A COMPARISON OF THE SEQUENTIAL PROCESSING ABILITIES OF DYSLEXIC AND NORMAL READERS, USING VISUAL AND AUDITORY TASKS

by

Mary E. Farmer

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

at

Dalhousie University,
Halifax, Nova Scotia.

July, 1993.

ISBN 0-315-93657-6

Name MARY E. FARMER

Dissertation Abstracts International is arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation. Enter the corresponding four-digit code in the spaces provided.

Clinical Psychology — SUBJECT TERM

0622 — SUBJECT CODE

U·M·I

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS
Architecture 0729
Art History 0377
Cinema 0900
Dance 0378
Fine Arts 0357
Information Science 0723
Journalism 0391
Library Science 0399
Mass Communications 0708
Music 0413
Speech Communication 0459
Theater 0465

EDUCATION
General 0515
Administration 0514
Adult and Continuing 0516
Agricultural 0517
Art 0273
Bilingual and Multicultural 0282
Business 0688
Community College 0275
Curriculum and Instruction 0727
Early Childhood 0518
Elementary 0524
Finance 0277
Guidance and Counseling 0519
Health 0680
Higher 0745
History of 0520
Home Economics 0278
Industrial 0521
Language and Literature 0279
Mathematics 0280
Music 0522
Philosophy of 0998
Physical 0523
Psychology 0525
Reading 0535
Religious 0527
Sciences 0714
Secondary 0533
Social Sciences 0534
Sociology of 0340
Special 0529
Teacher Training 0530
Technology 0710
Tests and Measurements 0288
Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS
Language
- General 0679
- Ancient 0289
- Linguistics 0290
- Modern 0291

Literature
- General 0401
- Classical 0294
- Comparative 0295
- Medieval 0297
- Modern 0298
- African 0316
- American 0591
- Asian 0305
- Canadian (English) 0352
- Canadian (French) 0355
- English 0593
- Germanic 0311
- Latin American 0312
- Middle Eastern 0315
- Romance 0313
- Slavic and East European 0314

PHILOSOPHY, RELIGION AND THEOLOGY
Philosophy 0422
Religion
- General 0318
- Biblical Studies 0321
- Clergy 0319
- History of 0320
- Philosophy of 0322

Theology 0469

SOCIAL SCIENCES
American Studies 0323
Anthropology
- Archaeology 0324
- Cultural 0326
- Physical 0327

Business Administration
- General 0310
- Accounting 0272
- Banking 0770
- Management 0454
- Marketing 0338

Canadian Studies 0385
Economics
- General 0501
- Agricultural 0503
- Commerce-Business 0505
- Finance 0508
- History 0509
- Labor 0510
- Theory 0511

Folklore 0358
Geography 0366
Gerontology 0351
History
- General 0578
- Ancient 0579
- Medieval 0581
- Modern 0582
- Black 0328
- African 0331
- Asia, Australia and Oceania 0332
- Canadian 0334
- European 0335
- Latin American 0336
- Middle Eastern 0333
- United States 0337

History of Science 0585
Law 0398
Political Science
- General 0615
- International Law and Relations 0616
- Public Administration 0617

Recreation 0814
Social Work 0452
Sociology
- General 0626
- Criminology and Penology 0627
- Demography 0938
- Ethnic and Racial Studies 0631
- Individual and Family Studies 0628
- Industrial and Labor Relations 0629
- Public and Social Welfare 0630
- Social Structure and Development 0700
- Theory and Methods 0344

Transportation 0709
Urban and Regional Planning 0999
Women's Studies 0453

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES
Agriculture
- General 0473
- Agronomy 0285
- Animal Culture and Nutrition 0475
- Animal Pathology 0476
- Food Science and Technology 0359
- Forestry and Wildlife 0478
- Plant Culture 0479
- Plant Pathology 0480
- Plant Physiology 0817
- Range Management 0777
- Wood Technology 0746

Biology
- General 0306
- Anatomy 0287
- Biostatistics 0308
- Botany 0309
- Cell 0379
- Ecology 0329
- Entomology 0353
- Genetics 0369
- Limnology 0793
- Microbiology 0410
- Molecular 0307
- Neuroscience 0317
- Oceanography 0416
- Physiology 0433
- Radiation 0821
- Veterinary Science 0778
- Zoology 0472

Biophysics
- General 0786
- Medical 0760

EARTH SCIENCES
Biogeochemistry 0425
Geochemistry 0996
Geodesy 0370
Geology 0372
Geophysics 0373
Hydrology 0388
Mineralogy 0411
Paleobotany 0345
Paleoecology 0426
Paleontology 0418
Paleozoology 0985
Palynology 0427
Physical Geography 0368
Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES
Environmental Sciences 0768
Health Sciences
- General 0566
- Audiology 0300
- Chemotherapy 0992
- Dentistry 0567
- Education 0350
- Hospital Management 0769
- Human Development 0758
- Immunology 0982
- Medicine and Surgery 0564
- Mental Health 0347
- Nursing 0569
- Nutrition 0570
- Obstetrics and Gynecology 0380
- Occupational Health and Therapy 0354
- Ophthalmology 0381
- Pathology 0571
- Pharmacology 0419
- Pharmacy 0572
- Physical Therapy 0382
- Public Health 0573
- Radiology 0574
- Recreation 0575
- Speech Pathology 0460
- Toxicology 0383

Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences
Chemistry
- General 0485
- Agricultural 0749
- Analytical 0486
- Biochemistry 0487
- Inorganic 0488
- Nuclear 0738
- Organic 0490
- Pharmaceutical 0491
- Physical 0494
- Polymer 0495
- Radiation 0754

Mathematics 0405
Physics
- General 0605
- Acoustics 0986
- Astronomy and Astrophysics 0606
- Atmospheric Science 0608
- Atomic 0748
- Electronics and Electricity 0607
- Elementary Particles and High Energy 0798
- Fluid and Plasma 0759
- Molecular 0609
- Nuclear 0610
- Optics 0752
- Radiation 0756
- Solid State 0611

Statistics 0463

Applied Sciences
Applied Mechanics 0346
Computer Science 0984
Engineering
- General 0537
- Aerospace 0538
- Agricultural 0539
- Automotive 0540
- Biomedical 0541
- Chemical 0542
- Civil 0543
- Electronics and Electrical 0544
- Heat and Thermodynamics 0348
- Hydraulic 0545
- Industrial 0546
- Marine 0547
- Materials Science 0794
- Mechanical 0548
- Metallurgy 0743
- Mining 0551
- Nuclear 0552
- Packaging 0549
- Petroleum 0765
- Sanitary and Municipal 0554
- System Science 0790

Geotechnology 0428
Operations Research 0796
Plastics Technology 0795
Textile Technology 0994

PSYCHOLOGY
General 0621
Behavioral 0384
Clinical 0622
Developmental 0620
Experimental 0623
Industrial 0624
Personality 0625
Physiological 0989
Psychobiology 0349
Psychometrics 0632
Social 0451

Table of contents

List of Figures

List of Tables

Abstract

Much of the research in reading disabilities in recent years has concentrated on the phonological coding problems of dyslexics, and many researchers have claimed that the deficit in dyslexia is purely a phonemic, or linguistic one. However, it has been suggested (Tallal, 1984; Tallal & Curtiss, in press) that the phonemic deficit is a symptom of an underlying difficulty, that of processing rapidly occurring sequential stimuli. In this study the rapid sequential processing ability of a group of 20 adolescent dyslexics was assessed, using auditory and visual tasks. Auditory tasks i) assessed the inter-stimulus interval required to segregate two rapidly presented clicks, ii) required a temporal order judgment for two different-frequency tones, and iii) involved same-different judgments for a series of long and short tones presented sequentially. Visual tasks involved i) an assessment of the inter-stimulus interval required to segregate two rapidly presented light flashes, ii) a temporal order judgment for two symbols, and iii) same-different judgments for patterns of light flashes, presented simultaneously or iv) sequentially. In addition performance on phonemic awareness tasks, and reading of both words and non-words, was assessed. The dyslexics' performance on all tasks was compared to that of both age-matched and reading-level matched normal readers of equivalent intellectual level. Results indicated qualified support for Tallal's hypothesis. Dyslexics were impaired compared to their age-matched controls on all reading and phonemic awareness tasks, on the auditory temporal order judgment task, and on the flash pattern matching task, with both sequential and simultaneous presentation. They also needed longer inter-stimulus intervals on the click fusion task, but response bias may have played a part in this result. The implications of these results for the hypothesis of a general temporal processing deficit in dyslexics, and its putative relationship to reading acquisition, are discussed, as is the possible developmental course of such a deficit in the visual and auditory modalities.

List of Abbreviations

AM	age-matched
CAT	Canadian Achievement Test
dB	decibels
DYS	dyslexic
FA	false alarms
GABA	gamma aminobutyric acid
H	hits
ISI	inter-stimulus interval
LED	light emitting diode
LGN	lateral geniculate nucleus
MGN	medial geniculate nucleus
ms	milliseconds
RM	reading-matched
RNT	reticular nucleus of the thalamus
RT	reaction time
s	seconds
SD	signal detection
SOA	stimulus onset asynchrony
TOJ	temporal order judgment
UNIV	university
vs	versus
WISC-R	Weschler Intelligence Scales for Children - Revised
WRAT-R	Wide Range Achievement Tests - Revised

Acknowledgments

During the writing of this dissertation, I have been helped immeasurably by family, friends and colleagues, both by way of critical feedback on my work, and moral support and encouragement. Special thanks are due to my supervisor, Dr. Raymond Klein, for all his support and helpful suggestions over the years. I am very grateful, too, to the members of my committee - Dr. Joan Backman, Dr. Phil Dunham, and Dr. Pat McGrath - for their many perceptive and helpful comments during the conception and undertaking of this research. I also thank Dr. Dennis Phillips, for his many helpful suggestions, and his interest in my work.

Grateful thanks are due to Gordon Troop and Ron Hoffman for their help in building and checking the special equipment required, and to Dr. Bill Hayes, for writing the computer programmes. Thanks are also due to Debbie Naugler-Haugen, for help in collecting some of the data. The support and encouragement of my fellow students throughout my studies have helped to ease the way when the going was tough, to keep a sense of perspective, and to stimulate my thinking. To each of them, for their different contributions, goes my heartfelt gratitude.

This research would not have been possible without the voluntary participation of the students involved. To them and their parents, and to the school board officials and school staff who facilitated this project, goes my sincere appreciation.

Finally, my thanks are due to my two daughters, who have put up with a part-time mother for so long, and who have helped in so many ways. The responsibility for the existence of this dissertation must be laid, however, at the feet of my husband, who suggested, 23 years ago: "Why don't you try taking a course at university? You might enjoy it." Thanks, Pat, for giving me the confidence to go all the way.

Introduction

Definition of dyslexia

The term dyslexia is usually reserved for cases of specific reading disability; that is, an inability to learn to read with no apparent contributing cause. Cases of reading disability which present as part of an overall pattern of cognitive under-development are not classified as dyslexia, and are usually referred to as reading backwardness. A generally accepted definition of dyslexia is that proposed by the World Federation of Neurology in 1968 (as cited in Snowling, 1987). Dyslexia is there defined as "a disorder manifested by difficulty in learning to read despite conventional instruction, adequate intelligence and sociocultural opportunity. It is dependent upon fundamental cognitive disabilities which are frequently of constitutional origin" (p.2).

One type of cognitive disability which is evident in a majority of dyslexics is a difficulty with tasks involving phonemic discrimination or phonological coding.

