Dyslexics’ Phonological Processing in Relation to Speech Perception

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2003
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ABSTRACT


The general aim of this thesis was to investigate phonological processing skills in dyslexic children and adults and their relation to speech perception. Dyslexia can be studied at various levels: at a biological, cognitive and an environmental level. This thesis mainly looks at environmental and cognitive factors. It is a commonly held view that dyslexia is related to problems with phonological processing, that is, dyslexics have problems dealing with the sound structure of language. The problem is for example seen in tasks where the individual has to manipulate sound segments in the spoken language, read non-words, rapidly name pictures and digits, keep verbal material in short-term memory, and categorize and discriminate sound contrasts in speech perception. To fully understand the dyslexic’s problems we have to investigate both children and adults since the problems might change during the lifespan as a result of changes in the language system and compensatory mechanisms in the poor reader. Research indicates that adult dyslexics can reach functional reading proficiency but still perform poorly on tasks of phonological processing. Even though they can manage many everyday reading situations problems often arise when adult dyslexics enter higher education. The phonological problems of dyslexics are believed to be related to the underlying phonological representations of the language. The phonological representations have been hypothesized to be weakly specified or indistinct and/or not enough segmented. Deviant phonological representations are believed to cause problems when the mapping of written language is to be made to the phonological representations of spoken language during reading acquisition. In Paper 1 adults’ phonological processing and reading habits were investigated in order to increase our understanding of how the reading problems develop into adulthood and what the social consequences are. The results showed that adult dyslexics remained impaired in their phonological processing and that they differed substantially from controls in their choices regarding higher education and also regarding reading habits. Paper 2 reviews research that has used the sine wave speech paradigm in studies of speech perception. The paper also gives a detailed description of how sine
wave speech is made and how it can be characterized. Sine wave speech is a course grained description of natural speech lacking phonetic detail. In **Paper 3** sine wave speech varying with regard to how much suprasegmental information it contains is employed. Results showed that dyslexics were poorer at identifying monosyllabic words but not disyllabic words and a sentence, plausibly because the dyslexics had problems identifying the phonetic information in monosyllabic words. **Paper 4** tested dyslexics’ categorization performance of fricative-vowel syllables and the results showed that dyslexics were less consistent than controls in their categorization indicating poorer sensitivity to phonetic detail. In all the results of the thesis are in line with the phonological deficit hypothesis as revealed by adult data and the performance on task of speech perception. It is concluded that dyslexic children and adults seem to have less well specified phonological representations.

**Key words:** Dyslexia, speech perception, phonological representations, reading acquisition, sine wave speech, phonological deficit hypothesis, phonological awareness, phonological processing, orthographic processing.
LIST OF PAPERS

This doctoral dissertation is based on the following studies.


INTRODUCTION AND BACKGROUND

During the last century reading proficiency has become increasingly important for people in everyday and professional life. It is hard to imagine full participation in most activities in a modern society without being able to read. Unfortunately some people never reach a functional level of reading ability and therefore have difficulties accessing written information that is obtainable to most people. The negative consequences for educational opportunity, using the internet, reading manuals and instructions, and having contact with authorities are of course serious enough, but perhaps it can also be argued that it is a democratic problem for any society if some citizens can not share important written information.

The problem of achieving reading proficiency has been termed dyslexia and today it occupies a large number of researchers around the world trying to understand the causes behind the problem and how to best remediate problems with reading and writing. Research is conducted both in applied areas directed towards classroom teaching and special education and in more theoretical areas of basic research where one tries to understand and describe the causes behind and factors related to dyslexia.

The general purpose of this thesis is to investigate the causes and consequences of dyslexia. The studies conducted for the thesis primarily try to answer the following questions: 1) what differentiates a group of adults diagnosed as dyslexics in childhood 20 years earlier from same aged controls regarding reading and reading related behaviour, for example, phonological processing, reading habits, educational status, and educational plans? (Paper 1); 2) are dyslexics’ problems differentially revealed when the amount of suprasegmental information is varied in a task of sine wave speech identification? (Paper 2 and 3); and 3) do dyslexic 10 and 15 year old children differ in their categorizations of fricative-vowel syllables, perhaps indicating deviant lexical restructuring during language development? (Paper 4).

Defining dyslexia

In 1887 the German ophthalmologist Berlin first used the term dyslexia to diagnose adult patients with reading difficulties who had suffered brain injury (Høien & Lundberg, 2000). Traditionally the term dyslexia has been defined with excluding criteria. Cited in Høien and Lundberg
(2000, p. 3) the World federation of Neurology in 1968 defined dyslexia as:

“a disorder manifested by difficulty learning to read, despite conventional instruction, adequate intelligence and sociocultural opportunity. It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin”.

One criticism against this kind of definition is that it defines dyslexia in negative terms, that is, it tells us primarily what it does not depend on. A useful definition should instead tell us something about the causes and symptoms of dyslexia. Also, the definition above implies sufficient intelligence as a requirement. In regard to intelligence Stanovich (1991) has reported that IQ is only weakly related to reading skill in a normal population and Høien and Lundberg (2000) report the correlation from several studies to be between 0.30 and 0.40, suggesting that only 10-15 % of the variability in reading skill can be explained by variability in IQ. Cited in Snowling (2000) the Orton Dyslexia Society (ODS) of the USA offered an alternative definition in 1994:

“Dyslexia is one of several distinct learning disabilities. It is a specific language-based disorder of constitutional origin characterized by difficulties in single word decoding, usually reflecting insufficient phonological processing abilities. These difficulties in single-word decoding are often unexpected in relation to age or other cognitive abilities; they are not the result of generalized developmental disability or sensory impairment. Dyslexia is manifested by a variable difficulty with different forms of language, including, in addition to a problem with reading, a conspicuous problem with acquiring proficiency in writing and spelling.”
Snowling (2000) notes that this definition contains several important points; First, it emphasizes the fact that dyslexia is a learning difficulty among others implicating that dyslexia should be considered separately for both theoretical and clinical reasons. Second, it points out the importance of phonological processing difficulties, especially regarding single word decoding in contrast to more general reading comprehension. Finally, it explicitly states that dyslexia encompasses spelling and writing problems. However, also this latter definition falls short of giving enough information for reliably diagnosing dyslexia. The ODS-definition does claim phonological processing problems to be at the core of the disability but still holds a discrepancy criterion. One definition that avoids a discrepancy criterion has been offered by Høien and Lundberg (2000):

“Dyslexia is a disturbance in certain language functions which are important for using the alphabetic principle in the decoding of language. The disturbance first appears as a difficulty in obtaining automatic word decoding in the reading process. The disturbance is also revealed in poor writing ability. The dyslexic disturbance is generally passed on in families and one can suppose that a genetic disposition underlies the condition. Another characteristic of dyslexia is that the disturbance is persistent. Even though reading ability can eventually reach an acceptable performance level, poor writing skills most often remain. With a more thorough testing of the phonological abilities, one finds that weakness in this area often persists into adulthood.”

This definition adds mainly two important criteria: it assumes heritability and also points out that the underlying cognitive processing weaknesses (i.e. phonological abilities) persist into adulthood. Another interesting contribution of this definition is that it explicitly states that
reading involves learning the alphabetic principle. Most useful will a
definition be that combines positive diagnostic markers also encompassing
early signs predicting reading difficulties so that practitioners are given the
possibility to intervene as early as possible with remedial action. Any
definition is of course a description at a theoretical level and has to be
operationally defined. Frith (1997) has summarized a schematic causal
model explicating all involved levels affecting dyslexia; at the biological
level genetic abnormalities might lead to specific deficits at the cognitive
level manifesting itself in poor learning of writing systems which in turn
causes specific behavioral impairments like poor literacy skill. The model
also points out that conditions at the biological level as well as the
cognitive level can interact with environmental conditions. Because
dyslexia is considered a developmental disorder, in contrast to an
acquired, its behavioral manifestations arguably change over time related
to maturation and environmental interactions. It thus becomes important
for research to describe the pattern of changing difficulties across age in
individuals and try to elucidate how biology, cognition and environment
interact to cause a given reading behavior at any age and developmental
stage. Frith (1999) concludes that there is an emerging consensus that 1)
dyslexia is a neuro-developmental disorder with a biological origin:
evidence exists for a genetic and a brain basis; 2) the cognitive bottleneck
seems to be phonological processing; 3) even though biological and
cognitive conditions underlie the reading deficit, environmental factors,
such as writing systems, home environment, and teaching methods have
to be taken into account to fully understand the symptoms at hand.

It should also be noted that the current presentation has largely been
limited to linguistic factors. However, as pointed out by Lundberg (2002)
research is also conducted in fields of automaticity and a possible
cerebellum involvement (Nicholson & Fawcett, 1999; van der Leij & Van
Daal, 1999) and with regard to the magnocellular deficit hypothesis, for a
review see (Stein, 2001).

**Biological explanations and dyslexia**

Several theories and hypothesis are trying to explain the aetiology of
dyslexia. Causal explanations involve investigating the inheritance and
genetic influence in dyslexia. Studies indicate that there is a genetic
predisposition in dyslexia (for reviews see Gayán & Olson, 1999; Fisher &
DeFries, 2002). Preliminary research has proposed that defects on
chromosome 1, 6, 15, and 18 are possible candidates (Wood &
Indications that heritability is a contributing factor also comes from research showing very early markers in newborn infants where ERPs of speech perception have been shown to predict later reading ability (Molfese, Molfese and Modgline, 2001) and ERP responses to pseudoword tokens with varying /t/ duration in an odd-ball paradigm have differentiated infants born to families with a history of dyslexia from those who are not (Leppänen, et al., 2002).

However, even if dyslexia is genetically predisposed we can expect an interaction with environment. Gilger, Hanebuth, Smith, and Pennington (1996) showed that the occurrence of dyslexia in offsprings was almost the same in families where one parent had persisting dyslexia and the other was compensated (i.e. showing functional reading ability in adulthood despite earlier diagnosed dyslexic problems) compared to when one parent was dyslexic and the other was not. If both parents were persistent dyslexic the occurrence of dyslexia in the offspring rose dramatically. It was concluded that not only genetic influence is important but also environmental factors, in this case the fact that an additional parent had reached some degree of reading proficiency although having a history of dyslexia.

