percentile was used. Children with other known (learning) disabilities were excluded. After selection, parents were informed about the research and asked for their permission to include their child in the study. For each study, the children were random divided into three groups.

Table 1 Characteristics of the experimental groups

			Age in months	
	N	% boys	*M*	*SD*
Study 1				
Counting intervention	10	60	66.9	3.1
Counting + WM	10	50	66.9	3.4
Control group	10	40	67.4	3.6
Study 2				
Number sense intervention	15	40	69.1	3.6
NS/WM combined	15	47	70.9	4.0
Control group	15	53	70.3	2.6

2.2 Instruments

2.2.1 Working Memory

The instruments used to measure working memory, asked the children to memorize, process and activate information simultaneously. All the instruments were administered using a computer. Each task consisted of several blocks with an ascending difficulty level. The task moved on to the next block when the child gave at least four correct answers in a block. If the child gave three wrong answers in one block, the task was ended.

Odd One Out

In Odd One Out three boxes with shapes were presented next to each other. One of the shapes was different from the other two and the child had to say which figure was different. Then three empty boxes appeared and the child had to point at the location of the different shape. Each block adds one additional row of figures. The test-retest reliability for Odd One Out is .81 (Alloway 2007).

Keep Track

The Keep Track task was adapted from the task used by Van der Sluis et al. (2007). The child was shown pictures, each of which belonged to one of five categories: sky, fruit, shapes, animals, and toys. The pictures were shown in series of 10. During the series, the child’s task was to name each picture. At the end of the series the child had to recall the last item of certain before mentioned categories. The number of to-be-remembered categories increased from 1 to 4.

Spatial Span

In Spatial Span the child sees two figures. The figure on the right is shown rotated in one of eight ways and has a red dot. The child has to say whether the figure with the red dot is the same as or opposite to the left figure. Thereafter, the figures disappear and three spots are shown. The child has to say on which of these spots the red dot was. Each block adds one additional set of two figures. The test-retest reliability for Spatial Span is .82 (Alloway 2007).

Backwards Digit Recall

In Backwards Digit Recall, a verbally presented sequence of numbers has to be repeated by the child in reverse order. In each block, one additional number is added to the sequence of numbers that has to be recalled. The test-retest reliability for Backwards Digit Recall is .64 (Alloway 2007).

Word Recall Backwards

Word Recall Backwards is equivalent to Backwards Digit Recall, except that words are used instead of numbers.

2.2.2 Number Sense

The instruments used to measure number sense are all adapted from previous studies on different components of number sense: counting, quantity discrimination and number line estimation, as is in line with the definition of number sense given above. In the second study, all tasks were administered using a computer.

Early Numeracy Test-Revised

To measure the counting skills of the children, part of the Early Numeracy Test-Revised (Van Luit and Van de Rijt 2009) was used. The original Early Numeracy Test-Revised consists of nine subscales and has two analogous versions, version A and version B. In this study, only the subscales of version A which measure counting are used, namely: (1) Use of number words, counting forwards and backwards up to 20, using cardinal and ordinal numbers; (2) Structured counting, counting while pointing to objects, recognizing numbers on a die; (3) Resultative counting, counting without pointing to objects; and (4) General understanding of number words, using numbers in everyday situations. Each subscale contains five items. The items are scored with 0 for a wrong answer and 1 for a right answer.

Quantity Comparison

This instrument was used to measure quantity discrimination. The child is required to compare two areas with dots and indicate the area with the highest amount of dots. The dots not only vary in amount, but also in size to examine the size congruency effect which is quite common in this type of tasks (cf. Gebuis et al. 2009). However, the physical size of the presented dots was not related to the score on this task. Therefore, all 30 items were taken into account for the score on this task. For each of the 30 items that was answered correctly, one point was awarded.

Number Line 1–10 and Number Line 1–100

The use of a mental number line can be measured using 'number-to-position tasks' (Whyte and Bull 2008). The child sees a line on the computer screen, with on the left end '1' above it, and on the right end '10' or '100' above it. In Number Line 1–10, the numbers 2–9 are presented in a random order, in Number Line 1–100 10 numbers between 2 and 99 are presented in a random order. The child has to indicate where each number belongs on the line. Linear fit scores were computed by fitting the answers of each individual child to a linear curve (cf. Geary et al. 2008).