The evidence for a phonemic deficit

A brief note about the use of the words "phonetic", "phonemic", and "phonological" might be in order before beginning this discussion. A phonetic representation of sounds would present the surface structure of phones in speech. A phoneme refers to a group of (phonetically different) sounds that are considered to be essentially the same vocal sound, and are represented the same way. Thus the "s" in "cats" (which occurs after an unvoiced consonant) and the "s" in "dogs" (which occurs after a voiced consonant) are phonemically the same but phonetically different (Liberman, 1983). Phonology refers to the science of vocal sounds, and is commonly thought of as the knowledge of grapheme-phoneme (letter-sound) correspondences (Seymour & Elder, 1986), or of the rules governing the legitimate sequencing of sounds in any language. Phonemic or phonological awareness refers to the ability to separate and/or recognize the component sounds in a word. In this paper, two assumptions are made. First, since phonetic discriminations are necessarily more complex and subtle than phonemic discriminations, it is assumed that a child who has difficulty distinguishing phonemes would also have difficulty with phonetic differences. Therefore the term "phonemic deficit" is used throughout to refer to such difficulties. Second, it is assumed, for the purposes of the discussion in this section, that a phonemic deficit is a sufficient (if not necessary) cause of impaired phonological processing.

A plethora of research in the last decade or so has provided ample evidence that a majority of dyslexics have problems with phonological processing (Liberman & Shankweiler, 1985; Mann, 1984; Stanovich, 1986a; Vellutino & Scanlon, 1987). Indications are that a phonemic/phonological-specific deficit is causal to reading disability (Bradley & Bryant, 1983; Stanovich, 1988a; Stanovich, Cunningham & Cramer, 1984; Wagner, 1986). Some reciprocity likely also exists, however, with reading skills contributing to the development of phonological skills (Wagner & Torgeson, 1987). Other well-documented differences noted between dyslexics and normal readers (e.g., memory, syntactic, semantic) may be the result of early difficulties with phonological coding (Jorm, 1983; Share & Silva, 1987). In fact, Stanovich (1986b, 1988b) has suggested that because of an initial processing difficulty, poor readers fall further and further behind as the demands on their skills increase, while proficient readers get better and better as they practise the skills they have learned.

Most researchers agree that this initial processing difficulty is a deficit in rapid and accurate phonological coding. The phonological abilities of dyslexics have been investigated in many areas, and poor performance relative to normal readers has been found on a wide variety of phonological tasks (Torgeson, 1985). For example, poor readers[1] have relative difficulty in producing names in response to pictures or verbal definitions of objects (Snowling, van Wagtendonk, & Stafford, 1988). When they do produce names, they tend to make many phonemic errors (Katz, 1986). Poor readers are slower than normal readers in rapid naming tests of drawings of objects, letters, digits, and colours (Bowers & Swanson, 1991; Denckla & Rudel, 1976; Katz & Shankweiler, 1985; Lovett, 1984, 1987; Mann, 1984; Wolf, 1986; Wolf & Obregon, 1992). Poor readers cannot produce as many rhyming words as normal readers, and are slower when they do produce them (Snowling, Stackhouse, & Rack, 1986). In the early reading stages, normal readers are less efficient at remembering lists of words or sentences containing many rhyming words, than they are at remembering phonemically dissimilar words. Poor readers do not show this same phonemic confusability effect in the early stages (Byrne & Shea, 1979; Jorm, 1983; Mann, Liberman, & Shankweiler, 1980), although there is some evidence that phonemic confusability may affect them in early adolescence (Johnston, 1982; Siegel & Linder, 1984). Normal readers show a reduction in the effect at this age, probably because of increased precision of phonemic discrimination (Olson, Davidson, Kliegl, & Davies, 1984). Finally, phoneme segmentation and awareness tasks have been shown not only to differentiate good and poor readers (Bradley & Bryant, 1983; Mann, 1984; Share, Jorm, Maclean, & Matthews, 1984; Snowling et al., 1986; Stanovich, 1988a; Wagner & Torgeson, 1987), but also to be good predictors of future reading ability (Lundberg & Hoien, 1989; Mann, 1993; Mann & Brady, 1988; Share et al., 1984; Stanovich et al., 1984; Stuart & Masterson, 1992).

In many cases, poor reading seems to be a familial trait (Elbert & Seale, 1988; Pennington & Smith, 1988; Scarborough, 1989; Snowling, 1991). In fact, it has been shown that it is the phonological coding deficit of dyslexics which is highly heritable. Orthographic, or word-specific, coding ability is only weakly related to phonological coding ability in disabled readers, however. Moreover, orthographic coding ability does not appear to be heritable, but to be influenced by environmental factors such as amount of exposure to reading (Olson, Wise, Conners, Rack, & Fulker, 1989).

Visual, or whole-word coding, may indeed be highly developed in reading disabled children, in an attempt to compensate for their phonemic deficit. As Frith (1986) has pointed out, when one component of the developing reading process is dysfunctional, it is extremely likely that other skills will become highly developed in compensation. There is, indeed, evidence that dyslexics are more highly reliant on visual, or orthographic, coding in reading-related tasks (Aaron, 1985; Foorman & Liberman, 1989; Gordon, 1984; Katz, Healy, & Shankweiler, 1983; Rack, 1985; Underwood & Boot, 1986; and see review by Snowling, 1991). For example, Rack (1985) presented dyslexics and reading-matched controls with a word to cue them for the recall of a previously paired word. The target word was orthographically similar to the cue word, and/or rhymed with it, or was unrelated. The dyslexics remembered more of the orthographically similar words than their reading-matched controls, but fewer of the rhyming words, suggesting that they were using an orthographic strategy to a much greater degree than their reading-matched controls, whether presentation was auditory or visual. Similarly, Gordon (1984) found that dyslexics tend to use a visual strategy when reading. He presented the letters "C", "A", and "T" such that they could be read sequentially, as "ACT", or spatially, as "CAT". Gordon found that while non-reading -disabled relatives of the dyslexics were likely to read the sequential "ACT", dyslexics tended to read "CAT", the spatial presentation.

Thus the existence of a phonological deficit in a majority of dyslexics, together with resultant compensatory visual skills enhancement in many instances, are firmly established. Studies which have shown, for example, normal recall by dyslexics of nonverbal stimuli but impaired recall of verbal stimuli (Holmes & McKeever, 1979; Katz, Shankweiler, & Liberman, 1981; Vellutino, Steger, Kaman & De Setto, 1975), have convinced many researchers that the deficit thus demonstrated is purely a phonemic, or linguistic, one (Brady, Mann, & Schmidt, 1987; Katz et al., 1981, 1983, 1984;

Liberman, 1989; Vellutino, 1987). However, as noted below in the section on discrimination of stimulus sequences, the methodologies used in some of these studies may have precluded the possibility of finding evidence for a more general deficit.

The basis for a phonemic deficit

If the consensus view is correct, then, and dyslexics can not read well because they have problems with phonemic discrimination and/or phonological coding/retrieval, what could be the underlying cause of these problems? Hypotheses which proposed a non-linguistic basis for dyslexia were in vogue earlier, but more recently have largely been dismissed (see the review by Stanovich, 1986a). However, as Stanovich has pointed out, it is possible that the plethora of deficits seen in reading disabled children might be the end result of a developmentally early specific processing deficit. Some researchers (e.g. Liberman, 1989; Vellutino, 1987) argue for the phonological deficit being the underlying basis for reading and related language problems. However, sufficient evidence has accumulated to question this view, and to raise the possibility of the existence of a more fundamental processing deficit.

Just such a processing deficit has been proposed by Tallal, who contends (1984; Tallal & Curtiss, in press) that the phonemic deficit is a symptom of a more general deficit in processing rapid temporal sequences. Perception of spoken language is particularly vulnerable to such a deficit, because speech is made up of component sounds, some of which (for example, the stop consonants - b, p, d, t, k, g) involve rapid spectral changes over a time period of just tens of milliseconds. Tallal proposes that as a result of this processing deficit, the inability to discriminate many speech sounds leads not only to the retrieval difficulties for phonological codes, and the impairment on phonemic awareness and segmentation tasks evidenced by poor readers, but contributes to the reading problem itself in that these readers are unable to adequately learn the phoneme-grapheme correspondences necessary for the normal development of reading skills (Tallal, 1988;

Tallal & Stark, 1982). The link between early language difficulties and later reading disorder has been firmly established (Beitchman & Inglis, 1991; Kamhi & Catts, 1989; Katz, Curtiss, & Tallal, 1992; Rapin & Allen, 1988; Scarborough, 1990; Stark, Bernstein, Condino, Bender, Tallal, & Catts, 1984; Tallal, 1988), even where language difficulties were not diagnosed in early childhood (Gibbs & Cooper, 1989; Kamhi & Catts, 1986).

In support of Tallal's hypothesis, there is evidence that dyslexics have a deficit in processing rapidly presented visual stimuli (whether verbally codable or not), as well as auditory stimuli, and possibly tactile stimuli. This evidence, which will be outlined below, has been obtained in a number of experiments that investigated the performance of dyslexics on various tasks which tapped one or more aspects of sequential processing. Before presenting this evidence, however, a discussion of what is meant by sequential, or temporal, processing is in order.

The factors involved in sequential processing

Sequential processing is a term that has been loosely used in the literature to describe any processing procedure involving two or more stimuli presented non-simultaneously. However, under this general rubric, many different processing requirements and stimulus dimensions are involved. What follows is an attempt to break down "sequential processing" into a logical sequence of the progressively more complex procedures which might be said to fall under this rubric. If indeed the different components of sequential processing are hierarchically linked, it might be hypothesized that a deficit in any task involving a procedure early in the sequence would lead to impaired performance in later tasks which incorporate the former. An alternative hypothesis would be that the component processes are in fact discrete, and an impairment in one would not necessarily be associated with an impairment in any other component.

First, it is obvious that detection of a single stimulus is a prerequisite before any task involving two or more stimuli can be successfully completed. That is, if we are to make any judgments about a subject's ability to process stimuli which appear sequentially, we must be sure first of all that that subject's ability to detect the presence or absence of a single stimulus is unimpaired.

Given that such detection is within normal limits, we can then consider the various components involved in processing sequentially presented stimuli. According to Hirsh and Sherrick (1961), there are at least two basic components of temporal, or sequential, resolution. The first is the introduction of a minimum time interval between two events or stimuli so that the two are perceived as just barely sequential, or nonsimultaneous. Determination of this minimum time has been called the separation threshold method (Di Lollo, Hanson, & McIntyre, 1983). We might call this aspect of the processing of sequential stimuli numerosity - the determination of whether one item or more than one has been presented. The stimuli involved may be auditory, visual, or tactile, and thus the duration of the inter-stimulus interval (ISI) may be said to be an amodal property. Similarly, the stimuli involved in both detection of a single stimulus and determination of numerosity may vary along amodal dimensions such as location and duration. This will be discussed further in the sections below.

Within each modality, stimuli may vary along dimensions which give them an identity peculiar to that modality - such as colour for visual stimuli, or pitch for auditory stimuli. Attaching identities to stimuli is essential for the determination of temporal order, which Hirsh and Sherrick (1961) identified as the second component of sequential resolution. (Attaching identities is a necessary, but not sufficient, prerequisite for temporal order: a subject may be able to identify two different stimuli presented sequentially, but not be able to correctly identify the order in which they were presented.) In order that a judgment of temporal order may be made, the two stimuli must differ along some dimension which confers an identifiable property to each. Thus temporal order judgment is necessarily a more complex operation than determination of numerosity, for which the stimuli need not differ in any modal property.

Finally, an even more complex task is judging the order or sequencing of a series of stimuli. Although this latter task might appear to differ only quantitatively from the temporal order judgment task, it is listed here as a separate component of processing of sequential stimuli because of the exponentially greater demands placed on processing resources as the number of stimuli increases. Additionally, the usual requirement in tasks involving series of stimuli is to match pairs of sequences. In such tasks, and tasks requiring reproduction of the order of a series of stimuli, a memory component is added to the perceptual requirements.

Thus four basic components involved in the processing of sequential stimuli have been identified: detection (or identification) of a single stimulus, determination of numerosity, temporal order judgment of the elements, and sequence matching or discrimination. These four components may involve variations along different dimensions - location, duration, and identity.