Several brain regions have been studied to see if dyslexics deviate from controls regarding both anatomical structure and function. A MRI study conducted by Larsen, Høien, Lundberg, and Ødegaard, (1990) showed that more dyslexics had symmetrical planum temporale compared to controls who instead more often had asymmetrical planum temporale. In a review article Morgan and Hynd (1998) conclude that research has shown that patterns of planum temporale symmetry/asymmetry do seem to differ between dyslexic and nondyslexic individuals and that especially phonological decoding deficits seem to be related to atypical patterns of planum temporale symmetry/asymmetry. Morgan and Hynd (1998) also summarize that further research is needed to establish (1) whether the relationship of atypical patterns of the planum temporale and linguistic ability is specific to dyslexia or if asymmetry covaries with linguistic performance also in a normal population; (2) what asymmetry coefficients hold the greatest functional significance (i.e. interhemispheric or intrahemispheric); and (3) if the dimension of length or area is better associated with differences in linguistic ability.

In a review Pugh et al. (2001) conclude that neuroimaging studies have shown that two posterior reading systems, one ventral and one dorsal region, are disrupted in reading disabled individuals indicated by both reduced activation and disrupted functional connectivity between these areas. The ventral region includes a lateral extrastriate area as well as a
left occipito-temporal area which has been shown to be functionally related to word and pseudoword reading. The dorsal region includes the angular gyrus and supramarginal gyrus in the inferior parietal lobe, and Wernicke’s area. Damage to this temporo-parietal system is known to cause reading inability and is believed to be functionally related to the process of mapping visual information of print onto phonological and semantic structures of language (Pugh et al., 2001). In the light of this a causal model is proposed where reading disability (RD) is explained by an inability to:

“develop a structured temporo-parietal system that can decode effectively, resulting in a failure to establish adequate linkages between phonology, orthography, and meaning. Because the temporo-parietal system does not develop normally, the RD reader subsequently fails to develop a highly integrated word form system in the ventral LH occipito-temporal area. “

It should be noted that since reading represents a highly artificial behaviour and written communication is of historically recent origin in human evolution, one can hardly expect to find a brain area responsible for reading as one would for spoken language. However, this does not mean that dyslexics can not have brain abnormalities responsible for reading since the involved subsystems on which the reading process relies might not be functionally organized or connected in a dyslexic brain. In a non-literate society someone with this kind of disorder would not experience the same functional problems, but might not have the same status if verbal ability was highly valued. There is also an ongoing discussion about whether dyslexia is a unitary neurodevelopmental disorder, largely because the nature and prevalence of dyslexia seems to differ across languages. In a recent PET-study Paulesu et al. (2001) demonstrated that in a task of explicit and implicit reading the same reduced activity in the left hemisphere could be shown for both Italian, French, and English dyslexics. These three languages are believed to differently support reading acquisition due to how closely the written language represents the oral language and data also shows that Italian dyslexics do read better than French and English dyslexics. All dyslexics in the study did however score equally poor relative to controls on reading
and phonological tasks. The results thus indicate a common biological origin. Because various problems with phonological processing is a core marker in dyslexia many researchers have come to focus extensive attention on disentangling how phonological processing relates to reading, reading acquisition and dyslexia.

**The phonological deficit hypothesis**

One of the most important findings in the area of developmental reading research is that it has demonstrated a relation between deficits in phonological processing and reading failure in a large number of otherwise normally developing children (Wagner & Torgesen, 1987; Stanovich, 1988; Snowling, 2000). Phonological processing involves various linguistic operations that make use of information about the speech sound (i.e., phonological) structure of the language. As mentioned earlier this ability appears to be largely independent of general cognitive ability, but highly related to reading development. The various aspects of language processing that have been examined and where a relation has been found between phonological processing and reading achievement include; (1) the explicit awareness of the phonological structure of the language (Lundberg, Olofsson, & Wall, 1980; Sawyer & Fox, 1991), (2) the encoding of phonological information in long-term memory (Kamhi, Catts, & Mauer, 1990), (3) the retrieval of phonological information from long-term memory (Wolf, 1997), (4) the use of speech sound information in short-term memory (Shankweiler, Liberman, Mark, Fowler, & Fisher, 1979; Gathercole & Baddeley, 1990), (5) the production of speech (Elbro, 1994; Stackhouse, 2000).

Reading failure thus seems to be associated with both a metaphonological ability (1), and several other subtle phonological abilities (2-5). Whether these subtle phonological abilities are closely interrelated or represent distinct cognitive abilities still needs more careful examination, but a growing number of studies point to a general phonological deficit (Rack, 1994). This general phonological deficit has been attributed to weak phonological representations and generated the phonological representation hypothesis (Snowling, 2000). Theoretically it seems plausible that efficient storing in long-term memory, resulting in 'high-quality' phonological representations, improves accuracy and speed of retrieval, and speed of retrieval in turn influences how automatically and accurately this information can be coded in working memory. Further, well specified phonological representations might facilitate the development of explicit awareness of this information.
An important question to ask is what tasks differentiate dyslexics from normal readers and thereby might indicate a deficient phonological system.

**Phonological awareness** Theoretically phonological awareness is important since reading novel words of a certain complexity requires (or is enhanced by) the concomitant awareness of the segmental nature and organization of language (Gombert, 1992). Tasks testing phonological awareness ability can for example require a person to segment a spoken word into syllables, complete a word when given only the first syllable, or swap the initial sounds of two words, so-called spoonerisms (John Barker \(\rightarrow\) Bon Jarker). Theoretically phonological awareness can be a precursor, a corequisite, or a consequence of reading acquisition. If research can show that awareness of the phonological nature of language is a prerequisite of reading acquisition and that dyslexics have some deficiency regarding this ability we could identify children at risk before they are taught reading. Morais, Cary, Alegria, and Bertelson (1979) showed that adult illiterates could not complete a phoneme deletion task indicating that phoneme awareness is not a pre-literate ability, but subsequent work by Lundberg (1994) has shown that some pre-literate children do have awareness of phonemes. It seems reasonable to assume a reciprocal relationship between literacy and phonological awareness (Perfetti, Beck, Bell, & Hughes, 1987). Phonological awareness is often operationally defined by tests requiring comparisons of sound elements (i.e., phonemes, syllables or rhymes) and manipulation of these elements independent of the meaning of the words and utterances of which the sound elements are a part. An important issue is not only whether phonological awareness develops independently of written words and letter knowledge, but also if awareness of certain phonological information more effectively predicts success in reading acquisition. If we knew what kind of phonological awareness was needed to predict reading success we might also get an answer to what level of phonological processing is affected in dyslexia. Bryant, MacLean, and Bradley (1990) found that children’s level of phonological awareness at the age of four was predictive of later reading ability suggesting a contribution independent of letter knowledge. Swan and Goswami (1997) compared the ability of dyslexic readers with CA- (chronological age) and RA- (reading age) controls on tasks of phoneme, syllable, and rime segmentation. When results were controlled for naming problems and performance was compared for the words that the children had previously named correctly groups differed only on phoneme
segmentation. This might indicate that phonemic awareness is more critical in predicting reading ability (Høien, Lundberg, Stanovich & Bjaalid, 1995). Beyond the level of awareness also other phonological problems of poor readers have been found, not necessarily requiring phonological awareness.

**Phoneme discrimination** Most phonological awareness tasks require phoneme discrimination which is considered a more basic process and is usually studied by means of nonsense syllables or minimal pairs of words where subjects are asked to identify words or sounds or to judge whether stimulus pairs are identical or not. On a theoretical level it has been assumed that poor phoneme discrimination could be due to indistinct representations, which probably would make words more difficult to remember, to recall, and to articulate. Phoneme discrimination might therefore contribute indirectly through other phonological processes to differences in reading acquisition (Elbro, 1996). Evidence for deficits in phonemic perception comes from severely dyslexic persons who tend to make more deviant categorizations, than normal readers, across the whole continuum of sounds when identifying synthetic /ba/-/da/-/ga/ syllables that are dispersed on a continuum of varying second formant transitions (i.e. a highly unnatural task). Although there is no longitudinal data on the relation between phonemic discrimination and initial reading development, early differences in this ability can not be excluded as being related to later differences in reading acquisition (Elbro, 1996).

**Short-term memory** Verbal short-term memory is another well documented area where poor readers show problems. Poor readers are less able than better readers to retain strings of words, digits, or other material that can be verbally encoded. That the difficulty is fundamentally phonological is indicated both by analysis of errors produced and by the lack of differences between good and poor readers on non-verbal memory tasks (Fowler, 1991; Nelson & Warrington, 1980; Snowling, Nation, Moxham, Gallagher, & Frith, 1997). However, de Jong (1998) argues that dyslexics short term memory problems are of a general verbal nature and not limited to the language domain indicated by dyslexics’ poorer performance also on computational span tasks.

**Naming** Naming involves the retrieval of phonological representations, where the subject has to rapidly and accurately produce the phonological labels for items known to be in the subject’s recognition vocabulary. There is evidence that poor readers are slow in rapid automatic naming and have difficulties naming objects (Denckla & Rudel, 1976; Snowling, Wagendonck & Stafford, 1988). Poor readers make more errors, producing forms phonologically related to the target
words, and perform overall more poorly on these tasks than good readers. According to Elbro (1996) this could be explained if we assume that poor readers possess indistinct or otherwise inefficient representations of words indicating problems with the representations themselves.

**Speech perception and production** One final area of phonological difficulty associated with reading disability concerns speech perception and production tasks. Several studies have found that poor readers have problems with the categorical perception of certain speech contrasts, and also make significantly more errors than good readers when asked to repeat words in noisy listening conditions although the two groups performed equivalently on non-verbal control tasks. Furthermore, poor readers appear to be less able to accurately produce tongue twisters or to repeat phonologically complex or unfamiliar lexical items, suggesting that their production skills may also be deficit (for review see, Fowler, 1991). Snowling (2000) has reviewed research that has looked at dyslexics’ ability to identify and repeat spoken words. Speech perception measures that have differentiated poor readers from controls have involved tasks where participants have had to categorize and discriminate speech sounds and also identify speech under difficult listening conditions. Reading group differences have been shown in tasks of categorical perception of stop consonants, such as /b/, /d/, /g/, /t/ and /p/ (de Weerd, 1988; Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Werker & Tees, 1987), repetition of speech presented with and without noise (Brady, Shankweiler, & Mann, 1983), perception of time compressed speech (Freeman & Beasley, 1978), and speech produced by infants (Lieberman, Meskill, Chatillon, & Schupack, 1985) and perception of sine wave sentences (Rosner et al. 2003). Note that differences between groups sometimes have been small or non-significant (Brandt & Rosen, 1980; McAnally, Hansen, Cornelissen, & Stein, 1997; Pennington, Van Orden, Smith, Green, & Haith, 1990; Steffens, Eilers, Gross-Glenn, & Jallad, 1992). In all it seems that the research so far is inconclusive and that it has been hypothesized that top-down processing providing semantic information might be responsible for the equal performance between dyslexics and control in tasks of word identification. It might also be that different representations are responsible in processes involving speech perception and speech production, explaining why tasks of speech production seem to differentiate better then tasks of speech perception between dyslexics and controls (Hulme & Snowling, 1992). To disentangle the exact nature of processes and representations involved in speech processing related to dyslexia further research is needed. Theoretically it does not seem farfetched to assume that speech-based
representations are responsible for problems in phonological processing if the dyslexic problem is to be understood as concerning preliterate language processing.