2.3 Procedure Study 1

Children were random divided into three groups (a) one group received no special intervention, (b) the second group received an intervention on counting skills, (c) the third group received the same intervention and also an intervention on working memory. Interventions were given in seven sessions of 20 min, within 4 weeks. The children in the counting condition received 7 × 20 min instruction, whereas the children in the counting + working memory condition received 7 × 40 min instruction, both in groups of five children. Pre- and post test consisted of the counting part of the Early Numeracy Test-Revised ([ENT-R]; Van Luit and Van de Rijt 2009) and two different working memory tests, a visual-spatial and a verbal one: Odd One Out (Alloway 2007) and Keep Track (see also Van der Sluis et al. 2007). Both at the pre-test and the post test, the children were individually tested. The assessments took place in a quiet room inside the schools.

2.4 Training Study 1

2.4.1 Counting Training

The counting intervention consisted of seven sessions. In the first session, the counting row up to ten was practiced, and children were asked to place numbers on a number line. The second session continued with counting up to 20. In the third session, children were also asked to place numbers on a number line from 1 to 20. The fourth session also included counting backwards from 10. In the fifth session, counting backwards from 20 was practiced. In the sixth session, children practiced with counting objects. In the final session, all elements were repeated once again.

2.4.2 Counting + Working Memory Training

Children in the counting + working memory condition received the same counting training, and received an additional working memory training. The first three sessions of the working memory intervention consisted of practice with remembering pictures. First, children were asked to remember one picture, followed by two and three pictures. The pictures were presented on a computer screen. The practice items shared some features with the Keep Track task, but did differ in the pictures and categories used. In the fourth, fifth and sixth session, children practiced in recognizing and remembering different pictures, like in the Odd One Out task. In the training, different pictures were used, and children received feedback and – if necessary – help on every item. In all sessions, children also received a verbal task in which they had to remember words. In the final session, all skills were repeated once.

2.5 Procedure Study 2

Children were random divided into three groups (a) one group received no special intervention, (b) the second group received an intervention on number sense, (c) the third group received a combined number sense/working memory intervention. Interventions were given in eight sessions of 30 min, within 4 weeks. The children were trained twice a week for about 30 min in groups of five children. The training lasted for 4 weeks. Pre- and post test consisted of the counting part of the Early Numeracy Test-Revised ([ENT-R]; Van Luit and Van de Rijt 2009), the comparison task and the number line tasks. Four different working memory tests were administered, two visual-spatial ones and two verbal ones: Spatial Span, Odd One Out, Backwards Digit Recall and Word Recall Backwards. Both at the pre-test and the posttest, the children were individually tested. The assessments took place in a quiet room inside the schools.

2.6 Training Study 2

2.6.1 Number Sense Training

In the first week of the training, the counting row up to 10 was practiced. The children also played a game in which they had to connect presented numbers with the corresponding amount of dots. A linear board game was played by using a number line puzzle. In all activities in the second week of the training, the numbers from 1 to 20 were used. The children counted forwards and backwards from 1 to 20. They played a linear board game containing the numbers 1–20. They also had to make a right sequence of paper digits from 1 to 20. In the third week of the training, the numbers from 1 to 20 were repeated. Also, the numbers from 1 to 50 were introduced and practiced. The children counted from 1 to 50. Again, they played a linear board game, but now containing the numbers 1 to 50. Estimating numbers from 1 to 10 on a number line was practiced. In the last week of the training the numbers from 1 to 50 were repeated and the sequence from 1 to 100 was practiced. The children counted from 1 to 100 and played a linear board game containing the numbers from 1 to 100. The children also had to estimate numbers on a number line from 1 to 10.