The four components will be described further below. For each component, those experiments which appear to have found evidence for (or against) a deficit for developmental dyslexics in that particular aspect will be discussed. In addition, some studies involving developmental language impaired subjects will be reported. The link between language impairment and dyslexia has been touched upon above. Moreover, Katz et al. (1992) have suggested that recent research indicates that there may be much more overlap between language impairment and dyslexia than hitherto suspected. Because of the relative paucity of studies with dyslexics examining some of the components of sequential processing just elaborated upon, it is felt that a report of the additional studies involving language-impaired children might contribute to an understanding of the deficits in question. It should be noted that there are methodological differences in the studies discussed in each section, such as the criteria used for selection of subjects, the age range of subjects, memory demands of the tasks involved, type and duration of stimuli, type of presentation of stimuli, and type of response required. For these reasons comparisons of the studies described below must be made cautiously.

1) Detection or identification of a single stimulus

Detection of a single stimulus may involve simple detection of the presence or absence of a stimulus, or it may involve more complex judgments of the duration, location, or identity of the stimulus. These latter judgments involve discrimination in addition to detection. Discrimination is a prerequisite for the more demanding judgments (such as temporal order) to be discussed below. In the auditory mode, simple detection may be tested by asking a subject to report the presence or absence of a click or tone, after a cue. Similarly, in the visual mode, the subject might report the presence or absence of a light flash after a cue. Variations which go beyond the simple detection task might involve duration judgments, such as requiring the subject to adjust the duration until a stimulus of similar duration to the test stimulus is produced. For location judgments a subject might have to choose to which ear an auditory stimulus had been presented, or to localize a sound along an arc. In the visual modality, the subject might judge whether a flash was presented to left or right of a fixation point. Identity can also be used as a variable - a subject might have to judge whether the pitch of a tone was high or low, or whether a light flash was red or green, or give the identity of a presented stimulus such as a letter or digit. In such cases, identity is a modality specific attribute. However, identification can also involve amodal properties such as the duration of a stimulus.

Most studies involving detection or identification of a single stimulus used visual stimuli and required motor responses, but age of subjects employed, criteria for subject selection, type and duration of stimuli, all varied considerably. As can be seen from the discussion below, there is little evidence in the literature that dyslexics have difficulty in either detecting or identifying a single stimulus. Only one study (Gross-Glen & Rothenberg, 1984) has reported a significant deficit in detection/identification of visual stimuli amongst reading impaired individuals. In that study, dyslexics aged 11-15 years required a longer exposure of stimuli than controls in order to identify single or double letters monocularly presented. For single letters, normal readers could identify one of four presented letters with 62% correctness with exposures of less than 25 ms duration. Dyslexics required significantly longer as a group to reach this criterion: mean duration thresholds (and standard deviations) for identification of a single letter from a set of four, left and right visual fields, was 41.4 (50.1) and 35.0 (47.6) ms for dyslexics, and 8.6 (4.7) and 7.6 (4.3) for normal readers. For double letter identification, means were 139.7 (119.3) and 119.1 (122.3) ms for dyslexics, and 20.8 (11.2) and 17.9 (9.4) for normal readers. Perusal of Gross-Glen and Rothenberg's data shows that the means for the dyslexics were mainly influenced by a minority of subjects: some 6 or 7 of the 16 dyslexics needed longer durations than 25 ms, with 3 subjects needing considerably longer; thus the ISI's required by a majority of the dyslexics were similar to those required by normal readers. Moreover, a notable difference between this study and others requiring detection or discrimination of a single stimulus and where group differences have not been found, is that Gross-Glenn and Rothenberg presented stimuli monocularly (to the dominant eye), to one side or the other of a central fixation point. The stimuli had to be detected peripherally (2^{o} visual angle from fixation point) rather than foveally, unlike the other studies described below. Accuracy in identifying letters does decline as retinal eccentricity is increased. It has been suggested that dyslexics may be less accurate than normal readers at identifying two letters close together, but not when they are further apart (Geiger and Lettvin, 1987). However, when single letters are presented at varying eccentricities around a fixation point, for 17 ms duration, adolescent dyslexics and adult poor readers perform as well as good readers (Klein, Berry, Briand, D'Entremont, & Farmer, 1990). The added methodological difference of monocular presentation in the Gross-Glen and Rothenberg study, however, may contribute to an explanation of the anomolous results.

Other studies have revealed no differences between good and poor readers for detecting or identifying single stimuli. Mason (1980) found no differences between good and poor college readers in identifying letters exposed for various durations from 20 to 130 ms. Additionally, Blackwell, McIntyre and Murray (1983) reported that learning disabled children were equivalent to controls in detecting and recognizing a single letter (T or F) displayed for 150 ms. Finally, Tallal (1980), using brief tones, found no significant differences between dyslexics or controls in detecting or discriminating between stimuli, or in learning the correct motor response; similar results were found with young language-impaired children and controls (Tallal, 1978).

Thus, the consensus appears to be that dyslexics do not have a difficulty with detecting, or even identifying, singly presented stimuli. As can be seen from the section on discrimination of sequences below, they also may not have difficulties when a number of stimuli are presented simultaneously, such that they can be viewed as a single entity or pattern. However, as can be seen in the following sections, when temporally separated stimuli must be processed, dyslexics may have difficulties when the temporal separations are very brief.

2) Determination of numerosity

Simple judgments of numerosity may involve two identical brief stimuli presented in the same location, separated temporally by an ISI. Stimuli may be auditory (e.g., clicks or tones) or visual (e.g., light flashes), and tasks using such stimuii are known as auditory or visual fusion tasks[2]. Such tasks might also involve stimuli of a longer duration, with different onset times. The shortest ISI's (or minimum separation thresholds) required by normal subjects to separate two stimuli are much longer in the visual modality than in the auditory. In click fusion tasks, normal subjects can determine when two clicks have been presented rather than one with ISI's as low as 2-3 ms (Albert & Bear, 1974; Auerbach, Allard, Naeser, Alexander, & Albert, 1982; Fay, 1966; Hirsh & Sherrick, 1961). With two tones, children aged 3 to 11 years need ISI's ranging from 4 to 24 ms, depending on age (Davis & McCroskey, 1980). In order to be seen as separate by normal subjects, visual stimuli must have ISI's of some 20 ms (Hirsh & Sherrick, 1961). Using sub-threshold stimuli, it has been shown that for double light flashes, complete summation occurs with ISI's below 16 ms, and an ISI of 65 ms is necessary before no summation occurs (Ripps & Weale, 1976). Since resolution of the second stimulus can be assumed to be associated with the degree of summation, the time required for numerosity judgments could be expected to be in this range.

Many of the studies involving numerosity judgments have required subjects to detect the gap between two stimuli, rather than just judge that two stimuli were presented. In such cases, the inter-stimulus gap might be regarded as a third event, which makes it apparent that two, rather than one, stimulus events have occurred. In order to detect the gap between two visual stimuli, normal adults require an ISI of 50-55 ms (Di Lollo, Arnett, & Kruk, 1982). For auditory stimuli, there is evidence that threshold or minimum ISI's decrease as intensity of tones increases, and that frequency may affect the ISI's needed in gap detection tasks, with longer gaps being needed at lower frequencies (Irwin, Ball, Kay, Stillman & Rosser, 1985). However, when very brief (17 ms) tones were used in an auditory fusion task, the frequency of the stimuli did not affect the threshold ISI (Davis & McCroskey, 1980; McCroskey & Kidder, 1980). Irwin et al. (1985) have suggested that the spread of energy associated with rapid signal switching such as used in these latter studies, may render such stimuli fairly similar in frequency content. If this were so, one would not expect to see an effect for frequency. For visual stimuli, ISI's decrease for normal subjects as contrast increases. There is also an effect of spatial frequency, with threshold ISI's being lower at low spatial frequency (Slaghuis & Lovegrove, 1985).

There is considerable evidence of a developmental trend, with younger children (under 9 years) needing longer ISI's to separate or detect a gap between two stimuli than older children. This evidence is seen both in the auditory domain (Davis & McCroskey, 1980; Irwin et al., 1985; McCroskey & Davis, 1976 [reported in McCroskey & Kidder, 1980]; Morrongiello & Trehub, 1987) and in the visual (Lovegrove & Heddle, 1980; see also the visual processing experiments of Arnett & Di Lollo, 1979, and the work with infants by Anthony, Zeigler, & Graham, 1987). Recent evidence suggests that there is considerable refinement in auditory temporal resolution in the early years. Werner, Marean, Halpin, Spetner, and Gillenwater (1992) found that in a gap detection task in broadband noise (with high-pass noise masking), the gap detection thresholds of adults ranged from approximately 16 ms at <500 Hz to approximately 5 ms at 8000 Hz. In all conditions the gap detection thresholds of infants were some 40-60 ms higher. At around the age of 12 months, the performance of some infants approached that of the adults, but there was considerable variability in performance at this age.

Numerosity judgment tasks almost invariably involve stimuli presented in the same location. Presentation of identical stimuli in different locations requires judgments of non-simultaneity rather than numerosity, and may involve the confound of apparent motion, in both the visual and auditory modalities. Another amodal property - duration of the stimuli - may be varied however. There is, in addition, a variation of the numerosity task which involves non-identical stimuli. This is the temporal integration of form task, and it introduces a spatial element. In this case, two dissimilar stimuli which occupy different parts of the same general location (such as the vertical and horizontal arms of a cross) are presented sequentially. The maximum ISI at which the stimuli are seen as a single form rather than as two separate stimuli is then determined (DiLollo et al., 1983).

There is considerable evidence that dyslexics and language impaired children are impaired in numerosity tasks. Most of this evidence is in the visual domain, but a few auditory experiments have been reported. In these studies, ISI's and response requirements are again varied, although the criteria for subject selection and age ranges involved have been more consistent than those of the studies involving detection or identification of a single stimulus. Stimuli used have varied greatly. Using two tones of 17 ms duration, and ISI's from 0-40 ms, McCroskey and Kidder (1980) found that both a reading disabled and a general learning disabled group of 9-year-olds needed a longer ISI than normals to separate the tones. The reading disabled children were affected by intensity, but not frequency. Haggerty and Stamm (1978) used a click fusion task, but rather than present the two clicks sequentially to both ears, they presented them either to both ears simultaneously, or with one ear leading. Their learning disabled group needed a longer ISI to separate clicks than the controls (1.67 ms vs 1.29 ms). Additionally, fusion intervals were highly correlated with consonant discrimination for the learning disabled children. In this study, however, the results of the numerosity task were confounded by the method of presenting the clicks to separate ears, which would introduce a spatial location cue.

In the visual domain, Lovegrove and his colleagues have repeatedly found that children with specific reading disability need longer ISI's than controls to detect blanks between two sine-wave gratings, but only at low spatial frequencies (Badcock & Lovegrove, 1981; Lovegrove, Heddle, & Slaghuis, 1980; Slaghuis & Lovegrove, 1985). At high spatial frequencies, these findings were reversed, with normal readers needing longer ISI's than the dyslexics. It should be noted, however, that the relative differences between the two groups were much greater at the low spatial frequencies. In a numerosity task employing two straight lines, 12-year-old dyslexics needed longer ISI's than controls to reach 75% accuracy (circa 45 ms vs. 30 ms) (O'Neill & Stanley, 1976). Di Lollo et al. (1983) also used two sequentially presented straight lines with 8-14 year -old dyslexics and controls. In their experiment, one of each pair of test trials consisted of the two lines separated by varying ISI's, and the other consisted of a single straight line, matched for duration and brightness. The dyslexics needed longer mean ISI's (115 ms) to detect which of the two trials contained the blank than did the controls (69 ms). Using a temporal integration of form task, Stanley and Hall (1973) presented two parts of a stimulus with 20 ms duration, and varying ISI's. To separate the two stimuli, dyslexics needed mean ISI's of 140 ms (compared to the normal readers' mean ISI of 102 ms), and to identify the stimuli dyslexics needed 327 ms, versus 182 ms for the normal readers. In another temporal integration of form task, adult dyslexics were found to have impaired sensitivity relative to controls when two parts of a stimulus were presented sequentially to adjacent retinal areas (Winters, Patterson, & Shontz, 1989).