Some researchers have come to characterize the deficit as a representational problem where the phonological representations are thought to be indistinct, weakly established or otherwise inefficient (Elbro, 1998; de Gelder & Vroomen, 1991; Fowler, 1991; Snowling, Wagtendonk, & Stafford, 1988). Elbro (1998) argues that dyslexia is caused by indistinct phonological representations where distinctness relates to feature specification so that phonological representations with many distinctive features are more distinct than representations with fewer distinctive features. Elbro (1998) hypothesizes that if dyslexics’ phonological representations are less distinct this might explain many of the above mentioned phonological problems; acquiring phonological awareness of speech sounds, naming speed problems because access to less specified words is slower than to better specified words, and also problems establishing automatic letter-sound correspondences. The Distinctness Hypothesis (DH) claims that the problems of the poor reader are related to phonological representations that are less well specified or distinct (Elbro, 1996). In the context of the DH, a person will not run into problems as long as phonological information can be uniquely identified when speaking or listening to speech. A phonological item is believed to become uniquely identified when it differs from any neighbor by at least one phonetic feature (or alternatively when top-down information helps in identification). So even if a word is not stored with complete feature specification most natural language use (e.g., listening and speaking) will probably proceed problem-free, which could be the case for dyslexics.

It is not clear why the representations become less distinct, but one reason could be that the child’s storing of lexical items during growth of vocabulary is affected by perceptual limitations. Whether the limitation is auditory or linguistic, the resulting stored phonological representations might consequently not become functionally (especially for the reading task) specified and distinct. This in turn could affect accuracy and speed of retrieval of stored phonological information and also influence how accurately and automatic the information will be coded in working memory. Further, poorly specified representations might obstruct the development of explicit awareness of phonological information (Elbro, Borstrom, & Petersen, 1998). Elbro et al. do not claim that the primary cause of indistinct phonological representations is perceptual. It is also pointed out that the DH does not specify whether the problem resides with the phonological representations themselves or with their
accessibility. Distinctness has to be seen as a property of the representation that is functionally determined by both completeness in terms of feature specification and in terms of specificalional similarity to neighbors. According to Elbro, distinctness can be referred to as “the magnitude of the difference between the lexical representation and its neighbors” (Elbro, 1998, p. 149). Empirical evidence for the DH comes from both receptive and productive measures. For example, dyslexic adults were outperformed by controls in a task where they were asked to choose synonyms to a heard word among words that were phonologically similar. Dyslexic adults also read target syllables in a sentence with less distinctness than controls when asked to read aloud as if they read to their children (Elbro, 1998).

From a theoretical view, and in order to explain individual differences, we still have to further define terms like weak, fragile, underspecified, or indistinct representations and inefficient phonological processing (Fowler, 1991).

The relation between speech and reading

De Gelder and Morais (1995) argue that at least three areas of speech processing are of interest when we try to understand how speech-based representations are related to the reading process. First, the nature of the phonological representations in on-line processing, second, the study of short-term memory since studies have shown that problems in verbal short-term memory differentiate between poor and good readers (e.g., McDougall, Hulme, Ellis & Monk, 1994), and thirdly, the development of speech representations. I will concentrate on the relation between speech and reading regarding the first and the third area mentioned above. If the beginning reader is to make use of already present representations of speech it is believed that the representations need to be in the size of phonemes in order to establish an effective so called phoneme-grapheme correspondence (Høien & Lundberg, 2000). Metsala and Walley (1998) and Walley (1993) argue that there is a segmental restructuring going on in an individual’s development of lexical representations as a result of vocabulary growth. The segmental restructuring is believed to occur as a growing number of words in the mental lexicon will overlap in their acoustic properties and thus put an increasing pressure on the system to organize more fine-grained representations. A segmental restructuring into more fine-grained representations is argued to facilitate fast and accurate discrimination of a growing number of lexical alternatives and also support more efficient articulation. One study that has given empirical evidence for lexical restructuring showed that 3- to 5-year-olds were less
sensitive than were 7-year olds and adults to frequency information in fricative noise when identifying fricative-vowel syllables, for example, syllables sounding more or less as /sa/ or /ʃa/ (Nittrouer & Studdert-Kennedy, 1987). The fricative noise was dispersed in 10 steps along a continuum and combined with a vowel that had been separated from a natural syllable starting with one of the end-fricatives of the continuum and therefore containing coarticulatory information of the fricative context from which it had been removed. The younger children to a larger degree used the coarticulation information in the vowel to identify the syllable. Since this coarticulation information is longer in time and also more dynamic compared to the fricative noise the younger children were believed to rely on larger representational segments in the task. Also identification functions were shallower for the younger children indicating that their phoneme categories were less well defined (Nittrouer & Studdert-Kennedy, 1987). Also, a relation between these coarticulatory effects and phonemic awareness has been shown in children with low socio-economic-status (SES) and children with chronic otitis media (OM) (Nittrouer, 1996). The above mentioned studies show that adults compared to children, and control children compared to children with low SES or chronic OM, have steeper identification functions and assign more weight to the fricative-noise spectrum than to the vocalic formant transition when labeling fricative-vowel syllables. The studies by Nittrouer and colleagues have led to the developmental weighting shift model (DWS) (Nittrouer, Manning, & Meyer, 1993). The DWS model suggests that as a child gains experience with a native language the weights it assigns to different acoustic speech parameters will change as a result of a developmental increase in sensitivity to phonetic structure. The tendency to use fricative-noise information is thus believed to reflect a more general developmental change in increased sensitivity to phonetic structure and to be caused by lexical restructuring. The DWS model can be thought of as the perceptual consequence of lexical restructuring. Metsala and Walley (1998) argue that this sensitivity due to lexical restructuring might also be related to the structure of phonological representations believed to be important for reading acquisition and that it could therefore explain reading disability. In the context of the phonological representation hypothesis Swan and Goswami (1997) argue that there are two versions of the hypothesis. The first is called the imprecise representation hypothesis and the second the delayed phonological organization hypothesis. According to the imprecise representation hypothesis all levels of phonological representation are affected; syllabic, onset-rime, and phonemic. According to the delayed phonological organization hypothesis only one or some
linguistic levels might be affected; representations that need to be developed in order for them to support for example phoneme awareness and thereby later reading acquisition. It should be noted at the outset that even if both learning to read and skilled reading capitalize on underlying phonological representations, logically it is not evident what the causal direction is: if we observe poor phonological processing in post-literate individuals we can not be certain that this deficit is not due to reading experience.

The empirical work in this thesis that has tried to answer question about the relation between speech perception, reading ability, and common phonological representations has to a great deal been influenced by the distinctness hypothesis (DH) and the lexical restructuring hypothesis (LRH) which seem to relate to the imprecise representation hypothesis and the delayed phonological organization hypothesis respectively. In order to test the distinctness hypothesis we used a speech identification task utilizing a speech stimulus that lacks most phonetic feature specification, sine wave speech. In order to test the LRH and DH hypothesis and its relation to dyslexia we used sine wave speech as degraded speech and varied the amount of suprasegmental information to see if dyslexics and controls would differ in speech repetition performance. We also used a similar approach as Nittrouer (1996) since data suggested that there was a relationship between representational characteristics and phonological awareness and also between representational characteristics and language experience. Since sine wave speech is perhaps not very well known, a description follows next.

**Sine wave speech**

Most familiar methods of synthetic speech production aim at copying natural acoustic elements as accurately as possible. This makes synthetic speech sound voicelike, despite the mechanical quality of its articulation. In contrast, sine wave replication discards all the acoustic attributes of natural speech, except one: the changing pattern of vocal resonance. By fitting 3 or 4 sinusoids to the pattern of resonance changes (i.e. to the frequency centres of the formants), sinusoidal signals preserve the dynamic properties (e.g., suprasegmental) of utterances without replicating the short-term acoustic products of vocalisation (e.g. fine-grained formant structure). This gives rise to a dual perceptual experience of 3 (or 4) simultaneously varying tones, sounding somewhat like whistlings, and of the linguistic properties of the utterance. For phonetic
perception to occur however, the subjects mostly have to be told that they are listening to synthesized speech.

How then are these sine wave replicas obtained? Starting from the formant patterns in a spectrogram the frequency and amplitude values are derived every 10 msec for the centre frequencies of the first 3 or 4 formants by the method of linear predictive coding (LPC). These values are then hand-smoothed, that is, manually adjusted in some portions to ensure continuity and used as synthesis parameters for a digital sine wave synthesiser. The energy spectra of the sinus tones differ greatly from those of natural or synthetic speech. First, voiced speech sounds, produced by pulsed laryngeal excitation of the supralaryngeal cavities, exhibit a characteristic spectrum of harmonically related values. Because the frequencies of individual sinus tones follow the formant centre frequencies, the components of the spectrum at any moment are not necessarily related as harmonics of a common fundamental. Thus the sinus tone pattern does not consist of harmonic spectra, although natural voiced speech does. Second, the short-time spectra of the sinus tone stimuli also lack the broadband formant structure that is typical of speech (including whispered speech). Formants consist of energy maxima at certain frequencies generated by the resonant properties of the supralaryngeal vocal tract which make some frequency regions contain more energy and neighbouring regions contain less. Because the sinus tone stimuli consist of no more than three sinusoids, no energy is present in the spectrum except at the particular frequencies of each tone. There is no formant structure to the three tone complexes, although the tones exhibit acoustic energy at the frequencies identical to the centre frequencies of the formants of the original natural utterance. Third, the dynamic spectral properties of speech and tone stimuli are quite different. Across phonetic segments, the relative energy of the harmonics of the speech spectrum changes. By following the changes in amplitude maxima of the harmonic spectrum the formant centre frequencies can be computed, but, natural speech signals do not exhibit continuous variation in formant frequency. In contrast to this, each sinus tone follows the computed peak of a changing resonance of the natural utterance.