2.6.2 Number Sense/Working Memory Training

Children in the combined number sense/working memory training received the same amount of instruction time as the number sense only group. The children played games in which they practiced both numerical and working memory skills. Each task trained both number sense and working memory, instead of having separate tasks, as was the case in study 1. In the first week of the training, the numbers from 1 to 10 were practiced. The children played a game, in which they had to remember things that you take on a holiday, and how much they took, for example: ‘I go on a holiday and I take two pyjamas’. The children also played the game Counting Recall. They saw triangles and circles on a computer screen and had to count the circles. After counting, the figures disappeared and the children had to remember how many circles they had seen. A linear board game was played in this training too, containing the numbers from 1 to 10. The children had to throw a dice with the numbers one, two and three on it and they had to remember the number they threw. When all the children had thrown the dice they were asked for the number they threw and they had to take the right amount of steps on the board. Another game that the children played is Memory. On one side of the table there were cards with dots, on the other side of the table there were cards with the numbers 1–10. The children took turns and turned one card with dots and one card with a number each time. They had to find the right pairs. The final game was a sorting game, in which two cards were presented repeatedly, one with a red number and one with the same number in blue. The children had to sort the cards by color and after sorting remember which number was on the cards. In the remaining 3 weeks of the training, the same games as in the first week were used, but with some small differences. In the second week the numbers from 1 to 20 were practiced. In the third week of the training the numbers from 1 to 20 were repeated and the numbers up to 50 were practiced. The holiday game was replaced with a zoo game. The children had to say: ‘I go to the zoo and I see...’ instead of ‘I go on a holiday and I take...’ They could pick a random number from 1 to 20 to tell how many animals they see in the zoo. The linear board game contained the numbers 1–50. In the last week of the training the numbers from 1 to 20 were repeated and the numbers up to 100 were practiced. In the zoo game the children had to use the numbers from 1 to 20 in the right order. The linear board game contained the numbers 1–100. The sorting game used cards with the numbers from 1 to 100. For numbers above 10, only tens were used.

2.7 *Statistical Analysis*

The two studies are analyzed separately. First, the improvement of the different conditions was tested with paired-samples t-tests. Second, to test whether the groups differed on the pretest or the posttest, a multivariate analysis of variance (MANOVA) was carried out with group as factor and the scores on the different tests as dependent variables. Significant results were further analyzed by means of univariate analyses and post-hoc tests. All tests where conducted with $\alpha = .05$. Before the analyses were carried out, the data were explored. Outliers were changed in scores two standard deviations above or below the mean, using the mean and standard deviation of the group the outlier was in.

3 Results Study 1

In Table 2, the descriptive statistics of the pre- and posttest scores are presented. The resuls of the t-tests are also shown in Table 2. Both intervention groups improved significantly on the math test.

However, only the counting + WM condition improved in working memory.

Furthermore, it was tested if the groups differed on the pretest. A MANOVA revealed that the groups did not differ on the pretest scores (Wilks' Lambda = .84, $p = .59$). Multivariate analyses showed a significant main effect for group at the

Table 2 Descriptives and results t-tests of scores on pre- and posttests study 1

	Pretest		Posttest		Difference pre-posttest		
	M	*SD*	*M*	*SD*	*t* (30)	*p*	Cohen's *d*
Counting intervention							
ENT-R	7.60	4.27	12.70	2.58	7.39	<.01	1.45
Odd One Out	5.50	3.31	7.40	2.41	2.69	.03	0.66
Keep Track	4.80	1.62	5.80	1.81	2.54	.03	0.58
Counting ± WM							
ENT-R	5.70	3.30	12.00	2.31	5.80	<.01	2.25
Odd One Out	5.70	2.83	11.80	2.78	8.11	<.01	2.17
Keep Track	4.10	1.45	6.10	.99	4.74	<.01	1.64
Control group							
ENT-R	8.40	4.53	8.70	3.09	0.33	.75	0.07
Odd One Out	7.60	2.27	8.10	2.56	1.86	.10	0.21
Keep Track	4.70	1.77	4.50	1.51	0.41	.69	−0.12

posttest (Wilks' Lambda = 5.05, $p < .01$). Univariate analyses showed that the groups differed on all three measures ($p < .05$). Post-hoc tests showed that children in the control group performed worse than children in both other conditions. On the ENT task, both intervention groups performed significantly better than the control group ($p < .01$), however, the scores of both intervention groups did not differ ($p > .10$). Regarding working memory, the children in the counting only intervention group did not differ from the control group. The children in the combined condition, performed better on the visuo-spatial working memory posttest than the children in the counting only condition ($p < .01$). No significant difference was found between both intervention groups on the verbal working memory task ($p > .10$).

These results demonstrate that the counting intervention showed a large effect on children's counting performance (Cohen's $d = 1.45$). Furthermore, the children who received the working memory intervention showed significant improvement on working memory tasks, moreover, they also improved significantly on counting performance (Cohen's $d = 2.25$).

4 Results Study 2

The descriptive statistics and the results of the t-tests of the pre- and posttest scores are presented in Tables 3 and 4. The children who received the number sense intervention, improved significantly on the ENT-R test, and a trend was visible on the comparison and number line 1–10 test. The combined working memory/ counting group improved on all WM tasks, and on the ENT-R. The control group did not improve during the intervention period.