Thus there is a body of evidence, mostly in the visual domain, that dyslexics are impaired in numerosity tasks which require temporal resolution. As can be seen from a comparison of the studies discussed in this and the previous section, group differences were found in only one study requiring detection of a single stimulus (when the stimuli were presented peripherally and monocularly), whereas group differences were found on virtually all tasks involving numerosity judgments.

3) Temporal order judgment

An even greater number of researchers have found deficits for dyslexics in the more complex task of temporal order judgment (TOJ). Whether dyslexics who are impaired on TOJ tasks are necessarily also impaired on numerosity tasks, or vice versa, remains to be shown.

The second component outlined by Hirsh and Sherrick (1961) involves a judgment of temporal order. In order to make a temporal order judgment, the events must be identifiable as discrete elements, so that the subject is able to specify which came first. This can be done amodally, by varying either the duration or the location of the stimuli. In the latter case, the necessity of providing distinctive, identifiable stimuli is avoided, as the subject need only point to (or otherwise indicate) the location of the leading stimulus. In this case, however, a spatial variable has been added to the basic temporal task. When the spatial variable is omitted by presenting the stimuli in the same location, the question of identity of the stimuli has been added. This can be the amodal property of duration (such as long and short tones or flashes), or stimuli can be identifiable along a modality-specific dimension, such as frequency of tones (e.g., high and low) or colour of light flashes (e.g., green and red).

Many of the studies involving temporal order judgment were carried out with younger children, but again, criteria for subject selection and response requirements varied widely, as did ISI's and stimuli used. Most of the studies comparing disabled readers with normal readers on temporal order judgment tasks have involved stimuli with modality-specific identities, although a very few have involved two stimuli presented in different locations. In addition, a few researchers have required simple same-different judgments for pairs of stimuli, rather than explicit order judgments. Nevertheless, the different identities within each pair must be determined if a correct judgment is to be made. These studies, which necessitate the use of distinctive, identifiable stimuli, but do not carry the requirement for explicit ordering of the stimuli, will be discussed before the temporal order judgment studies.

Poor readers were found to be worse than good readers on same-different judgments for pairs of synthesized consonant-vowel syllables (ba/da) from a phoneme continuum (Reed, 1989). As noted earlier, the stop consonants involve spectral changes in the time frame of tens of milliseconds and any impairment in the ability to process the order of these changes would result in impaired discrimination of the sounds. Reed also found the poor readers to be worse than controls at identifying the phonemes from the middle of the continuum, where the boundaries between the two phonemes become more fuzzy. De Weirdt (1988) found similar results for the discrimination of the phoneme pairs pa/ta, both in 9-year-old dyslexics, and in 6-year-old pre-readers who were shown to be relatively poor readers in later testing. De Weirdt also found reading group differences for same-different judgments involving pairs of different-frequency tones.

In work with both reading disabled children and developmental dysphasics, Tallal found both groups to be impaired relative to controls in making same-different judgments for pairs of high and/or low tones with short ISI's. The dysphasics did as well as their controls with long ISI's, but not with shorter ISI's (Tallal, 1976, 1978). The reading disabled children were impaired relative to controls at ISI's of 305 ms and below (Tallal, 1980). In the latter study, Tallal also found the disabled readers to be impaired in explicit temporal order judgments for high-low tones with short ISI's. Although these disabled readers did make more errors in the order judgment task than in the same-different judgment task, neither they nor the controls showed any significant difference in performance on the two tasks. Thus, even where an overt ordering judgment was not required, the ISI's involved in the task were sufficiently short to preclude a correct decision being made as to the similarity of the stimuli. Results on this rapid auditory perception task were significantly correlated with a number of reading measures, particularly the reading of pronounceable non-words.

Using temporal order judgments for pairs of tones or consonant-vowel syllables, and ISI's of 10-400 ms, Reed (1989) found her reading disabled group to be impaired relative to controls as ISI's decreased. However, it should be noted that the disabled readers were not impaired on tasks when the stimuli were pairs of vowels. This result is not surprising, given the different temporal processing requirements for vowels versus consonants (see Phillips and Farmer, 1990). These steady-state vowel stimuli were also each 250 ms in duration, as opposed to the 75 ms duration tones used in this and the Tallal (1980) study. Ludlow, Cudahy, Bassich, & Brown (1983) found all four of their learning disabled groups (which included a group of hyperactives with reading disability) to be impaired relative to controls on temporal order judgment tasks for two tones. However, Ludlow et al. did note that generally the performance of the hyperactive children in their sample was worse than that of the language-impaired children, and thus a relationship between language impairment and temporal processing had not been exclusively shown.

Using visual stimuli, not all researchers have shown a deficit for disabled readers or language impaired children on temporal order judgment tasks. Reed (1989) found no significant differences between her reading disabled and normal groups (ca. 8-10 years) for order judgments of two symbols with ISI's of 50-400 ms. Tallal and Piercy (1973) found no differences between their developmental dysphasic and normal groups (7-9 years) using two 75-ms light flashes of different shades of green with ISI's of 30-428 ms (see also Tallal, 1978). However, Stark and Tallal (1981) found their language-impaired group to be deficient on auditory, visual and cross-modal tasks, as well as motor tasks. They did note, however, that only the younger children (from the total sample of 5 to 8 1/2-year-olds) appeared to be impaired on the visual tasks. Tallal, Stark, Kallman, and Mellits (1981) noted that the younger (5-6 years) language impaired children's performance was as impaired on visual tasks as it was on auditory ones, whereas the older (7-8 years) language-impaired children were only worse relative to controls on the auditory tasks. Thus it appears that the ability to make temporal order judgments in the visual modality may be ameliorated in older learning disabled children, relative to such judgments in the auditory domain. However, such amelioration may not occur for all children. Muller and Bakker (1968; reported in Bakker, 1970) found 13-year-old learning disabled children who were approximately 4 years behind in reading scored significantly lower (not much above chance level) than children two years behind in reading in a temporal order judgment task with red and yellow light flashes with a 75 ms ISI.

Williams and her colleagues have employed location as a variable in temporal order judgment tasks. Brannan and Williams (1988) presented a 3-letter word or 3-symbol non-word for 900 ms, with a second word or non-word following at a stimulus onset asynchrony (SOA) of varying lengths. The two stimuli appeared on the left or right of a fixation point on a screen, and the subject was required to point to which side appeared first. At every age level (from 8 to 12 years) the poor readers required an SOA of some 20 ms longer than the controls (circa 45-68 ms, with the higher SOA's at the lower ages). The results were highly correlated with reading level, especially those of the task using symbols. May, Williams, and Dunlap (1988) required good and poor readers to report which of two adjacent words (either side-by-side or one above the other) with varying SOA's appeared first, and also which position appeared first (no identification required). To identify the word, poor readers required significantly longer SOA's compared to controls (83.4 ms vs. 45 ms). To judge the position, poor readers required 67.9 ms, and good readers 52.2 ms. No significant hemifield effects were found for either judgment. Thus, even when no identification was required, poor readers needed longer ISI's in order to make a temporal order judgment.

Thus, it can be seen that there is compelling evidence for a deficit in dyslexics for TOJ's in the auditory domain, and conflicting evidence for such a deficit in the visual domain. Results of studies would indicate, however, that younger poor readers, and older more severely disabled readers, may well manifest a TOJ deficit in visual tasks. As noted above, however, the hypothesis that disabled readers who have a TOJ deficit would also necessarily show a deficit in numerosity tasks has not been tested. In the same way, it has not been shown that those poor readers who show deficits in the more complex task of sequence matching, as outlined below, would also show deficits in TOJ tasks.

4) Discrimination of stimulus sequences

Extensions of the basic temporal order judgment task usually involve discrimination of stimulus sequences composed of multiple (more than two) elements. That is, pairs of stimulus sequences are presented, and the subject's task is to make a same-different judgment for each pair. As in previous processing tasks, stimuli can be varied along several dimensions. Sequences may differ along the amodal dimensions of duration and location. Thus either light flashes or identical-frequency tones (or even tactile stimuli) can be presented in sequences of long and short stimuli, or of same-length stimuli with varying intervals. Similarly, sequences of identical stimuli, particularly visual or tactile, can be presented in various locations, with either the locations themselves varying, or the order of locations varying. The former (duration) tasks avoid the spatial element, but necessitate the registration of time intervals, and thus the perception of rhythm.

The issue of identity is avoided in tasks which employ either location or duration variables, although it could be argued that subjects may in fact code stimuli or intervals of different lengths as "long" or "short", and thus confer identities in the latter case. Some researchers using sequence matching tasks do introduce modal-specific variables such as frequency or form, and thus require subjects to match on the basis of the order of the identities of the stimuli presented.

The major difference between sequence matching tasks and the temporal order judgment tasks previously described, however, is the emphasis on a memory requirement. All matching of sequence tasks place substantial demands on memory, as the first sequence must be remembered if the second is to be compared to it.

A number of studies have been conducted in which dyslexic or language impaired children have been found to be impaired on sequence matching tasks. Zurif and Carson (1970) found dyslexics to be impaired on both auditory and visual tasks, involving sequences of 5-7 beats (the Seashore Measures of Musical Talents rhythm sub-test) and light flashes with long (1s) and short (500 ms) intervals. The dyslexics were also impaired on cross-modal matching tasks (matching dot patterns to click patterns), and results were correlated with reading skill. Impairment compared to controls on the Seashore Rhythm Test was also found for reading disabled children (and learning disabled children) in Grades 1 to 3 by McGivern, Berka, Languis, and Chapman (1991). Bryden (1972) found his poor readers to be worse than controls on several auditory or cross -modal sequence matching tasks, with performance correlated with reading ability. Bryden surmised that the deficit was one of verbal coding rather than in temporal rhythm perception per se. It should be noted that his subjects were only on average about 1.5 years behind in reading, as tested on the Gates-MacGinitie reading tests, and were from regular classrooms. In addition, stimuli were presented relatively slowly, with a stimulus duration of 250 ms and ISI's of approximately 500-750 ms. Slow presentation was also used by Bakker (1967) when he found that his more severely disabled readers (4 years behind) were worse than his less severely disabled readers (2 years behind) on a task requiring reproduction of the order of presentation of letters and meaningful figures, but not on tasks involving meaningless figures. On a task using digits, the severely disabled readers did make more errors than the less severely disabled readers, but the trend was not statistically significant ($p<.10$). Bakker (1967) did not advance an explanation for this last result, other than to speculate that the task may have been too easy. Each stimulus in the set of four was presented for 2 s, with an ISI of 4 s. Again, these tasks may have used too slow a presentation to identify any temporal processing deficit that might have been present, and might only have measured a phonemic or verbal coding deficit, or perhaps a memory deficit.

Tallal and Piercy (1973) found their young language impaired children to be worse than controls on all matching tasks using 3, 4 or 5 tones of 75 ms duration with ISI's of 428 ms. With 250 ms tones, however, they were only impaired when 4 or 5 element patterns were presented, and their performance was equal to that of controls when light flashes of different shades of green were used. Again, it should be noted that the ISI's in these tasks (428 ms) were relatively long. Using sequences of 3-7 tones or visual symbols with 5-9 year-old language impaired children, Tallal et al. (1981) found these children to be worse than controls for remembering the order of stimulus presentation on both the auditory and visual tasks. As in the temporal order judgment tasks of these researchers reported earlier, the younger language impaired children performed equally on tasks in the two modalities, and the older language impaired children were worse on the auditory than on the visual task. On these sequence matching tasks, however, the older language impaired children's performance did not reach the level of that of the controls.

As with numerosity tasks (see earlier) there is evidence that children's ability to detect changes in duration of ISI's in sequences of auditory stimuli (such as white-noise bursts) improves with age. While adults can detect changes of 10 ms, children (aged 5 1/2 years) need 15 ms or more, and infants (aged 6 months) need 20 ms or more (Morrongiello & Trehub, 1987).