In sum, the pattern consisting of the three sinus tones is a deliberately abstract representation of the time-varying spectral changes of the naturally produced utterance, although lacking its short-time detail. Consisting of neither fundamental period nor formant structure, the sinusoidal signal consists of none of those distinctive elemental acoustic attributes that are traditionally (e.g., Kluender, 1994) assumed to underlie speech perception. For example, there are no formant frequency
transitions, which cue manner and place of articulation; no steady-state formants, which cue vowel colour and consonant voicing; and no fundamental frequency changes, which cue voicing and stress. Further, the short-time spectral cues, which depend on precise amplitude and frequency characteristics across the harmonic spectrum, are absent from the sinusoidal stimuli (e.g. the onset spectra that is often claimed to underlie perception of place features) (Remez, Rubin, Pisoni & Carrell, 1981). However, Barker and Cooke, (1999) have argued that there is some between-formant correlations in SWS that might act as grouping cues (non speech-specific) revealing a common articulatory origin which could explain the perceptibility of SWS.

**SWS in the context of phonological representations**

Sine Wave Speech (SWS) replicas of natural speech, first developed at the Haskins Laboratory, consist of no more than three or four frequency and amplitude modulated pure tones roughly approximating the frequency center of the first three or four formants in speech. The stimuli have mainly been used in studies investigating perceptual organization of speech (Best, Studdert-Kennedy, Manuel, & Rubin-Spitz, 1989; Carrell & Opie, 1992; Remez, Rubin, Berns, Pardo, & Lang, 1994; Remez, Rubin, Pisoni, & Carrell, 1981; Whalen & Liberman, 1987; Xu, Liberman, & Whalen, 1997), but are well suited for perceptual tasks in the current context. As other areas in psychology, speech research often employs degraded stimuli because of the robustness of the perceptual system and the redundancy of information in speech and hence possible processing weaknesses are revealed more easily if the load on the perceptual system is increased. One might also want to degrade the stimulus because there is an interest in certain perceptual limitations in relation to stimulus characteristics. Sine wave replicas of natural speech are themselves highly degraded and can be used for both purposes since the physical parameters of the stimulus can be manipulated in a large variety of ways (e.g., temporal aspects, frequency and amplitude properties). Also, intelligibility of SWS can be manipulated with instruction, that is, the participant has to be told that he or she is listening to speech, otherwise they often report strange noises etc (e.g., strange electronic music and radio interference) (Remez, Rubin et al. 1981). The SWS stimuli in the present studies have not been manipulated further, as one of the primary objectives was to validate the testing method.

The SWS listening task as used in this thesis is a repetition task where participants are instructed to repeat what they hear, hence the whole range
of processes and related representations from perception to production are presumed to be involved.

In sum, sine wave speech is a course grained description of speech void of most spectral redundancy cueing phonetic features important for effective and accurate speech perception. SWS is a useful measure when trying to investigate the quality of phonological representations since it can be argued that a person having indistinct or qualitatively poorer representations will suffer when identifying a stimulus that lacks many of the important speech cues. It should however be noted that even when speech is highly degraded with respect to phonetic detail, for example suprasegmental cues can probably be used to compensate for the lack of fine grained spectral information in the stimulus (Sheffert, Pisoni, Fellowes, & Remez, 2002).

Objectives of the thesis

The objectives of this thesis has been twofold: 1) to investigate reading related habits in adults that had been diagnosed as dyslexics in childhood; 2) to examine the nature of relation between dyslexia and phonological representations in relation to the distinctness hypothesis (DH) and the lexical restructuring hypothesis (LRH). The first objective is addressed in Paper 1 and the second objective is addressed in Paper 1-3. In order to address the first objective adults who had been diagnosed to have reading problems in childhood were compared to controls who had been diagnosed in childhood to have no reading problems. Questionnaire data is also reported from these adults. The second objective was addresses in three papers. The first (Paper 2) reviews research using the sine wave speech paradigm, partly in order to validate some fundamental speech perceptual principals in this kind of stimulus. Sine wave speech was also used in Paper 3 to test dyslexics’ speech perception of degraded speech that varied in the amount of suprasegmental information. In Paper 4 we investigated categorization performance of fricative-vowel syllables in 10 and 15 year old children who were diagnosed as poor readers or as normal readers.
SUMMARY OF THE PAPERS IN THE THESIS

Paper 1

This study is a follow up on adults who were diagnosed as dyslexics in childhood 20 years earlier at 7 to 8 years of age. The purpose of the study was to investigate if there had been any consequences from their reading problems in childhood on later reading and reading related behavior, such as school history, educational background, current reading habits in various situations, current social and professional status, and future plans.

Two groups of adults were tested. The first group included adults who were diagnosed in childhood as dyslexic (20 years earlier); the selection criteria were based on the discrepancy between Raven’s matrices (non-verbal ability, Raven, 1960) and poor word recognition and/or spelling on two consecutive test occasions six months apart. (see Lundberg, 1985, for details). Participants in the second group, which served as a control group, were selected from the same primary schools as the dyslexic group and matched on Raven but had normal reading ability.

In the original study the groups consisted of 46 dyslexic and 44 control children. About half of the subjects could be found and they were mailed a questionnaire. This questionnaire documented their school history, educational background, social status, job, reading habits and future plans. Twenty-five of these individuals (10 dyslexic and 15 controls) agreed to participate in additional testing. Pairwise tests of differences on childhood variables between the subgroup revisited as adults and not found as adults were conducted in order to rule out any selection bias. The results yielded, with the exception of one comparison, no group differences between found and not found groups. The exception was a significant difference between the revisited and not revisited controls on a word decoding test. However, on the word decoding test the revisited subgroup of controls had a poorer result than their not revisited control peers, so if this difference is caused by selection bias this bias is likely to attenuate any reading-related differences in adulthood between dyslexics and controls. Thus, there was no evidence for a selection bias in the recovered sample. Dyslexic and control subjects were also matched in terms of non-verbal ability for the two Raven test occasions and when comparing between subjects tested as adults and between subjects with only questionnaire data as adults, the revisited dyslexics tend to have lower means than their revisited controls but this tendency was present already at the first Raven test and thus is not likely a selection bias.
Tasks used in the additional testing of the revisited adults

The test battery consisted of various tests tapping phonological processing and reading variables.

**Spelling** The spelling test was constructed to give a quick and “non-offending” measure of spelling knowledge of the Swedish j-sound. Eight low-frequency one- and two-syllable words with regular spelling of the j-sound were used. Swedish spelling generally represents the j-sound with the letters j or g. On occasion the j-sound can be represented by the letters hj, gj, dj and lj. In Swedish, a strict rule-based spelling of the j-sound would give approximately 20% spelling errors. The number of spelling errors was scored and the maximum score was eight.

**Word knowledge** The participants read a word and then had to choose a synonym from one of three alternative written words. The alternatives (all real words) were chosen in order to maximize the phonological similarity between them. The number of correct was scored and the maximum score was 19. This task was adopted from a similar Danish task used by Elbro et al. (1994).

**Digit naming speed** Two lists of 50 randomly ordered digits were read aloud. The mean reading time in seconds for each list was measured. Typically, very few errors were made on this task. The inter-list correlation was .80. The test is similar to the digit naming task used by Snowling et al. (1997).

**Word span** for phonologically confusable words. This test was modeled after Schneider, Küspert, Roth, and Visé (1997) who used it with children. Originally the word span task was developed by Case, Kurland, and Goldberg, (1982). The participants first heard a series of three words, which they were instructed to recall in the correct order. If two three-word sets were recalled correctly the number of words to reproduce was increased by one. Testing stopped if the participant made errors on two sets of the same size. The score was the maximum number of words correctly reproduced. The words consisted of two-syllable nouns and verbs with within each set phonologically confusable structures, e.g. visa syne fina nysa. The maximum score obtained in the sample was six.

**Sound deletion** In this sound elision task, the orally presented word had to be pronounced without a target sound. The instruction was similar to e.g. "Say stop, but without /p/". All of the resulting words were common Swedish words. For two of the items the to-be-deleted phoneme was present in two positions in the word. Both solutions (deletions) were
scored as correct, even if the resulting word was a pseudoword. The number of successful responses was scored, giving eight as maximum score.

**Phonological coding** in word recognition. This task was a paper and pencil Swedish adaptation of the computerized phonological coding task used by Olson, Forsberg, Wise, & Rack (1994). The task was to decide, and underline with a pencil, which one of three or four pseudo-words is a pseudo-homophone of a real word. (That is, “sounds” like a real word). There were four lists of 20 groups (rows) each of three or four word alternatives. Subjects were given two minutes to complete the task. The score was the number of words correctly chosen minus the number of wrong choices. The number of errors was very low, 68% of the participants made no errors and 12% made one error. The maximum score was 80.

**Orthographic coding** in word recognition. This task is a Swedish adaptation of the computerized orthographic coding task used by Olson et al. (1994). The participant had to underline the true word in true word-pseudohomophone pairs. Stimuli were presented on six lists of 20 pairs each. Note that the phonological codes for the pairs are identical so both the word and its pseudohomophone would be pronounced the same in Swedish. Thus, in order to make a correct response the reader must use word-specific orthographic knowledge. The score was the number of correctly chosen words in two minutes minus the number of wrong choices. Errors were more common than in the phonological coding task. Only one third of the participants made no errors. The maximum score was 120.

**Word decoding** For this task the participant had to silently read “chains” of words that were concatenated by deletion of the inter-word blank space. Each chain consisted of two to four words, randomly ordered, and the reader had to mark each word boundary with a pencil. The chains were constructed to have no ambiguity regarding the boundary location and the chains were composed of a large proportion of high frequency words. The number of correctly marked chains in three minutes minus the number of errors were scored. Maximum score was 120. This test is very similar to one of the measures by Miller Guron (1999).

**Proof reading** A simple text with 289 words in 22 sentences had to be read and each misspelled word had to be underlined. The text contained 35 common Swedish homophones (c.f. *there*, *their*, in English) that were misspelled. That is, the wrong word in the homophone pair was used in the text. The score was computed as the number of detected
misspellings in 2.5 minutes minus the number of incorrect choices. The maximum score was 35.

**Reading comprehension** The test consisted of two texts, each written on a standard page and with a difficulty level not above every day newspaper reading. For each text there were two multiple choice questions. The first, with four alternatives, asked the participant to select an appropriate header for the text. The second consisted of six alternative sentences related to the text and the reader had to select the sentences that were true. Four of the alternatives were true; one inference, two paraphrases and one identical to the text. The erroneous alternatives included one highly plausible statement not mentioned in the text and a statement in which one word had been replaced by a word with an opposite meaning. The maximum score was 10.