Table 3 Descriptives and results t-tests of scores on working memory pre- and posttests study 2

	Pretest		Posttest		Difference pre-post		
	M	*SD*	*M*	*SD*	*t*(45)	*p*	Cohen's *d*
NS intervention							
Odd One Out	7.80	2.27	9.93	2.82	3.16	<.01	0.84
Spatial Span	4.80	2.88	5.93	4.40	0.92	.38	0.31
Digit Recall bw	3.53	2.64	5.13	2.56	2.28	.04	0.62
Word Recall bw	3.53	1.96	4.33	0.98	1.82	.09	0.54
NS/WM							
Odd one Out	8.07	3.20	11.60	4.01	3.98	<.01	0.98
Spatial Span	3.87	3.70	6.73	4.83	2.44	.03	0.67
Digit Recall bw	3.53	2.97	5.80	2.62	2.75	.02	0.81
Word Recall bw	3.13	1.89	4.20	1.94	2.54	.02	0.56
Control group							
Odd One Out	7.67	3.13	8.53	2.70	1.55	.14	0.30
Spatial Span	5.13	4.09	6.20	3.75	1.17	.26	0.27
Digit Recall bw	3.93	2.69	5.07	2.43	1.75	.10	0.45
Word Recall bw	3.40	2.17	3.60	1.64	0.44	.67	0.10

Table 4 Descriptives and results t-tests of scores on math pre- and posttests study 2

	Pretest		Posttest		Difference pre-post		
	M	*SD*	*M*	*SD*	*t*(45)	*p*	Cohen's *d*
NS intervention							
ENT-R	7.33	2.92	12.40	3.62	5.65	<.01	1.55
Comparison	23.33	5.79	26.13	2.50	1.83	.09	0.68
Number Lines 1–10	.55	.36	.79	.25	2.05	.06	0.79
Number Lines 1–100	.27	.19	.23	.23	0.80	.44	0.19
NS/WM							
ENT-R	7.60	3.11	10.27	3.37	3.84	<.01	0.82
Comparison	25.40	2.92	26.40	3.91	1.30	.21	0.29
Number Lines 1–10	.66	.31	.62	.35	0.85	.41	0.12
Number Lines 1–100	.25	.21	.24	.21	0.32	.75	0.05
Control group							
ENT-R	6.33	3.06	6.40	3.52	0.12	.90	0.02
Comparison	23.73	5.33	24.93	5.19	1.00	.33	0.23
Number Lines 1–10	.75	.26	.72	.27	1.09	.29	0.11
Number Lines 1–100	.21	.23	.22	.24	0.17	.87	0.04

Secondly, the differences between the groups on the working memory measures were examined. The groups did not differ significantly from each other at pretest (Wilks' Lambda $= .95, p = .97$). Also, no significant multivariate effect was found at posttest (Wilks' Lambda $= .79$, $p = .29$). The groups neither differed significantly from each other at the math pretest (Wilks' Lambda $= .82$, $p = .41$). However, the groups differed significantly at the math posttest (Wilks' Lambda $= .54$, $p < .01$). Univariate analyses showed only an effect for the ENT-R posttest, F (2.42) $= 11.29$, $p < .01$. Both intervention groups outperformed the control group ($p < .01$). However, both groups did not differ significantly from each other ($p > .10$).

These results demonstrate that the number sense intervention had a large effect on children's number sense skills (Cohen's $d = 1.55$). Furthermore, the children who received the working memory intervention showed significant improvement on working memory tasks, and they also improved significantly on number sense skills (Cohen's $d = 0.82$).

5 Discussion

The goal of this study was to investigate whether working memory can be trained in kindergarten children and whether this contributes to the improvement of number sense. These questions were studied in two consecutive studies. Children received either a math (counting or number sense) intervention or an intervention in which both math and working memory skills were practiced. The counting intervention in the first study focused only on counting, while the number sense intervention in the second study also practiced with linear board games, estimation games and number lines. The counting and number sense interventions were very effective, especially for counting skills as measured with the ENT-R (effect sizes 1.45–1.55). It should be noticed, however, that the training did not have a significant effect on other number sense skills, such as quantity comparison or number line estimation, although a non-significant positive trend was found.