Finally, Farmer and Bryson (in preparation) assessed the ability of dyslexics to reproduce visual patterns of letters, presented at various rates either sequentially or simultaneously, relative to both age-matched and reading-level matched controls. It should be noted that this is virtually the only study cited which used both reading-matched and age-matched controls. Most other studies used age-matched controls only. When four letters were presented simultaneously (for 200, 400, or 800 ms) at various locations in a 4 x 4 matrix, dyslexics were able to reproduce the location of the letters as well as their age-matched controls. When the letters were presented sequentially (for 100, 200, or 400 ms per letter), the dyslexics' performance was significantly worse than that of the age -matched controls. When both location and identity had to be reproduced correctly, the dyslexics' performance deteriorated even more, relative to the two control groups, particularly at the slowest rate of presentation. At this slowest rate, analysis of the errors showed that visual coding was no longer primarily being used by the dyslexics. The results of these experiments were taken as evidence in support of a rapid sequential visual processing deficit in dyslexics in addition to the phonemic deficit (which was apparent at the slowest rates of presentation).

A few studies requiring matching or recall of sequences of stimuli have suggested that dyslexics perform at the same level as normal readers when nonverbal stimuli are employed, but are impaired when verbal stimuli are used. Such results have generally been taken as evidence that dyslexics have a purely phonemic or linguistic deficit, rather than a general sequencing deficit. However, the studies in question have not been designed so that they might assess the possibility of a temporal processing deficit. Some have employed simultaneous rather than sequential presentation, and others have employed slow sequential presentation of stimuli. For instance, in the study by Katz et al. (1981), each stimulus set (five nonsense drawings or five common object drawings) was presented simultaneously for 4 s. The dyslexics were only impaired when common object drawings (which were verbally codable) were presented. Note that in the previously mentioned study by Farmer and Bryson (in preparation), dyslexics were no worse than age-matched controls when stimuli (4 letters) were presented simultaneously, but were less able to reproduce the correct location/identity of the letters when they were presented rapidly sequentially. Vellutino et al. (1975) found no group differences using 3-5 Hebrew letters with non-Hebrew-speaking subjects, but again simultaneous presentation (for 3-5

s) was used. Studies which did not find the hypothesized group differences when stimuli were presented sequentially used very slow presentation. Holmes and McKeever (1979) presented 20 words or faces, after which subjects were asked to put the stimuli in the order in which they had been presented. Dyslexics did not recall the order of the words as well as their age-matched controls. Both groups recalled the order of the faces equally poorly. The stimuli were presented at the rate of one per 3 s, far too slow for any temporal processing deficit to become apparent. In the study by Katz et al. (1983), poor readers were found to be impaired versus age-matched controls on tasks in which either the temporal or the spatial order of letters had to be recalled. Evidence that the poor readers were using spatial cues rather than a phonemic strategy led Katz et al. (1983) to conclude that the dyslexics' deficit was linguistic in nature. Again, however, the slow presentation of the stimuli (approximately one per second) precluded any assessment of a temporal processing deficit for rapidly presented material.

In addition, a study by Brady, Shankweiler and Mann (1983) concluded that poor readers were impaired versus controls in the auditory perception of speech sounds presented in noise, but not in the perception of non-speech sounds. However, the non-speech sounds used were environmental sounds such as a piano, knocking on a door, thunder, church bells, etc. No attempt was apparently made to match the acoustic properties of the non-speech sounds to those of speech.

The conclusions drawn in studies such as that of Vellutino et al. (1975) have been questioned by Gross and Rothenberg (1979), who caution against the erroneous and premature rejection of a hypothesis (in this case the temporal processing deficit hypothesis) for which supporting evidence has not been found, particularly when the hypothesis has been tested on such a heterogeneous group as dyslexics. Such studies as these, although they may provide evidence for the presence of a phonemic deficit, do not enable us to determine whether a sequential or temporal processing deficit (which may underlie the phonemic deficit) is also present. To make such a determination, we need to examine studies which employed nonverbal stimuli presented both sequentially and rapidly.

As will be seen from the preceding discussion, not all studies have found differences between dyslexics and controls on tasks requiring discrimination of stimulus sequences. However, the following comments are in order: a) studies which have found group differences for verbally codable but not for verbally non-codable stimuli have used either simultaneous presentation of sets or very slow sequential presentation; b) in such studies, the performance of the controls for non-codable stimuli is generally impaired relative to their performance for codable stimuli, while the dyslexics' performance is generally similar for the two types of stimuli; c) even in the studies discussed where group differences have been found for both verbal and non-verbal stimuli, the presentation rate has almost always been relatively slow. Thus it is possible that the group differences found may have been due to the contribution of a phonemic deficit in dyslexics which did not allow them to fully utilize mnemonic strategies in these tasks. However, as pointed out, such a phonemic deficit may itself be a symptom of an underlying temporal processing deficit, and sequence discrimination tasks which use slow presentation do not allow for an investigation of the presence of such a deficit. Thus there is a need for research using verbally non-codable stimuli with rapid sequential presentation to assess the performance of dyslexics on such tasks.

Summary of temporal processing discussions

Under the general rubric of "sequential processing" four separate components of information processing have been discussed: detection or identification of a single stimulus, numerosity or minimum separation threshold determination (including temporal integration of form), temporal order judgments, and discrimination of sequences. Researchers who have investigated the temporal processing abilities of dyslexics and normal readers have used various of these types of tasks (some involving verbally codable, and some nonverbal, stimuli), and as has been shown, dyslexics are impaired on a number of these tasks involving one or other component of temporal or sequential processing. However, as can be seen from the above discussion, rarely have dyslexics been found to be impaired on tasks requiring detection or identification of a single stimulus. Because so many of the studies in which dyslexics were found to be impaired involved tasks using nonlinguistic stimuli, the hypothesis that dyslexics' problems are based purely on phonemic, or linguistic, deficits cannot be the whole story. Moreover, it has not always been clear that the subjects in these investigations can be considered comparable. A greatly heterogeneous group of "dyslexics" has been studied, with many of the subjects being described as "poor readers" etc., and perhaps not meeting the accepted criteria for dyslexia. Furthermore, rarely have these subjects been compared to reading-matched as well as age-matched controls.

However, if a sizable sub-group of dyslexics does display a temporal processing deficit, and if this deficit plays a role in phonemic and later reading difficulties, this would account for the findings of both these studies and those reporting phonemic/linguistic difficulties in dyslexics. The difficulty lies in determining how such a temporal processing deficit might contribute to phonemic and reading difficulties, and if in fact it is causal, or perhaps resulting from linguistic difficulties (Watkins, 1990). The possible role of temporal processing deficits in reading disabilities will now be discussed.

The possible role of temporal processing deficits in reading disability

As can be seen from the evidence outlined above, temporal processing deficits at various levels have been found in dyslexics using auditory and visual tasks. It is not yet clear, however, whether a deficit in any aspect of temporal processing might be general (i.e., across modalities) or confined to a specific modality. It has been suggested that higher level sequential processing may be independent of modality (Hirsh & Sherrick, 1961). There is evidence of a link between visual and auditory deficits on segmentation tasks. In one study (Johnston, Anderson, Perrett, & Holligan, 1990), ten-year-old poor readers performed at the same level as reading-matched controls, but significantly worse than their age-matched controls, on both a visual segmentation task (the Children's Embedded Figures Test) and an auditory segmentation task (the "odd word out" task of Bradley & Bryant, 1978). The poor readers performed as well as the age-matched controls on a test of visual closure (the Mooney Test) and a memory pre-test. Performance on the two segmentation tasks was significantly correlated for the poor readers (as it was for the age-matched controls), even after partialling out chronological and reading age effects. Thus there is a link, at least for segmentation tasks, between the auditory and visual domains in poor readers. However, it should be noted that the visual segmentation task does not involve rapid presentation of stimuli. One further study has found a link among performance on visual tasks, phonological tasks, and reading ability. Eden, Stein, and Wood (1993) found that the performance of good and poor readers on visual tasks which tapped ability to localize and orientate small targets, and those measuring binocular stability, were correlated with reading ability. The visual tests, particularly left field tests, discriminated between good and poor readers almost as well as the phonological tasks. Again, however, most of the visual tasks in this study did not involve rapid presentation of stimuli. Further, the subjects were not randomly selected, which limits generalization. Such studies do, however, suggest that the relationships among reading ability, phonological ability, and visual task impairments should be explored further.

It is clear that a temporal processing deficit in either modality could affect reading ability. The co-existence of such a deficit in both modalities could create considerable difficulties for those learning to read. In view of the different time frames involved for processing of auditory or visual stimuli, the co-existence of a processing deficit at each level of temporal processing in both modalities needs to be investigated.

A temporal processing deficit might manifest itself in the various modalities, and affect reading ability, to different degrees. It may be that a processing deficit for rapidly presented stimuli in the auditory modality has a more pervasive effect on language development and subsequently on reading ability than does a deficit in the visual modality, especially in the early years when phoneme-grapheme correspondences are being learned. Normal readers attain rapid and automatic learning of these correspondences at this time, and an inability to do so will seriously affect the ability to progress in reading. The phonological processing impairment evident in dyslexics is what has contributed to the hypothesis that the problem in dyslexia is related specifically to language. Proponents of the linguistic hypothesis argue that areas of the human brain are specialized for processing speech sounds, and it is in these areas that dyslexics are experiencing difficulty. However, it has been argued that the so-called "speech" areas do not exclusively process speech sounds, but rather process any rapid auditory stimuli, many of which in human experience happen to be speech sounds (Tallal, 1984; Tallal & Curtiss, in press). Certainly the ability to use phonemes as part of a complex communicative system is exclusively human. However, the ability to discriminate phonemes based on their acoustic properties is not. In support of the argument against a specialized speech sounds perception area is the evidence that various species can be taught to discriminate phonemes such as the stop consonants, and even vowels. These species include primates such as baboons (Hienz & Brady, 1988) and birds such as Japanese quail (Kluender, Kiehl, & Killeen, 1987). A review and discussion of the evidence for categorical perception of phonemic features in animals may be found in Kuhl (1986). If non-human species can learn to categorically perceive phonemes, this argues against a specialized area in the human brain which is devoted purely to perceiving speech sounds, and nothing else.

In speech, the stop consonants involve the most rapid spectral changes, on the order of about 40 ms, with sounds such as fricatives and nasals involving much less rapid changes, and vowels being the speech sounds requiring the least temporal auditory differentiation (Phillips & Farmer, 1990). Work with infants has shown that even at the age of two months, children categorize both speech and non-speech sounds (Jusczyk, Rosner, Reed, & Kennedy, 1989). These categorizations were made when all three sets of stimuli (pa/ba, du/tu, and tones) had their categorical boundaries in the 20-40 ms range. Jusczyk et al. concluded that the infants' sensitivity to temporal order differences in the same range for both non-speech and speech stimuli suggests that the existence of specialized speech processing mechanisms to categorize voicing contrasts does not need to be invoked. The ability to categorize the speech sounds specific to one's native language appears to evolve over the first few months of life (Kuhl, 1992; Werker, 1989). Young infants have the ability to discriminate the phonemes of any language, but lose the ability to distinguish non-native language sounds at 6 to 12 months of age (Werker, 1989). It appears that experience with prototypes of a phoneme influences the perception of non -prototypical examples of the phonemes, such that outliers are categorized with the prototypes (Kuhl, 1992). Although the auditory capacity to discriminate non-native sounds remains (adults can discriminate non-native phonemes when they are shortened so that they no longer are perceived as language sounds), the ability to discriminate language -like sounds that are not part of the native language is lost in the first year of life (Werker, 1989).