**Visual motor figure chains** This test was a non-verbal visual-motor task which was, in some aspects, analogous to the word decoding (word chain) task above. Eighty “chains” made by 8 to 14 small figures (generated by a computer font) were presented in two columns on three pages. Within each chain there were two positions where the same figure (character) was repeated. The task was to find and mark each position where the figure was doubled. The number of correctly marked chains in 90 seconds was scored. Maximum score was 80.

**Questionnaire** A 60 item questionnaire was used. Twenty four items recorded various facts about educational history. Eleven items measured preferences for different school subjects and 20 measured the participant’s current habits and behaviors. The remaining items tapped current status for family and job. Both five- and six-point rating scales and yes-no answers were used.

The participants were tested individually in a quite room at the university, except one individual who was tested in an office room at his job. The testing was completed in a single session of approximately one hour, allowing for breaks between the blocks.

**Results and discussion**

The results from the adult testing show that the dyslexics scored significantly lower on all the other measures except on the reading comprehension test, the figure chains, sound deletion and on the short-term memory span. In the word decoding task the number of correct did not differ significantly, but the direction of the difference between the sample means is in favor of the control group. Although the dyslexic adults did not differ significantly from the controls in the number of items
judged correctly, they made significantly more errors in this task. It is likely that there is a trade-off between the errors and speed in this test and a plausible interpretation is that in some sense the dyslexics pay for their speed with a higher error rate.

The effect sizes indicate that the largest single difference is found for word knowledge and for the proof reading variable. However, in more general terms it can be said that the largest effect sizes are found for the phonological variables. The tasks placing high demands on the participants' phonological processing system showed large group differences and the tasks involving more moderate demands on phonological skills tended to discriminate less well between groups. The word knowledge task could be expected to be very sensitive since the task involves both decoding and knowledge of phonologically, and hence also orthographically, confusable words. The effect sizes should only be used in comparisons between the different variables in the present sample because the absolute size of an effect is also dependent on the procedure in the original sample selection.

To summarize, the results for the subsample that took part in the testing session showed that the dyslexics still 20 years later have deficits in low level decoding and spelling skills as well as in phonological awareness and rapid naming.

We now turn to the data from the questionnaire, which was answered by 15 adult dyslexics and 22 normal readers. Group differences were found for amount of reading and writing on the job, a difference that seems to be due to writing in Swedish and reading in English but the difference in Swedish reading was not statistically significant. For leisure time reading there was no difference in amount of reading Swedish but the nondisabled reported more reading in English.

The nondisabled readers reported significantly higher preferences for the language subjects in school; Literature, writing and English. The size of the effect was remarkably large for the rating of Literature. Multivariate analysis of variance (MANOVA) showed no significant differences between groups on the non-language academic subjects (Mathematics, Political science, Chemistry and Science) but the univariate test was significant for all except for Chemistry. For the less academic subjects, Sports, Handcraft and Music the results revealed a rather different picture with no differences between the groups. Finally, when it came to the preference for Special Education the dyslexics reported a higher, although not statistically different, mean value.

When asked to predict, on a five-point scale, the probability of attending a university course within the next 15 years the adults with a
history of reading problems choose a significantly lower value. The results showed no differences between the groups regarding family status, social relationships and a variety of general competencies (like having a driving license, or military service etc.). The occupational status differed between the groups, a difference caused by the existence of 10 university students in the control group but none in the dyslexic group. This fundamental difference between the groups was reflected strongly by the questions tapping the participants’ educational history and their future plans for university courses. The groups’ educational history also differed significantly on the high school level where the dyslexics completely avoided advanced theoretical programs and to a higher extent had chosen practical programs. There were large systematic effects in the choices of advanced versus standard courses in language and mathematics as well as their choice of a third language. Some of the dyslexics also stated that regardless of their own interests, they chose the program expected to put the lowest demands on reading and spelling ability. However, the awareness of the real bases for their decision did not arise until several years later.

The participants self-rating of their academic skills revealed a significant difference for spelling ability. The dyslexics also reported having more problems in second language (English) learning than the controls. The frequency of using a lexicon or dictionary differed greatly between the groups. The adult dyslexics seemed to have a pronounced dislike for the process of trying to find anything according to alphabetical order. The groups also differed in the amount of writing and reading in English in their professional work. This measure is of course also correlated to the fact that more of the good readers are full time students.

There were in fact a few variables where the adult dyslexics in a sense “scored” higher on reading than the controls. One is their behavior in the hypothetical situation of having to learn to operate a new piece of equipment or machine. Here the adult dyslexics more often answered that they would read the whole manual and a few of them answered that they would not read it at all (the difference was however non significant).

Paper 2

This paper is a technical report that reviews research that has used the sine wave speech paradigm in studies of speech perception. A comprehensive account of how sine wave speech is made is also given. Since a description of research on sine wave speech has already been given above I will limit this presentation to a procedural description of how SWS is made and
make a few remarks regarding possible theoretical implications for research on speech perception in general and for the use of SWS in the study included in the thesis.

The first step in obtaining the sine-wave speech replica is to record a spoken sentence or word and transfer this recording into a computer as a sound file. A program capable of spectral sound analysis was employed to estimate the pattern of spectral change of the first three formants (F1, F2, and F3) using an LPC-analysis (Linear Predictive Coding). The result is a record of formant-centre frequency and amplitude values at regular intervals (10 ms) throughout an utterance. This numerical description of the spectra of an utterance is then used as the parameter for a sine-wave synthesis program (the sine-wave synthesis program was originally written and supplied by Liljencrants at KTH, Stockholm). This gives us a pattern of sinusoids, each fit to the frequency and amplitude track of a formant in the natural utterance.

Because this kind of stimulus material (i.e., sine-wave replicas of natural speech), to our knowledge, had not been construed in Sweden before, the first task became to create reliable stimuli that seemed identical/comparable to the American sine-wave sentences that had been down-loaded from the Haskins Laboratory home-page from a perceptual point of view. This means that a sound file of a natural American sentence (i.e., “Where were you a year ago?”) was down-loaded from the Haskins home-page and used to make a sine wave replica in the laboratory at Umeå university and then perceptually compared to the original Haskins sine wave replica which also was taken from the Haskins home-page. This first step proved to be quite successful, that is, when we listened and compared the original SWS version (from the Haskins Laboratories home-page) and our version made from the same natural sentence they sounded almost identical. A second task became to create a set of sine wave replicas from Swedish sentences and words. During the course of this work it became apparent that for some reason not all sine wave sentences or words elicited the same degree of intelligibility. Although very interesting, this finding is considered a secondary problem and effort has instead been put into creating replicas that are not impossible to understand.

It seems obvious that the information conveyed by sine wave speech is more course-grained than the information conveyed by natural speech or synthetic speech. Research indicates that intonation information is at least partly preserved (Remez, 1984). The crucial point of interest seems to be what information in a speech signal is needed to elicit a phonetic percept and what information do our lexical representations need to initiate a lexical search. The picture that seems to emerge is that speech can be
understood as long as frequency and time critical information is preserved although spectral detail is not.

**Perceptual effects of sinus tone stimuli**

What then are the perceptual effects of these sinus tone stimuli? Remez, Rubin, Berns, Pardo, and Lang (1994) point out a variety of perceptual effects when the time-varying frequencies of the formant centres are replicated by sinusoids:

- listeners can simultaneously resolve to the auditory form of the tone analogue of the second formant in a sine wave word as they resolve its phonetic effects; this is a kind of duplex perception;
- listeners identify the resulting tone-complexes as several simultaneously varying tones, as radio interference, as bad electronic music, as equipment failure, as experimenter error, etc. Impressions reported by subjects seem to describe the auditory forms as such, or offer hypothetical events that might have caused such sounds;
- listeners do recognise the linguistic properties of sine wave replicas once asked to attend to them as "synthetic speech";
- the phonetic effects of the tonal analogues are not available from tones presented as singletons; the first and second formant analogues have to be presented as an ensemble for the listener to obtain any phonetic effects;
- slight departure from natural time-variation in sine wave replicas destroys the phonetic coherence;
- the quality of the sine wave voice is reported to be unnatural, far more unnatural than signals produced by conventional speech synthesis;
- the perception of intonation of sine wave sentences (lacking comodulated formants, the natural source of intonation, and the fundamental frequency, which is absent from sine wave replicas of speech) is attributable to the multiple use of the analogue of the first formant; apparently, it is responsible for phonetic information approximate to the lowest oral resonance of natural speech, and it is responsible for the pitch contour of the sentence; whether it is also heard as an auditory form without phonetic attributes is yet to be determined;
- unlike the multistable percepts in the visual system, which alternate (e.g. the reversals of the Rubin vase, the Schroeder staircase, or the Necker cube), the multistable perception of a sine wave word is simultaneous, not successive; one is phonetic (the word or sentence), the other an impression of the auditory forms (several tones changing in pitch and loudness);
- even though most subjects exhibit no problems in perceiving phonetic coherence from the sinusoidal stimuli, there appears to exist large
individual differences in the extent of how much phonetic coherence the subjects exhibit and some subjects even fail altogether (Remez et al., 1994).

What conclusions can be drawn about the perceptual organisation of speech from this line of research? First, by using sine wave utterances it has been shown that phonetic and auditory organisation is independently accomplished. In this respect it can thus be concluded that the auditory account of perceptual organisation fails to rationalise the grouping of acoustic elements composing a speech signal, and prohibits the action of a phonetic mode of organisation independent of the auditory mode. This also implicates that phonetic organisation occurs early in perception and proceeds independently. Second, in large these findings are consistent with some of the criteria of modular function defined by Fodor (1983): The processes of phonetic and auditory organisation are both fast and domain specific. On other grounds however, the principles of modularity are violated: Phonetic perception of tone replicas is not mandatory, nor is the process informationally encapsulated. The former is violated because phonetic perception did not occur unless instructions where given, and the latter because the instructions where able to change the perceptual experience.

In sum, perception of speech seems to be accomplished by resources reserved for determining phonetic attributes, but it seems unlikely that this perceptual mode operates in an orthodox modular way. Further, the function of phonetic organisation is engaged by the occurrence of spectro-temporal patterns specific to linguistically governed vocalisation.

One interesting issue that research on sine wave speech perception has not tried to answer is why there are large individual differences in the ability to understand sine wave speech. This is perhaps not surprising, since the main interest has been focused on the fact that the course-grained character of sine wave replicas are enough to evoke phonetic impressions, and most studies have therefore tried to answer questions related to the perceptibility issue. From our point of view however, amongst others interested in individual differences in reading and writing difficulties, and the related hypothesized phonological weaknesses, the individual differences in sine wave perception are most interesting. It might be that they reflect some perceptual/organizational process in the language system (e.g. reflecting individual differences in representations at some level of linguistic processing).