A more important question was if children's working memory skills can be effectively trained by a short intervention. Two working memory interventions were implemented. In the first study, children practiced with both verbal and visuo-spatial tasks that shared some features with the tasks administered at pre- and posttest. The effects of this training were large (effect sizes 1.64–2.17). In the second study, the training tasks were made more distinctive from the pre- and posttest measures. Furthermore, the difficulty level may have been higher because a numerical content was added to the tasks. However, the group children that received the working memory intervention, still improved significantly on all four measures (effect sizes 0.56–0.98). The results discussed in this chapter show that working memory can be trained, which is in line with previous studies that showed that working memory can be improved through training in older children (Holmes et al. 2009) but also in preschool children (Dowsett and Livesey 2000; Kroesbergen et al. 2012; Thorell et al. 2009). The present studies show large effects after a relatively short intervention of seven to eight sessions.

The most important goal of the studies described in this chapter, however, was to examine the effects of the working memory training on children's number sense skills. Although both studies yielded positive results, the interpretation is not unambiguous. The results of the first study were very promising. The children who received an additional working memory intervention, showed a large improvement on the counting task (effect size 2.25). Possibly due to the small sample size, it was not possible to find a significant difference with the counting condition, but the effect size indicates a promising result that has important implications for helping children at risk for math difficulties. Of course, the sample size was small and conclusions should be drawn with care. Furthermore, the children in the working memory condition received twice as much instruction time as the counting condition, which may have influenced the results. Therefore, a second study was conducted with a different sample of children. Both interventions were integrated into one, by adding a numerical content to the working memory training, to make the total intervention time the same for the counting condition and the combined condition. This resulted in less total instruction and practice time than for the working memory/counting training in study 1. The second study partly replicated the results from the first study: both groups improved in counting, while no significant differences were found between the two intervention conditions. The groups did not improve in the other number sense components. Besides this, while in the first study the working memory group appeared to be slightly more effective, the opposite was found in the second study. A possible explanation could be the smaller amount of total working memory and number sense instruction time in the second study. Moreover, it is possible that the integration of number sense and working memory tasks has led to less emphasis on the separate components, which has resulted in less improvement. Still, however, the combined number sense/working memory intervention group significantly improved in counting skills, in spite of the smaller amount of total instruction time than in study 1. A cautious conclusion could be drawn that training working memory may have a positive influence on children's math skills.

Another remarkable finding is that the children in the counting conditions, also improved on some of the working memory measures (Odd One Out, Keep Track, and Digit Recall Backwards). A possible explanation is that working memory is also trained in the counting intervention, because working memory is necessary for all math tasks, including those practiced in the intervention. Better math skills may thus lead to better working memory skills, a suggestion that is also made by Witt (2007) based on the results of his study. He found that working memory and math skills mutually influence each other. Besides this, Digit Recall Backwards uses numbers to measure working memory. More familiarity with numbers may lead to better results on Digit Recall Backwards.

From the results of these studies, it appears that training both number sense and working memory is the most effective for helping children at risk for mathematical learning difficulties, but when intervention time is scarce – as it is usually – it is more beneficial to spend this time on a math-specific training than on a working memory training. However, far more research is needed to get further insight in the important underlying processes. For example, there are other processes that could have been influenced by the working memory intervention and in turn influenced number sense. There is some evidence that training working memory also leads to better attention skills (Holmes et al. 2009; Thorell et al. 2009). However, although attention and working memory are related, they both contribute uniquely to the prediction of math abilities (Fuchs et al. 2005). Moreover, it was found in the study of Thorell et al. (2009) that the difference in improvement between the working memory intervention and the control group was larger for working memory skills than for attention. This may lead to the preliminary conclusion that – although attention improves as well – working memory training in the first place improves working memory skills. However, more research is needed to disentangle the influences of training on working memory and attention. Besides this, the present studies were relatively short and no follow-up data are collected. The question would be if the positive effects remain after a no intervention period and what the effects are of an intervention that lasts longer. It can be assumed that the long-term effects of training working memory are larger than the short-term effects, as found in the study by Van der Molen (2009). And finally, it would be interesting to measure the effects of the working memory training also in other domains like reading. If a working memory training has a positive effect on all academic skills, it may be more effective to train working memory than to invest all possible time in domain-specific academic skills.

Thus, although the sample sizes of the described studies are small and the outcomes need cautious interpretation, the results are promising. An intervention focused on the improvement of working memory skills seems to have additional effects on the training of domain specific number sense skills. Future research should further examine the effects of working memory training in the domain of number sense and later math but also in other (pre-) academic skills. This could lead to a better understanding of the development of math skills which will have implications for intervention programs. Instruments for early screening and remediation of math problems should possibly include domain general working memory tasks instead of focusing on domain specific skills only.

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