In dyslexics, there is considerable evidence that phoneme discrimination is impaired. There is also some evidence, however, that this impairment extends to non -speech stimuli in the same time frames. Poor readers have been shown to be impaired on identification and discrimination tasks for speech sounds such as stop consonants (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Reed, 1989), as well as for pairs of nonverbal sounds such as tones (De Weirdt, 1988). In addition to difficulty in discrimination of rapid speech sounds (Werker & Tees, 1987), they have also been found to have problems with articulation, particularly with the voicing features of stops (Snowling et al., 1986), and to make many more consonant addition errors in the reading of non-words (Werker, Bryson, & Wassenberg, 1989). In an interesting study of children who lived in an apartment housing complex built above a busy expressway, Cohen, Glass, and Singer (1973) found that phonemic discrimination ability was correlated with reading ability and floor level of the home (and thus proximity to traffic noise). These results held even after social class and physiological damage were partialled out. Thus difficulties with phoneme discrimination associated with reading problems can be related to environmental causes. Not all studies have found dyslexics to have poor phoneme discrimination skills. In her study of preschoolers who were later found to be reading disabled, Scarborough (1990) reported that the children were deficient on phonemic awareness but not speech discrimination tasks. One possible explanation for this is that the task used (the Phoneme Discrimination Series) may not have been subtle enough to detect group differences. Certainly, as noted above, many researchers have found dyslexics to have impaired phoneme discrimination skills. When studies in which environmental sounds matched to speech sounds in acoustic features are undertaken, it may be that dyslexics are found to be impaired on nonverbal discrimination also (Breedin, Martin, & Jerger, 1989). Certainly in some of the tasks involving nonverbal auditory stimuli (e.g. Tallal, 1980) the time frames involved are similar to those involved in speech sounds.

A processing deficit in the visual modality can also affect reading ability. Di Lollo et al. (1983) suggest that slower processing rates in dyslexics cause an information bottleneck, resulting in incomplete processing and impaired perception. Lovegrove and colleagues have expanded on this explanation (Lovegrove, Martin, & Slaghius, 1986).

Based on evidence of increased visible persistence in dyslexics with low, but not high, spatial frequencies, Lovegrove has suggested that reading disabled subjects have a transient system deficit. Two classes of cells transmit information about stimuli in the visual system: parvocellular neurons (equivalent to x cells in the cat) respond to sustained stimuli, and magnocellular neurons (equivalent to y cells in the cat) respond to the onset and offset of stimuli (transience). Magnocellular neurons are more dominant in peripheral vision, and parvocellular neurons in central, or foveal, vision. Lovegrove et al. (1986) suggested that a transient system deficit may affect reading in two major ways. Firstly, reduced transient activity may result in a failure to inhibit the sustained system, and thus in interference with processing through masking by integration, as Di Lollo et al. (1983) have suggested. Secondly, decreased transient activity would delay or reduce the amount of parafoveal information available during reading. Good readers integrate such information with foveal information during successive fixations to facilitate fluent reading (Pollatsek, Lesch, Morris, & Rayner, 1992; Rayner, 1975; Rayner & Pollatsek, 1987).

Support for the first suggestion has come from Breitmeyer (1989), who proposes that in normal readers, saccadic suppression is initiated by the transient system's pick-up of information during saccades. This suppression "clears" the retinotopically organized image maintained by the sustained system, allowing for separate retinal images to follow temporally, without masking interference. Breitmeyer suggests that the longer visible persistence of reading disabled children is a symptom of their weaker saccadic suppression. This leads to increased retinal image blur and visual instability symptoms such as those reported by Stein (Stein, 1989; Stein, Riddell, & Fowler, 1989) to occur in 60 to 70% of dyslexic cases. This latter figure is consistent with the percentage of specifically reading disabled children found by Lovegrove and his colleagues to have increased visible persistence (Lovegrove et al., 1986). Support for the transient system deficit in dyslexics also comes from a study by Solman and May (1990), who found that poor readers were worse than controls at locating parafoveal patterns, but not when patterns were presented close to the fovea.

Hulme (1988) has challenged the hypothesis that low-level visual problems such as the transient system deficit proposed by Lovegrove et al. (1986) are causal to reading disabilities. Hulme bases his challenge on the evidence that most dyslexics have greater difficulty with reading single words than words in context, as well as on the evidence that a majority of dyslexics have difficulty with phonological coding/phonemic awareness tasks, and perform as well as normal readers on visual memory tasks. The latter two lines of evidence have already been addressed in this paper: the phonemic deficit might well be a manifestation of a temporal processing deficit in the auditory modality, and dyslexics often perform as well as controls on tasks involving simultaneous or slow presentation of visual stimuli. The first argument would, at first blush, appear to be more persuasive. Hulme points out that Boder's (1971) dyseidetic dyslexics (and the mixed dyslexics), who have difficulty recognizing words as visual patterns, are relatively uncommon; whereas Lovegrove et al. have found visible persistence difficulties in around 75% of the reading disabled children they have studied. Furthermore, Hulme maintains that Lovegrove et al.'s finding that their poor readers were impaired at reading nonsense words is further evidence for a phonological rather than a visual basis to the reading problems. However, while skilled readers may have reached the stage where they recognize words as wholes, or recognize within words syllables which have high-frequency letter formations, beginning and poor readers are still using what decoding skills they have to read individual words. Thus for a skilled reader parafoveal information will extend to additional words, but for poor readers attention is concentrated more on individual letters of a word, and so, except for very short words, additional (parafoveal) information will be within that word, and difficulties with the parafoveal system may well interfere with decoding of a single word. This would also interfere with the reading of non-words which, being novel, can not be recognized as a visual whole. (Good readers will read non -words more quickly and accurately by analogy to frequently seen spelling units in real words.) For instance, in a study by Shapiro, Ogden, and Lind-Blad (1990), dyslexics performed as well as age-matched controls when reading short words presented for 100 ms or 300 ms. Dyslexics were worse than controls, however, when reading long words (which required a second eye fixation) presented for 300 ms. When the long words were presented for 100 ms, giving insufficient time for a second fixation, dyslexics and controls did equally well. Additional investigation showed that given a sufficiently long presentation (3000 ms) the dyslexics could read all the words as well as controls, and that both groups made one eye fixation to short words, and two to long words. Shapiro et al. (1990) thus concluded that in dyslexics information from the second eye fixation was interfering with that from the first.

Further evidence to support the hypothesis of a transient system deficit which affects parafoveal information processing has been suggested by Livingstone, Rosen, Drislane, and Galaburda (1991). These researchers found evidence of abnormalities in the lateral geniculate nuclei in dyslexic brains. The abnormalities were confined to the magnocellular layers, where the neurons were smaller than those in control brains, whereas the parvocellular layers were not significantly different from controls. Findings of abnormalities in the magnocellular pathways of dyslexics have since been reported by Chase and Jenner (in press) and Lehmkuhle, Garzia, Turner, Hash, and Baro (1993). Since smaller neurons likely means thinner axons, with resultant slower conduction velocities, Livingstone et al. (1991) concluded that these results were consistent with the visual evoked potential (VEP) findings in dyslexics. VEP responses to slow stimuli were normal, but diminished in dyslexics at low contrast levels when rapid stimuli were presented. Since in primates the magnocellular system is capable of rapid axonal conduction, while the parvocellular region is not so heavily myelinated, Livingstone et al.

(1991) hypothesized that their findings provide an explanation for the poor performance of dyslexics on tasks involving rapid visual stimuli, and speculated that fast subdivisions of other cortical systems, such as the auditory system, might be similarly affected in dyslexics.They suggested that "(t)he neuronal subdivisions involved in fast information processing in each modality.....may share particular molecular entities and might therefore be vulnerable to the same pathogenic factors. We hypothesize that in dyslexics the rapid subdivisons (the magnocellular homologues) of many forebrain systems might be slower than normal." (p.7946)

Thus there is considerable evidence for a visual temporal processing deficit. Clearly a majority of dyslexics have a phonemic deficit; a visual processing deficit would add to the problems engendered by phonological difficulties. Studies which investigate whether dyslexics have a temporal processing deficit in the visual modality, linked to such a deficit in the auditory modality and associated with a phonemic deficit, are clearly needed.

The developmental course of temporal processing deficits is also relevant. There is currently some evidence that the visual persistence of stimuli noted in many dyslexics may be ameliorated in the pre-adolescent and adolescent years (Badcock & Lovegrove, 1981; Di Lollo et al., 1983; Martos & Marmolejo, 1992). This evidence coincides with that of increased phonemic awareness at this age (Johnston, 1982; Siegel & Linder, 1984). There is also evidence, however, that visual persistence may continue to be a problem for some dyslexics into adulthood (Winters et al., 1989). If indeed such visual temporal processing difficulties do exist in many dyslexics but generally resolve during development, and possibly before disabled readers are identified, the task of finding evidence of these deficits is a daunting one (Snowling, 1991). However, mapping the course of such deficits, and in particular mapping individual improvements and abilities, would be essential in order to provide the optimal remediation for dyslexics at each stage of their development.

Those dyslexics whose temporal processing deficit is overcome during development may be those whom Lovett (1984, 1987) has labelled "rate disabled". They are able to decode accurately, but not with the automaticity and speed that normal readers have acquired. They will very likely benefit from intensive phonemic remediation. However, such remediation is unlikely to be of benefit to those dyslexics who still show evidence of a temporal processing deficit well into their school years, and beyond. These may fall into Lovett's "accuracy disabled" category - those who still have great difficulty in accurately decoding words. It is these severely disabled readers who must rely on an increasing sight vocabulary to advance their reading level, albeit far behind their peers. In our own study (Farmer & Bryson, in preparation), which found a visual temporal processing deficit in a group of adolescent dyslexics, the students involved were severely disabled readers, and would fall into the latter (accuracy disabled) category. They were decoding on average six grade levels below their age-matched controls. They also showed evidence of unimpaired visual pattern perception, an ability that would be essential to aid them in acquiring a sight vocabulary. However, this had not been sufficient to enable them to read at anywhere close to the level of their peers.

Rationale for the study

The evidence for a deficit in some aspect of processing rapidly incoming stimuli in the visual and auditory modalities has been discussed above. Tallal has suggested that such a processing deficit, at least in the auditory modality, underlies the phonemic deficits of dyslexics which are evident from the many studies cited in an earlier section of this paper. It is important to investigate this possibility further for a number of reasons.

First, support for the hypothesis that the phonemic deficit apparent in so many dyslexics is simply a symptom of a more general auditory processing deficit will transfer the emphasis of research from the purely linguistic to the more general auditory area. Second, it is important to know whether different types of processing deficit in different modalities are correlated. Are auditory processing deficits usually associated with visual processing deficits of the same type in the same children, or can they be dissociated? Third, confirmation that such deficits, whether separate or co-existing, are correlated with reading or phonological coding ability, is also essential.

None of the studies reviewed had attempted to investigate the relationship of the temporal processing abilities of dyslexics for analagous auditory and visual tasks for the various levels of temporal processing outlined earlier. Moveover, virtually none of the studies had compared the performance of dyslexics on temporal processing tasks with that of both age-matched and reading-matched controls.

This study was therefore designed to investigate the existence of a deficit at the various levels of temporal processing outlined above, in students with dyslexia. Because basic perception of rapidly occurring sequential sounds is assumed to be a prerequisite to all further processing of such sounds, the separation threshold for sounds in dyslexics and normal readers was investigated, by means of a click fusion task. Studies with normal subjects have indicated that successively presented clicks can be perceived as separate stimuli with inter-click intervals as low as 1-3 ms (Auerbach et al., 1982). Only one click fusion test with dyslexics has so far been reported (Haggerty & Stamm, 1978), and this study involved clicks presented sequentially to separate ears. Tests with word deaf patients have shown that such subjects need inter-click intervals of up to 30 ms before the signals are perceptually segregated (Albert & Bear, 1974; Auerbach et al., 1982; Yaqub, Gascon, Al-Nosha, & Whitaker, 1988). The minimum separation threshold for visual stimuli was also investigated, by means of a flash fusion task. Previous studies involving sequential presentation of visual stimuli have generally found normal readers to be able to segregate the stimuli with ISI's in the vicinity of 50-100 ms, whereas dyslexics need ISI's on the order of 120-150 ms (Di Lollo et al., 1983; Stanley & Hall, 1973). Those studies that have tested for separation thresholds have generally used a method of adjustment to determine the ISI at which fusion occurs. However, this method is susceptible to response bias on the part of the subject. Some subjects may choose to respond conservatively. The data might thus indicate a sensitivity difference which in fact was a response bias. One way to check for this is to include a signal detection task (SDT) using a forced choice response. Therefore both types of task (method of adjustment and SDT) were used for the auditory and visual fusion tasks.