Contrary to an earlier view (see e.g. Remez, Rubin, Berns, Pardo, & Lang, 1994) it is now argued that sine wave speech contains both phonetic and suprasegmental information from natural speech (Sheffert,
Pisoni, Fellowes, & Remez, 2002). Barker and Cooke (1997) have suggested that individuals who perform well in perceiving sine wave speech have developed listening strategies that the auditory system has developed in order to hear natural speech in noise. It remains to describe how these listening strategies work and what information is used when employing different strategies. It will also be of great interest to see if different strategies can account for the different individual results on sine wave speech perception.

Paper 3

This paper reports a study that attempts to answer at what level of phonological processing dyslexic readers might be deficient. The study used the same participants as in Paper 1 but the focus here is on how phonological processing relates to performance on the measure of sine wave speech repetition. Testing for this paper was administered simultaneously as the testing for Paper 1. A recent study by Rosner et al. (2003) has compared dyslexic adults and controls ability to perceive continuous speech reduced of acoustic information (i.e., sine wave speech) in order to test the hypothesis that dyslexics might have the capability to exploit syntactic or semantic information in these stimuli. Results showed that comprehension of sine wave speech seems impaired in most, but not all, dyslexic adults compared to controls and the authors conclude that a reduced auditory memory capacity might in part explain the deficit (Rosner et al., 2003). Although Rosner et al. start by pointing out that the present intact information in sine wave speech is syntactic and semantic information they do not conclude that dyslexics have problems making sense of this kind of information, in spite of the result and the original hypothesis. However, in light of the different levels of possible weakness in the dyslexics’ phonological system and the data in Rosner et al. it seems possible that not only segmental phonology is affected but also the ability to process suprasegmental cues. By using stimuli that vary in how much segmental or suprasegmental, information they contain it would be possible to test if the results of Rosner et al. are due to a deficit in auditory memory or if the results are due to a deficit in the processing of phonological information.

We have used the same kind of stimulus material as Rosner et al., sine wave speech, and compared adult dyslexics with adult controls. Instead of using only sentences we tested repetition performance for a sentence, disyllabic words and monosyllabic words. Because these different stimuli contain various amounts of suprasegmental information it is argued that
repetition performance will give us an increased understanding regarding the character of a possible difference between poor readers’ and controls’ perceptual abilities. At least three alternative results could extend the findings by Rosner et al. If our data shows that dyslexics perform worse on all sine wave speech material results would indicate that dyslexics have more general perceptual problems. If on the other hand results show that there is no difference in performance between groups regardless of amount of suprasegmental information in the stimuli this might indicate that Rosner et al.s’ results are purely due to short-term memory problems. Finally, if results show a differentiation of groups in the relation between repetition performance and amount of suprasegmental information in the stimuli so that dyslexics had more problems repeating stimuli with less suprasegmental information, this might indicate that dyslexics have more specific perceptual problems. Results will also be discussed in relation to the distinctness hypothesis and the segmentation hypothesis.

Our main purpose was to investigate if the relation in repetition performance between dyslexic and controls changes when the amount of suprasegmental information in the stimuli is varied. This paper therefore adds to the studies conducted on the relation between speech perception and dyslexia in general and to the findings of Rosner et al. in particular.

Tasks

The variables used were the same as in Paper 1 except for the questionnaire which is only presented in Paper 1 and the sine wave repetition task which is only presented in this paper, Paper 3. An example of a sine wave speech sentence we used is given in Figure 1.

In all the sine wave stimulus material consisted of one sentence (seen in Figure 1), eight disyllabic and four monosyllabic words. The sentence had five syllables. The following material was used in this order (with English translations in parenthesis): *var var du igår* [where were you yesterday], *pappa* [father], *gemma* [old woman], *gul* [yellow], *gubben* [the old man], *grön* [green], *kicka* [kick], *mamma* [mother], *röd* [red], *dumma* [plur. of *dum*], *dubben* [the knob], *titta* [look], *blå* [blue]. Immediately before testing the participants were presented with one disyllabic word and one sentence with seven syllables in order to get familiarized with the sine wave speech stimuli. They were all told what the word and sentence was. When testing started all participants heard the sentence, disyllabic- and monosyllabic words in a mixed order. The order was the same for all participants. Scoring was done so that one point was given for each correct syllable in a correct position and half a point for each correct
phoneme in a correct position. The maximum score for monosyllabic words was four, for disyllabic words 16, and for the sentence five.

Figure 1. Sine wave analogs to the first, second, and third formant of the sentence “Var var du igår” [Where were you yesterday].

Results and discussion

Results showed that dyslexics scored significantly lower on almost all reading and phonological decoding measures. Noteworthy is that the dyslexics did not differ from the controls in reading comprehension, visual motor figure chain, or the SWS repetition task. The effects sizes indicated that the largest difference was found for the proof reading variable followed by the vocabulary variable. Success on both these tasks is believed to rely on well-established and effectively functioning orthographic representations and processes. Further indications for poor orthographic skill are the results on spelling, orthographic coding, and word decoding. All these tasks can be assumed to put higher demands on the reader than would a normal reading situation, indicated by the normal performance on reading comprehension. However, also the tasks that more directly try to measure phonological processing skill differentiated between the two groups. The phonological decoding tasks involved digit naming speed, initial phoneme analysis, phonological coding, and sound deletion. Only sound deletion did not differentiate between groups, perhaps due to inclusion of more high frequent words than in the initial phoneme analysis.
task. This interpretation is however not obvious since it implies that the task was easy and the performance in the two groups should then perhaps reached ceiling levels. Since not both tasks of phonological awareness differentiated between groups no simple conclusion can be drawn regarding differences in phonological awareness.

Results demonstrated that dyslexics’ poor reading was not revealed through a simple reading comprehension test but very clearly in almost any reading task that puts high demands on exact and efficient orthographic and phonological processing.

When analyzing the results on sine wave speech repetition it turned out that one dyslexic scored extremely well on the sine wave measure compared to both the other dyslexics and controls, especially on the words with one syllable. This participant had the highest score for monosyllabic words, \( z = 2.5 \) from the dyslexic mean, and the second highest score overall for all participants when summarizing the different scores on sine wave speech repetition and was therefore treated as an outlier and not included in the analysis. Zero scores were obtained by four dyslexics and two controls for monosyllabic words, none in any group for disyllabic words, and by two dyslexics and one control for the sentence. When omitting the outlier in the dyslexic group it can be seen that there was a significant difference between groups on monosyllabic words, \( t(20) = 2.17, p < .05 \), but not for disyllabic words or the sentence. There were differences in means between groups also for disyllabic words and the sentence but these differences were far from statistically significant. If we would have included the dyslexic outlier the statistically significant difference between groups on monosyllabic words disappeared, \( t(20) = 1.06, p = .30 \), but the pattern of results still holds: group differences decreased with increasing suprasegmental information in the stimulus and the marked difference between groups was for monosyllabic words.

Because the order of the three different kinds of stimuli was not manipulated, that is, monosyllabic words, disyllabic words, and the sentence were presented in the same mixed order for all participants we could not use stimulus type as a factor to perform a repeated measures ANOVA.

The results of this study indicate that performance on tasks of speech repetition in dyslexia is dependent on the amount of suprasegmental cues in speech. Dyslexics were outperformed by controls when listening to and repeating monosyllabic words but not when the stimuli contained disyllabic words or a sentence. These results are consistent with the idea that dyslexic have problems dealing with phonological information at a
segmental level but not at a suprasegmental level which we believe is implied by the segmentation hypothesis (e.g., Fowler, 1991; Walley, 1993) and which has been discussed by Ramus (2001). Our results do not support the results by Rosner et al. (2003) because we could not find a group difference for the sentence. The results in Rosner et al. were unclear regarding whether group differences were only due to short-term memory problems or also more general perceptual problems dealing with the analysis of phonetic content in speech. The reason why Rosner et al. could not show that dyslexics have less problems analyzing speech with sufficient suprasegmental information is because they used sentences so long that the dyslexics were punished due to poorer short-term memory function. Our results are consistent with the original hypothesis by Rosner et al. (2003) which stated that there might not be any group differences for sentences because poor readers might be able to compensate when the stimulus contains more than just segmental information.

**Paper 4**

This study was conducted in order to test the hypothesis that poor reading is related to inadequate lexical restructuring. As mentioned above earlier studies where participants had to categorize fricative-vowel syllables have shown several interesting and in the context of dyslexia potentially related results. First, younger children are more inclined to attend to coarticulatory information in the syllable than older children and adults. This is believed to reflect that the younger children have not yet developed lexical (phonological) representations detailed enough to utilize the fricative information in the fricative-vowel syllable but instead focus on the vowel’s coarticulation content (Nittrouer, 1992; Nittrouer & Studdert-Kennedy, 1987). Second, there is a relation between the coarticulatory effects and phonological awareness in children with low socio-economic status (SES) and children with chronic otitis media (OM) (Nittrouer, 1996) and between coarticulatory affect and phonological processing (Nittrouer, 1999). Children with chronic OM, low SES background and children with poor phonological processing demonstrate the same pattern of performance as younger children, that is, they seemed to rely more on the dynamic information in the transition of the vowel than in the static fricative noise compared to controls.

In order to extend and replicate the finding by Nittrouer and colleagues we investigated 10 and 15 year old dyslexics and controls. Dyslexics have, as mentioned above, been hypothesized to be deficient in their phonological representations and processes and we wanted to see if
also dyslexics’ perceptual weighting strategies would prove immature. The question seemed plausible because dyslexics are known to have poor phonemic awareness and to be deficient in phonological processing and thus might perform similar to the OM, low-SES and poor phonological processing children mentioned earlier. This could also extend the finding from Gruber and Olofsson (2003) on what aspects of the syllable that caused difficulties for poor readers. If dyslexics and controls have different developmental weighting strategies this might indicate that the dyslexics’ problems are at the level of processing and representing phonemic information. In accordance with the findings of Nitttrouer and colleagues we also expected to find shallower identification functions for dyslexics compared to controls but no such differences due to age. The results in Nitttrouer and Studdert-Kennedy (1987) and in Nitttrouer (1999; 2002) showed that the development in weighting strategies decreased after the age of seven and eight indicated by the fact that there was only a small or no difference between adults and 7 to 10 year old children. We would therefore expect no difference between our 10 and 15 year old children regarding weighting strategies and if so replicate the previous findings.

**Tasks**

A continuum of voiceless fricatives from a dental /s/ to a dorso-palatal/velar fricative /ʃ/ was created using the formant synthesis model developed at the Department of Speech, Music and Hearing at KTH in Stockholm (Carlson, Granström, & Hunnicutt, 1982). The first and second fricative formant frequencies and bandwidths as well as the frication source level (i.e., the amplitude) were varied in nine steps from a /s/ to a /ʃ/. These fricative noises were 230 ms in duration. Subsequently, a set of CV syllables was formed by splicing a natural vowel (i.e., /ɛ:/ produced by one male speaker with the synthetic fricatives. The stimuli consisted of synthetic fricative noises, concatenated with natural /ɛ:/ vowel portions taken from a male speaker saying /sɛ:/ or /ʃɛ:/ . The first fricative formant frequency ranged from 1525 Hz to 4675 Hz in nine 350-Hz steps. The fricative noise was removed from each natural token, and the vocalic portion was then combined with each of the ten synthetic noises, making 200 stimuli (10 fricative noises x 2 vocalic portions x 10 tokens of each). The vowel portions were 490 ms and 510 ms in duration thus making each stimulus 720 ms and 740 ms in duration.
The children had to listen to one syllable at a time (out of 20 possible different syllables) and decide if they heard /sɛ:/ or /sə:/ from a list of 200 randomly presented items (syllables). Spoken responses were written down by the experiment leader.

Results and discussion

A probit analysis was conducted in order to get the frequency value at which the participants responded 50% /sɛ:/ and /sə:/, and in order to get the probit regression coefficient indicating the slope parameter. The difference between boundary points of the two probit functions (i.e., at which the participants responded 50% /sɛ:/ and /sə:/) was used as a measure of transition effect, that is, a measure of how much each participant had relied on the transition in the vowel when categorizing the syllables. Because the only difference between the two probit functions was the transition information identical functions would imply that only fricative noise information had been used and the greater the difference between functions the greater the transition effect. The slope parameter was a measure of how consistent the participants had categorized the syllables, that is, if they responded with the same syllable identity each time the heard the same item. The slope parameter was thus believed to indicate a more general sensitivity to the fricative spectrum. An inspection of our response data showed that some individuals did not reach a response level of 50% /sɛ:/ or /sə:/ when the syllable vowel had originated from a natural /sə:/ syllable. These response data belonged to nine individuals; one 15 year old dyslexic, three 15 year old controls, one 10 year old dyslexic, and four 10 year old controls. For these individuals the probit analysis resulted in frequency values higher than the maximum frequency level for any fricative noise in the material, that is, higher than 4675 Hz. For these nine individuals the value entering the analysis was set to 4675.

A MANOVA showed a main effect on the /(s)ɛ:/ slope for diagnosis group, F(1, 59) = 4.81, p = .032, and close to an interaction effect on /(s)ɛ:/ slope, F(1,59) = 3.61, p = .062. Dyslexics thus seem to be poorer at categorizing these fricative-vowel syllables, especially when the vocalic part of the stimulus originated from a natural /sɛ:/ syllable. All other effects were far from significant with F-values ranging from .005 to 1.45. This means that neither diagnosis (dyslexic or control) nor age (10 or 15 years old) had any effect on transition performance. As mentioned earlier for
nine of the participants data analysis showed that the assumptions for a probit analysis were not met. Of course replacing these individual values with the maximum value of 4675 violates the method. In order to investigate the reliability of these values a second and different analysis was conducted. In this analysis the frequency of /sɛ:/ responses were counted for the two conditions, that is, when the syllable contained coarticulatory information from /sɛ:/ or /.shapes/. Since all things else were equal (i.e. fricative noise being used), it was believed that the difference in amount of /sɛ:/ responses between the two conditions would reflect use of the coarticulation information in the vowel. This new measure was correlated with the values from the probit analysis giving \( r = .99 \). Additional MANOVA analysis using this new measure revealed the same pattern of results as the analysis with the measures from the probit analysis. It should be noted that the frequency analysis does not assume categorization since the frequency values do not depend on a categorization boundary, as was the case with the probit analysis.

We had predicted that there would be a difference between groups so that dyslexics would assign less weight to the fricative noise compared to controls when categorizing fricative-vowel syllables as indicated by transition effect. Our results did not show such a difference. We also predicted that controls would show higher sensitivity to the fricative spectrum compared to dyslexics as indicated by slope coefficients. This prediction was met. Finally we predicted that there would be no difference between groups regarding age on weight assigned to the fricative noise or on sensitivity to the fricative spectrum. This prediction was also met.

The experiment was designed to test specific predictions arising from the hypothesis that individuals with dyslexia have less segmented phonological representations compared to controls. Dyslexics should therefore assign less weight to a static fricative noise and instead use the dynamic properties of the transition present in the vowel when categorizing fricative-vowel syllables. The hypothesis was empirically motivated by research showing a relation between poor phonological awareness and phonological processing, and weighting strategy (Nuttrouer, 1996; 1999). The hypothesis was further motivated on theoretical grounds from claims made by Metsala and Walley (1998) that gradual segmental restructuring of lexical representations is crucial for the development of phonemic awareness and that the problems dyslexics show with phonological processing can be explained by deficits in lexical restructuring. It was assumed that the lexical restructuring model (Metsala & Walley, 1998) is related to the developmental weighting shift model
(Nittrouer, Manning, & Meyer, 1993) in the way that developmental changes in weighting strategy describes the perceptual consequences of lexical restructuring.

At least one question arises from these results. Why did our dyslexics seemingly use the same information when categorizing fricative-vowel syllables, but yet show less sensitivity to the fricative spectrum? It is possible that there is more to the phonological problems in poor readers than lexical restructuring and the corresponding developmental weighting shift. Elbro (1996; 1998) and Snowling and Hulme (1994) have proposed that children need well-specified phonological representations in order to establish links between the letters of the printed word and the sounds of the spoken word. Our results might be explained if we assume that poor readers’ phonological representations are not necessarily different regarding segmental size but perhaps instead concerning phonetic detail, that is, that they are less specified in terms of how well they can be distinguished from any lexical neighbor. Elbro (1998) has proposed the distinctness hypothesis according to which distinctness can be understood in terms of the magnitude in which a representation differs from its lexical neighbors. Magnitude should here be interpreted as degree of uniqueness in representational specificity. In line with the distinctness hypothesis we would then not necessarily predict that dyslexics make use of different linguistic information in the speech signal compared to controls but that they would perform worse if the task was to distinguish between similar speech stimuli. This is what our results indicate. Dyslexics used the same information to categorize the stimuli but showed poorer sensitivity to the fricative spectrum indicated by shallower slopes. Our results showed a correlation between the use of fricative noise and sensitivity to the fricative spectrum. It does not seem farfetched to assume that someone who is sensitive to the fricative spectrum is also more inclined to use the fricative in the categorization task. However, only between 13% (i.e., for /s)s:/ slope and transition) and 28% (i.e., for /s)s:/ slope and transition) of the variation in one variable accounts for the variation in the other. It should be noted that although the lexical restructuring model assumes that the reason for dyslexics poor phonological processing is deviant lexical restructuring, one might assume that children at the age of 10 and 15 have developed functional segmentation for some speech sounds but not for others. We therefore do not rule out the lexical restructuring model as a candidate for explaining dyslexics poor phonological processing. Had we used a different set of contrasts we might have seen a group difference in weighting strategy. Future studies need to further examine the relation between linguistic constraints and reading skill as proposed by Perry and
Ziegler (2000) and the role of lexical structure for the development of phonological representations necessary for reading acquisition.

In sum, dyslexics and controls used static fricative noise information to the same extent when categorizing fricative-vowel syllables dispersed along a /s/-/s/ continuum. This indicates that 10 and 15 year old dyslexics do represent the fricative as a segment in the same way as controls. Dyslexics did however respond less consistent to identical stimuli, perhaps showing less sensitivity for the fricative spectrum. Thus, although dyslexics have the fricative represented, perhaps the representation is poorly specified making retrieval ambiguous.

GENERAL DISCUSSION

One objective of this thesis was to gain more knowledge from a longitudinal perspective about adult dyslexics’ reading related habits and reading abilities. Another purpose was to investigate the relationship between dyslexics processing and representation of speech and their reading ability. I will address the former objective first and thereafter turn to the latter.

**Adult and dyslexic**

Are the problems with reading the same in childhood and later as one becomes an adult? Our study as well as previous studies show that teenagers and adult dyslexics might develop seemingly functional reading ability, both subjectively and objectively, but still fail in tasks of phonological processing, even when they have entered college (Gallagher, Laxon, Armstrong, & Frith, 1996). It is also interesting that some individuals reach higher education although they perform poorly in tasks of for example non-word reading (Snowling, Nation, Moxham, Gallagher, & Frith, 1997). Although these compensated dyslexics perform within the range of normal reading ability it is likely that they will reach a “ceiling” in reading ability sooner than normal readers; if not before, this will likely show up in higher education. Both the results in Gallagher et al. and in Snowling et al. showed that the dyslexics performed poorly on non-word reading. Why is this of special interest? Well, because university studies imply reading a lot of novel material, containing many unknown words, the task of reading an academic text might sometimes be equal to reading non-words.
Of course, as the data from our study show, many dyslexics will probably due to early experiences with reading failure not even consider higher education, even if they potentially have the cognitive ability to do so. It thus seems to be a matter of great concern to remediate reading problems at an early age so that reading experience in the first school years becomes a positive experience and perhaps gives the child the self confidence necessary to imagine future studies. Also, when the adult dyslexic reaches university and is forced to realize his or her limitations, we need to compensate for the lack of remediation in earlier school years. This is already done in many universities where the dyslexic for example has the opportunity to be given oral exams instead of in a written form and get some of the literature in a recorded spoken form. This is however not a long-term solution since this kind of help is not realistic out in everyday life situations. The only long-term solution is to provide remedial reading instruction and the sooner it is done the better.

There is unfortunately not much research done on the effect of remediation on adult dyslexics. Leij (1994) concluded from computer assisted instruction in Dutch students that reading disabled students made only small improvements compared to control conditions. It seems obvious that more research is needed in order to gain knowledge about what training methods will promote adult dyslexics reading skill. Because some adult dyslexics seem to be able to compensate it also is important that diagnostic tools reveal their underlying problems (Rack, 1997). Useful indicators could be spelling performance, speeded non-word reading and naming and reading comprehension (Everatt, 1997). Research does seem to indicate that not only decoding abilities are deficient but also comprehension abilities, and therefore training is needed for both decoding and for metacognitive strategies to successfully comprehend a text (Simmons & Singleton, 2000). The data presented in this thesis in Paper 1 shows that adult who had been diagnosed in childhood as dyslexic still perform poorly in tasks that demands efficient phonological and orthographic processing. It should be noted however that although our results are in line with the phonological deficit hypothesis it is not possible to draw any conclusions about the causal relation between phonological ability, as measured though tasks of for example phonological awareness and digit naming, and reading ability from the data presented in Paper 1. If we do assume that deviant pre-literal phonological qualities of the language system cause problems in later reading acquisition the relation between early linguistic abilities and adult reading performance is certainly nuanced and research should be committed to several levels of investigation (Lundberg, 2002).
Speech perception and dyslexia

The results from the two empirical studies examining the relation between speech perception and dyslexia in this thesis (i.e., Paper 3 and 4) were conducted in order to investigate two hypotheses concerning the question of what characterizes dyslexics’ deviant phonological representations.