Secondly, given that two events are indeed perceived as separate, it is essential that the temporal order of the events be correctly perceived, both for the auditory identification of phonemes and the visual identity of graphemes. Thus the temporal order judgment abilities of dyslexics was investigated also, in both modalities. A third aspect of sequential processing which is felt to be crucial to both language development and reading ability is the discrimination of sequences. Sequences of incoming rapid spectral changes must be matched to phoneme representations in order for sounds to be heard as speech. In the same way, sequences of visual stimuli (the letters in words) must be mapped on to existing words in the lexicon, and on to phonological representations of those words, if reading is to proceed. Thus this study also investigated the ability of dyslexics to discriminate sequences, using auditory and visual stimuli. Nonverbal stimuli were used to avoid the confound of a phonemic deficit.

Finally, the relationship of auditory and visual temporal processing deficits with each other, and with phonemic awareness and reading ability, was explored by means of correlational analyses. For all tasks, the performance of the dyslexic students was compared to that of both age-matched and reading-matched controls, individually matched to each dyslexic student. It was considered advisable to include a reading-matched group as well as an age-matched group in order to control for reading experience, and to indicate whether any differences found might be consistent with developmental delay or deviance (Backman, Mamen, & Ferguson, 1984; Stanovich, 1988a). Since normal young readers rapidly progress through stages of reading, a group matched by mean only may not in fact accurately match the dyslexics (Bradley, 1989). Individual matches, rather than group mean matches, avoid such problems. The method and results for the three groups are described below under the heading of Experiment 1.

In addition to school-aged subjects, a group of university students was tested using the same tasks. This group's performance was not compared to the dyslexic and control subjects' performance, as they were not matched in any way to the former, and as there were minor methodological differences in administering one or two of the tasks. Interest was therefore purely in the within-group correlations for the university-level subjects, to see if the expected trends were apparent in an unselected population. The testing and results of this group will be described separately, under the heading of Experiment 2.

Experiment 1

Method

Subjects

Three groups, each of 20 children, participated in the study. Dyslexic subjects (the DYS group) were selected from a special school for the learning disabled in Wolfville, Nova Scotia. They ranged in age from 12.3 to 15.6 years, and had a mean age of 14.07 years. All were reading at least three years below grade level (median reading level = 3B, range = 1M to 7B, where B represents the beginning of the grade level, M the middle, and E the end). The average discrepancy between expected grade level and actual reading grade level was 5.75 years (range 3-7 years). In each case a diagnosis of specific reading disability had already been made by the referring school board. The examination of academic histories and relevant testing under the auspices of the joint provincial body responsible for student sponsorship at the school ensured that a diagnosis of dyslexia was appropriate in each case. It was felt that if a temporal processing deficit is correlated with dyslexia, the severity of the disability in these cases should ensure that any processing deficit has not yet been developmentally resolved (see Farmer & Bryson, in preparation). The subjects were of normal or above normal intelligence as measured by the Weschler Intelligence Scales for Children - Revised (WISC-R). Mean Performance IQ was 114, with a range of 104-129. In order to obtain as homogeneous and representative a sample as possible, only those subjects were selected whose Performance IQ on the WISC-R was higher than their Verbal IQ (mean difference was 18.25 points, with a range of 6-32 points). Such discrepancies have been used by Boder (1971) in her subtyping of reading disabled children. The pattern of higher Performance than Verbal IQ was noted in a majority of cases, and was associated with Boder's dysphonetic dyslexic group. Doehring, Trites, Patel, & Fiedorowicz (1981) also noted that a majority of disabled readers evidence this pattern. The files of all subjects were examined for evidence of any condition which might affect performance, such as hearing or uncorrected visual problems, hyperactivity or attention problems. Any subject who showed evidence of any such condition was excluded from the study. This exclusion applied to the control subjects as well as to the dyslexics.

Two control groups of normal readers were selected from the Halifax City public school system. The age-matched (AM) group consisted of 20 subjects, each matched individually for age and intellectual level to the dyslexic subjects. The criteria used were that each match should be within 3 months (plus or minus) of the age, and that the Full-Scale IQ or standard score on the available measure of achievement should be within 5 points (plus or minus) of the Performance IQ of the dyslexic subject. Performance IQ was used for the dyslexics because it is more indicative of the subject's actual intellectual level, since Verbal IQ is affected by reading ability and experience. Where WISC-R scores were not available for the control subjects (the majority of cases), matching was done on the basis of full-scale Canadian Achievement Test (CAT) results. The CAT is a group-administered test which measures various areas of educational achievement, with the emphasis on language and mathematics. Mean age of the AM group was 14.10 years (range = 12.4 to 15.3 years). Median reading level was 8E (range = 5E to 12E). Mean IQ/CAT score was 113 (range = 100 to 127).

The reading-matched (RM) group consisted of 20 subjects matched individually for reading level and IQ. The criteria were that each dyslexic was matched with a child whose reading level was within a year of the same grade level. For the three subjects in the RM group for whom IQ or CAT scores were available, the Full-Scale IQ or equivalent of the control subject was within 5 points (plus or minus) of the Performance IQ of the matched dyslexic. No test scores were available for the younger (Grades 2 and 3) children (the remaining 17 subjects in the RM group), because the school system in question does not routinely administer group tests of cognitive ability until the end of the third grade. In these cases the selection of students was based on their teachers' appraisal of their intellectual level. Dyslexics to be matched at each Grade 2 or 3 reading level were classified as "average" or "above average" in intelligence, based on their Performance IQ score, and teachers were asked to select students at the appropriate reading level whom they deemed to be in the same classification as the dyslexic to be matched. To verify the teacher's appraisal, an approximation of IQ was made using the Block Design sub-test of the WISC-R for each Grade 2 and Grade 3 student. This is considered to be the best of the Performance Scale sub-tests for measuring g, and it correlates reasonably well with both Performance IQ and Full-Scale IQ (Sattler, 1982). Mean age of the RM group was 8.8 years (range 7.4-12.8 years). Median reading level was 3B (range = 2M to 8B). It was not possible to calculate a mean IQ for this group because of the lack of IQ or CAT scores. However, scaled scores on the Block Design sub-test for the Grades 2 and 3 students confirmed the teachers' assessments of intellectual level in the following way: a scaled score of 9, 10, or 11 on the Block Design sub-test was considered as equivalent to average intelligence, and a scaled score of 12 or higher was equated to above average intelligence. In each case the scaled score category matched the teacher's assessment.

The mean age, Performance (or Full Scale) IQ/CAT score, and median reading level for all three groups are shown in Table 1. There was no significant difference between the two older school-age groups (DYS and AM) in intellectual level ($F_{1,38}$=1.25, p>.1), or in age ($F_{1,38}$=1.05, p>.1). There was no significant difference in reading level (raw scores on the WRAT-R) between the DYS and RM groups ($F_{1,38}$=2.05, p>.1). Although parental socioeconomic status was not formally measured, the subjects in each group were judged to be from essentially comparable socioeconomic backgrounds. The public school from which the control subjects were recruited served an area which encompassed both lower and middle class neighbourhoods. Control subjects came from many different parts of this area. Dyslexic subjects came from a variety of areas within the Maritime Provinces: rural areas, small towns, and cities. None was privately funded at the special school.

Subjects in this study were treated in accordance with the guidelines outlined in the Canadian Code of Ethics for Psychologists issued by the Canadian Psychological Association (1988). Before subjects were recruited the proposal for this study was approved by the Ethics Committee of Dalhousie University, by the Halifax City School Board, and by the staff of the schools concerned.

Dyslexics were recruited by sending a letter and a description of the proposed study to the parents of all subjects in the school files who met the criteria outlined above. Twenty-eight such subjects were identified. Eight of these declined to take part in the study. The older control subjects were recruited by examining the school files for students who matched one of the dyslexic subjects who took part in the study. Younger controls were recruited by asking the teacher of the appropriate grade level class to supply the names of students who met the criteria to match each dyslexic. A letter and description of the study were then sent to each student's parents. If the student or parents refused the request to take part in the study, another match was sought through the school files or the appropriate teacher. In all 27 subjects were approached before 20 subjects were recruited for the AM group; 23 subjects were approached for the RM group. The subjects who declined to take part in the study did not differ in any obvious way from those who accepted. In every case, written consent was obtained from a parent before the student participated in the study. Verbal consent was also obtained from each student before any tasks were administered, after the procedure was clearly explained. Every student was told that he/she was under no obligation to take part in the study just because parents had given permission, and that if at any time he/she did not like what he/she was being asked to do, or felt uncomfortable, then he/she had the right to leave, without any explanation, and that there would be no consequences for such discontinuation. Every care was taken to ensure that the younger children, in particular, understood this clearly. No subject took advantage of this right.

Stimuli and Apparatus

All visual and auditory task stimuli were produced by means of an Apple IIe computer with an Apple III screen, using a John Bell Engineering, Inc. 6522 parallel interface card. Auditory stimuli were presented to the subject by means of a pair of Jana stereo headphones, model BJ-2004, fed through a peripheral driver box. Volume of the tones was tested using a Bruel and Kjaer Type 2203 audiometer calibrater, with a Type 4152 artificial ear. Using an A weighting, the level of the high tone was 74 dB, and the low tone was 69 dB. There was less than half a decibel difference between the left and right earphones. It was not possible to measure the volume of the click stimuli because of the brevity of the signal. All subjects were asked if they could hear the clicks adequately, and no subject expressed any difficulty. Visual stimuli were presented either on the screen or by means of a red 20 milliamps light emitting diode (LED) within a small metal box taped to the right-hand side of the computer screen at eye level, and controlled by the computer through the peripheral driver box. The metal box measured 5.5 cm high by 4 cm wide, and the light was visible through a 6.4 mm aperture recessed 2.5 cm deep in a 2 cm diameter circular opening in the centre of the front of the box. The subject was seated in front of the computer, approximately 44 cm from the screen. The approximate luminance of the screen in each testing situation was assessed periodically throughout each day, using an Asahi Pentax digital spotmeter, approximately one and a half meters from the computer screen. A reading between 1.0 and 1.9 foot-lamberts was considered acceptable. Where necessary (because of bright sunshine), light conditions were adjusted using window screens. This was only necessary in the case of 12 of the dyslexic students, on the first session for each. Since the first session involved only the reading and phonemic awareness tasks, and the auditory tasks, no visual tasks were affected. Each subject was asked at the beginning of the visual tasks if he/she had any difficulty with seeing the stimuli, and none expressed any problems. Responses were recorded by means of a two-key keypad constructed with microswitches, placed to the right of the computer keyboard, using the subject's dominant hand. The two keys were appropriately labelled for each task by means of small Velcro tabs which could be affixed above each key.

In the click fusion task, clicks were square waves. They were approximately 0.1 ms (0.0997 ms) in duration, and ISI's could be increased or decreased, to a minimum and maximum of 0 and approximately 20 (19.947) ms, by means of the left and right arrow keys on the computer keyboard. Tones consisted of trains of square wave clicks, each 25.422 microseconds in duration. Total duration of tones was as close to 75 ms as possible, with virtually zero rise and decay times. "High" tones were set at 305 Hz (70.439 ms), and "low" tones at 100 Hz (71.615 ms). In the flash fusion task, flashes were presented by means of the LED light in the small metal box. Each flash was 20 ms in duration, and ISI's could be increased or decreased by increments of 10 ms, to a minimum and maximum of 0 and 150 ms, by means of the left and right arrow keys on the computer keyboard. Symbols in the temporal order judgment task were presented on the computer screen, and were designed to be not easily verbally codable. The two symbols ( and ) each occupied a 5 x 12-pixel cell and each was comprised of 36 pixels. Each symbol was 6 mm high and 4 mm wide, subtending a visual angle of 0.78 degrees. Matrices in the sequence matching tasks were presented on the computer screen, and consisted of 16 outlined boxes in a 4 x 4 configuration. The complete matrix measured approximately 8 cm high by 8.5 cm wide, and subtended a visual angle of 11.07 degrees. Each box measured approximately 2 cm high by 2.1 cm wide, and the light flashes which appeared within the boxes each measured approximately 6 mm high by 5 mm wide. Flashes were of 100 or 400 ms duration. All frequency durations and waveform characteristics were checked using a Hewlett-Packard Oscilloscope, Model Number 1701A.