Results from the study on sine wave speech repetition (Paper 3) indicated that dyslexic adults had difficulties with monosyllabic words but not with disyllabic words and the sentence. It was proposed that perhaps dyslexics made use of suprasegmental information in order to successfully repeat the disyllabic words and the sentence, and that the lack of enough suprasegmental information in order to compensate made the monosyllabic words more difficult for the dyslexics to repeat. The reason why monosyllabic words would be more difficult for the dyslexics to perceive is then hypothesized to depend on either less well specified (or indistinct) phonological representations or that the dyslexics do not have phonological representations that are sufficiently segmented for the task. The design in Paper 3 did not allow any conclusion regarding what did best explain the results of the study; indistinct representations or insufficiently segmented representations. It should be noted that the lexical restructuring hypothesis and the distinctness hypothesis do not contradict each other. It is also worth noting that the results from Paper 3 do not tell us if the poorer performance in repetition for monosyllabic words by dyslexics is due to deviant preliterate language abilities or due to a failure in acquiring literacy skill. From the results in Paper 3 alone one might argue that what differentiates good readers from poor readers is their ability to attend to segmental information. Awareness for the segmental aspects of speech is what is being taught during reading instruction, and the poorer performance on identification of monosyllabic words might then be a consequence of not being able to attend to these aspects.

In Paper 4 the characteristics of dyslexics’ phonological representations were further investigated by testing the categorization performance of fricative-vowel syllables. Results showed that dyslexics utilized the same information as controls to categorize the syllables. However, categorization consistency was significantly poorer in the dyslexic group. In relation to the lexical restructuring hypothesis it was concluded that 10 and 15 year old dyslexic can categorize fricative vowel syllables using the static information in the fricative. This indicates that dyslexics could have undergone a lexical restructuring and developed a representation of the /s/
The poorer categorization consistency in dyslexics would with Nittrouers (1996) vocabulary mean that they were less sensitive to the fricative spectrum compared to controls. It should be noted here that sensitivity in a psychophysical sense probably should be tested using a discrimination task. In this context it is perhaps more appropriate to use the term categorization consistency. This result is however consistent with the distinctness hypothesis since it would predict that categorization might be difficult for dyslexics if their categories are not distinct enough. It should be remembered that the studies in Paper 3 and 4 were not intended to disentangle the lexical restructuring hypothesis and the distinctness hypothesis. These two hypotheses were used as a theoretical framework to interpret the results. However, a result that would have favored the lexical restructuring hypothesis before the distinctness hypothesis is if the dyslexics had used the transition information present in the vowel to a greater extent than controls and at the same time had been equally consistent in their categorization as controls.

In sum, the results from the two studies showed that 1) dyslexics had bigger problems than controls to make use of segmental information when identifying degraded speech but seem to be able to compensate for this when there was enough suprasegmental information in the words or sentence and 2) dyslexics were less consistent when categorizing fricative-vowel syllables although they used the same information present in the syllable, fricative and/or coarticulation in the vowel, to perform the categorizations.

Recent studies showing differences between dyslexics and controls in tasks of speech perception have looked at phoneme identification in /bil/-/pil/ and /bis/-/pis/ continua in 7 year old children (Chiappe, Chiappe, & Siegel, 2001), perception of stimulus da and deviant ga with a mismatch negativity measurement in adults (Schulte-Körne, Deimel, Bartling, Remschmidt, 2001), identification of voicing and place-of-articulation contrasts in 8 year old children (Maasen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001), perception of voice and tone onset time continua in children between 7 and 15 years of age (Breier et al., 2001), categorization of a sine wave syllables dispersed along a /ba/-/da/ continuum in children between 12 and 13 years of age (Serniclaes, Srenger-Charolles, Carré, & Demonet, 2001), and perception of sine wave speech sentences in adults (Rosner, Talcott, Witton, Hogg, Richardson, Hansen, and Stein, 2003). Interestingly the children in Serniclaes et al.'s study were better at discriminating between stimuli belonging to the same category compared to controls. This was taken to
indicate that perception was less categorical in dyslexic children (Serniclaes et al., 2001). This result seems in line with the results in Paper 4 and might suggest that dyslexics have less well specified phonological representations.

However, Joanisse, Manis, Keating, and Seidenberg (2000) did not get any group differences between 7-9 year old dyslexics and controls on two categorization tasks using “dug-tug” (i.e., voice onset time) and “spy-sky” (i.e., place of articulation) continua. Group means were calculated from categorization slope parameters. Joanisse et al. remark that they had not tested all aspects of speech perception and therefore can not be sure that the dyslexics’ speech perception was normal in all respects but conclude that their results imply that “only a small minority of dyslexics appear to have perceptual difficulties” (p. 50). Similarly we also are limited to conclusions regarding that linguistic material that was actually used in the studies in Paper 3 and Paper 4.

The picture emerging from the studies of the thesis and the studies mentioned above is not completely straightforward. One question is of course why dyslexics do not perform poor on all discrimination and categorization tasks where the discriminative information between stimuli regards phonetic detail. However, neither the lexical restructuring hypothesis nor the distinctness hypothesis claims that all speech contrasts have to be difficult for a dyslexic. Walley, Metsala, and Garlock (2003) argue that more research is needed in order to fully understand how word familiarity, age of acquisition of a word, and neighborhood density effects lexical restructuring. Walley et al. also point out that more studies are needed to establish a cross-linguistic validity regarding basic speech perception and word recognition and its relation to phonological awareness and reading ability. Obviously many dyslexics do have problems categorizing and discriminating speech stimuli. As our results show they also have problems identifying degraded spoken words, possibly due to lack of compensatory opportunity. As with Paper 1, the results from Paper 3 and 4 are in line with the phonological deficit hypothesis but do not tell us the direction of causation regarding reading ability and phonological representations.

Mayo (2000) has made some interesting studies regarding the relation between phonemic awareness and cue weighting in speech perception. One of the assumptions in Nittrouer’s work is that phonemic awareness develops as a consequence of a developmental weighting shift in the perceptual system (e.g., Nittrouer & Studdert-Kennedy, 1987). In a longitudinal study Mayo (2000) showed that whereas phonemic awareness predicted cue weighting strategy the opposite seemed true for the slope of
the response curves, that is, here instead categorization consistency predicted phonemic awareness. In one instance phonemic awareness impacts on perception and in the other perception impacts on phonemic awareness. According to Mayos results cue weighting shifts only occur in literate adults and becoming-literate children, not in children who are not learning to read and are not becoming phonemically aware. Thus cue weighting does not seem to be maturational but instead related to development of phonemic awareness. Mayo concludes that changes in cue weighting seem to be the results of alphabetic literacy instruction (Mayo, 2000). This does not explain why we did not get any cue weighting differences between dyslexics and controls since they can be assumed to differ in phonemic awareness, although we did not use any such measures in Paper 4. There is a possible confounding in the categorization task in Paper 4, as in Nittrouers studies, because it allows the listener to use either the fricative or the transition in the vowel to categorize the syllables, someone with a sensitive perceptual system might detect that there is an invariant property in the vowel signaling fricative identity and develop the strategy to keep to this information when categorizing the syllables. Perhaps this is what these individuals did. This might then also imply that responses where coarticulation information is consistently used indicates good categorization performance. Those individuals who seemed to have used mainly the coarticulation information, which occurred primarily when the vowel contained a /ʃ/ transition, belonged in seven out of nine cases to the control groups. This would be in line with the results on categorization consistency perhaps indicating more distinct phonological representation compared to dyslexics. If the perceptual characteristics shown in categorization consistency do predict phonemic awareness this might explain our results showing that dyslexics were poorer at consistently categorizing the fricative-vowel syllables. That categorization consistency, according to Mayo (2000), does predict phonemic awareness but not the other way round implies that the results of Paper 4 where dyslexics performed poorly on categorization consistency is due to some preliteterate deficit.

It has been beyond the scope and intention of this thesis to thoroughly address the issue of whether the perceptual problems seen in dyslexics are primarily auditory or linguistic. A general auditory deficit hypothesis has been proposed by some researchers claiming that dyslexics’ perceptual problems involve processing rapidly presented auditory stimuli (Tallal, 1980; Tallal, Miller, & Fitch, 1993) and a lowered sensitivity to particular rates of auditory frequency modulation (Witton et al., 1998). For a review of the temporal processing deficit hypothesis, see Farmer and Klein
Many studies have however failed to confirm a general temporal processing deficit in dyslexics and results instead indicate a speech specific deficit (Breier, Gray, Fletcher, Foorman, & Klaas, 2002; Chiappe, Stringer, Siegel, & Stanovich, 2002; Marchall, Snowling, & Bailey, 2001; Mody, Studdert-Kennedy, & Brady, 1997; Nittrouer, 1999; Rosen & Manganari, 2001; Share, Jorm, Maclean, & Matthews, 2002).

Conclusions

The results in this thesis strengthen the view that dyslexia involves poor phonological processing and that these problems continue into adulthood, even when the person has compensated and developed a seemingly functional reading capacity for everyday life situations. Early reading problems do also have consequences later in life regarding, for example, choices of educational content, possibly due to reading requirements.

It is also concluded that dyslexic 10 and 15 year olds are poorer at categorizing fricative-vowel syllables compared to controls and dyslexic adults and dyslexic adults are poorer at identifying degraded monosyllabic words, but not disyllabic words and a sentence. The difficulties dyslexics have in task of speech perception seem to involve dealing with phonetic detail, possibly due to weakly specified phonological representations. There is a lot more to be done in order to fully understand the reciprocal relation between phonemic awareness and reading ability and in order to understand how preliterate language abilities might facilitate or cause problems when entering literacy instruction. Morais (2003) calls for case studies of dyslexics and training studies investigating the direction of causality also between perceptual and post-perceptual segmentation.

Future research should also look at the relation between poor readers’ lexical structure as measured in reading, writing, articulation and speech perception in order to fully understand the underlying phonological representation deficit, also at an individual level.
REFERENCES


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