<u>Procedure</u>

All school-age subjects were tested individually in a quiet room in their own schools, during classroom hours. Before proceeding with any testing, the experimenter reminded the subject of the general nature of the experiment, and thanked him/her for volunteering his/her help. Each subject was reminded that he/she was free to discontinue the testing at any time, should he/she so wish.

Testing took place over two or three sessions. During the first session, the two reading tests (single word decoding and nonsense word decoding) and the phonemic awareness tasks were administered, followed by the temporal order judgment for tones task, the click fusion task and finally the tone sequence matching task. This session lasted approximately 50-60 minutes, and for the younger children was split into two shorter sessions, with the reading and phonemic awareness tasks in the first session, and the auditory tasks in the second. During the final session, the second visual task (temporal order judgment for symbols) was presented, followed by the first, third and fourth visual tasks (flash fusion, and the two pattern matching tasks). This session lasted about 30-35 minutes. Counterbalancing was not employed for two practical reasons. First, pilot testing indicated that the tasks were fairly difficult for the younger children, and it was easier for them to follow them in the prescribed order. Second, because of task difficulty, it was not clear at the outset that the youngest subjects would be able to finish all of the tasks. Therefore it was decided not to use counterbalancing so that at least some of the tasks would be completed by all subjects. Furthermore, because comparisons were being made across groups, rather than across tasks, counterbalancing was deemed not to be essential. While it is possible that fatigue might affect some groups differentially, and thus affect results, it was anticipated that the two age-equivalent groups would perform equivalently in this respect. Splitting the first session's tasks into two separate sessions was done to counteract fatigue effects in the younger children.

All tasks were explained thoroughly, and a short practice session was given for each to ensure that the subjects were familiar with the requirements and the necessary responses. At the end of the testing procedure all subjects were thanked again, and the youngest subjects (elementary school level) were given coloured stickers to reward them for their participation.

Measurements

(a) Reading tests.

A more precise reading level than that derived from the school files was obtained for all subjects by use of the Wide Range Achievement Test - Revised (WRAT-R)

Reading Test (Jastak & Wilkinson, 1984). This is an untimed test of single word recognition. A word recognition test was used in order to assess the sight vocabulary of subjects without the aid of contextual cues. Limited information is available on the reliability and validity of this test, although the test-retest reliabilities that have been reported are satisfactory, and modest correlations have been reported between the WRAT -R and the Woodcock-Johnson Achievement Test (Spreen & Strauss, 1991). Test-retest reliability coefficients reported by the test authors ranged from .90 to .96, and moderately high correlations were reported with various achievement tests (Jastak & Wilkinson, 1984). While this test is not recommended for individual diagnostic or remediation design purposes, it is considered of value for assessing a subject's level of development in comparison with normative populations (Spreen & Strauss, 1991). Level I of the WRAT -R was used for control subjects aged 11 years and below, and Level II was used for control subjects aged 12 years and above. All dyslexic subjects were given the Level I test. In addition to the WRAT-R Reading Test, a test of non-word decoding ability was also administered. This was the Word Attack sub-test of the Woodcock Reading Mastery Tests (WRMT) (Woodcock, 1987). The split-half reliability coefficients reported are good (in the .80's and .90's), and modest to high correlations have been reported with other tests of achievement (Spreen & Strauss, 1991; Woodcock, 1987). It was considered desirable to obtain the level of non-word reading, because a majority of dyslexics (particularly those evidencing the Performance > Verbal IQ pattern) are deficient at assembling the phonological pronunciations required to read non-words (Bryson & Werker, 1989; Lovett, 1984). Both the above tests were scored in accordance with the test instructions in the relevant manuals. In order to counteract any possible experimenter bias in scoring, subjects' responses were tape-recorded and also scored by a second rater who was blind to group membership and the aims of this study. In cases of dispute a third rater, also blind to group membership and study aims, made the final decision.

(b) Phonemic awareness tasks

Tasks (i) and (ii) were based on those used by Bradley & Bryant (1978; 1983; see also Bradley, 1989).

(i) In this task (the odd-one-out task), subjects were read four monosyllabic, three -phoneme words (generally CVC words). Three had the same first (or second, or last) phoneme, one was different. The subject's task was to identify the word which differed in the designated phoneme. After a practice set to illustrate what was required, six sets of four words were presented for each phoneme position. The sets of words for each phoneme position are listed in Appendix 1. The word selected was recorded by the experimenter.

(ii) Subjects were required to produce as many words as they could in thirty seconds, which rhymed with a monosyllabic word. Five such words were presented, one at a time. The words were: meet, sand, beam, white, punt. The subject's score was calculated as the mean number of rhyming words produced for test words. Non-rhyming words or non-words were not included in the scoring.

(iii) Twenty selected items from Rosner's auditory analysis test (Rosner & Simon, 1971) were presented. In this test, the subject is required to say what a word will sound like with a certain phoneme removed. The complete list of words and phonemes to be removed which was used is presented in Appendix 2. The subject's score was the number of correct "remainders" enunciated.

(c) Auditory temporal processing tasks.

Three auditory tasks were presented: a click fusion task, a temporal order judgment task using tones, and a tone sequence matching task.

(i) Click fusion: In this task, pairs of clicks were produced with no or extremely small ISI's and subjects were required to judge whether one or two clicks had been presented. ISI's were measured from offset of the first click to onset of the second. Subjects were first given a demonstration of how the clicks sounded. Starting with an ISI of 5 ms, the ISI was increased to 20 ms and then decreased to 0 ms, so that the subject could hear the difference between one and two clicks. The ISI was then reset at 5 ms, and subjects were asked to increase or decrease the intervals until they reached the lowest ISI at which they felt that two clicks were presented. The computer continued to generate pairs of clicks with that ISI, with 3 s between pairs, until the subject designated a new ISI. When the subject indicated that he/she was satisfied with the level reached, the experimenter pressed the "C" key to indicate an ISI had been selected. The computer recorded the level of ISI selected. Following this, 40 pairs of clicks were presented, with either a 4 ms or a 0 ms ISI, presented in random order, in order to provide a second measure of sensitivity and to assess response bias. Subjects were told that in some cases only one click would be presented, and in other cases, two clicks. They indicated whether they heard one or two clicks by pressing the appropriately marked keys ("1" or "2") on the computer keyboard.

(ii) Temporal order judgments for pairs of high/low tones: this task was similar to the sequencing test employed by Tallal (1980). During phase 1 of this task, subjects were trained to respond to the high (H) tone by pressing the right-hand panel on the keypad (marked "Hi"), and to the low (L) tone by pressing the left-hand panel (marked "Lo"). Feedback was given by means of a plus or minus sign on the computer screen, and stimuli were presented until the subject reached a criterion of 6 out of 8 presentations correct. In phase 2, pairs of tones were presented with ISI's of 430 ms, and subjects were trained to respond by pressing the panels of the keypad to correspond to the order of the tones. Pairs of LL, LH, HL, or HH tones were randomly generated by the computer, with the over-riding criterion that identical pairs could not be presented more than twice in succession. If the subject considered that only one tone had been presented, one key -press was acceptable. In all phases, if no response was made within 8 seconds, the computer issued a low beep before proceeding with the next trial. Feedback was given as before until the subject reached a criterion of 6 out of 8 presentations correct. The number of practice trials to reach criterion was recorded in both phases 1 and 2. In phase 3, the task proper, 24 two-element patterns were presented, with 8 each having ISI's of 40, 120, and 360 ms. Pseudo-random order had been generated for the patterns, and all subjects received the stimuli in the same order. No feedback was given in this phase, and responses and reaction times for each key-press were recorded. Reaction times were calculated from the offset of the second stimulus. Subjects were scored for the number of correct trials (both responses correct). Reaction time was calculated as the mean reaction time for correct trials.

(iii) Sequence matching task: Subjects were presented with pairs of tone sequences, each sequence consisting of four high or low tones of 75 ms duration each. The first tone in each pair was always identical, and the pair either followed the same pattern (e.g., HLLH/HLLH) or differed in one or more of the succeeding tones (e.g., HLHH/HHLH). There was a 2 s interval between the presentation of the first and second sequences. The subject was required to press the left key on the keypad (marked S) if the sequences were the same, and the right key (marked D) if they were different. Three different lengths of between-tone intervals were randomly used. In the first, ISI's were 40 ms, in the second, ISI's were 120 ms, and in the third, ISI's were 360 ms. Sixty pairs of sequences were presented (30 same, and 30 different, in random order, with 20 pairs at each ISI). There were an equal number of same/different pairs at each ISI. Reaction times and responses were recorded. Reaction times were calculated from the beginning of the second series in each trial. Responses with reaction times of less 150 ms were not used in calculating means, as it was assumed that such responses must have been made before the second series of tones had been heard. The subject's score was the number of correct decisions. The reaction time was calculated as the mean reaction time for correct decisions.

(c) Visual temporal processing tasks.

Four visual tasks were presented: a flash fusion task, a temporal order judgment task using symbols, and two sequence matching tasks (one with sequential and one with simultaneous presentation).

(i) Flash fusion: The first visual task was somewhat analogous to auditory task (i), the click fusion task. In the visual task, two light flashes were presented by LED with short ISI's, and the subject was required to judge whether one or two flashes had been presented. During pilot study work, it was found that a demonstration of what the two flashes looked like in rapid succession was not necessary. The starting ISI was 50 ms and ISI's could be increased or decreased by increments of 10 ms (down to 0 ms and up to 150 ms) by the subject, using the left and right arrow keys on the computer keyboard. The subject was asked to adjust the intervals until he/she reached the lowest level at which it was felt that two flashes had been presented. Pairs of flashes were shown, with inter -trial intervals of 3 s, until the subject selected a new ISI, When the subject indicated that the level had been selected, the experimenter pressed the 'C' key on the keyboard. The computer recorded the ISI level selected. Following this, 40 pairs of flashes were presented, with either an 80 ms or 0 ms ISI, in random order, to provide a second measure of sensitivity and to assess for response bias. Subjects were told that in some cases one flash would appear, and in other cases two would be presented. They pressed the appropriate keys ("1" or "2") on the computer keyboard to record their decision as to the number of flashes.

(ii) Temporal order judgment task: This task was analogous to the second auditory task. In phase 1, subjects were trained to press either the left or right panel of the keypad to correspond to the symbol presented. Reproductions of the symbols were attached above the panels to assist in learning the responses. Feedback was given during the training phase, as in the auditory task. When the criterion of 6 correct responses out of 8 was reached, phase 2 was begun. Pairs of symbols were presented, with a 400 ms ISI, and subjects were trained, with feedback, to respond by pressing the panels in order of the presentation, until a criterion of 6 correct responses out of 8 was reached. The subjects were told if they thought only one symbol was presented, they should press only one key. In all phases, if no response was made within 8 seconds, the computer issued a low beep before proceeding with the next trial. Symbols remained on the screen for 100 ms in all phases of this task. The number of training trials to reach criterion was recorded. In phase 3, the task proper, 24 two-element patterns were presented, with 8 each having ISI's of 50, 100, and 250 ms. No feedback was given during this phase. Reaction times (calculated from the offset of the second stimulus) and responses were recorded. The subject's score was the number of correct trials (both responses correct). Reaction time was calculated as the mean reaction time for correct trials.

(iii) Pattern matching task (sequential): Subjects were asked to make same-different judgments for patterns of light flashes briefly displayed sequentially (one flash at a time) in a 4 x 4 matrix. A blank matrix first appeared on the monitor screen. After a 1 s delay, four light flashes appeared sequentially in four of the 16 boxes in the matrix. The patterns were randomly determined prior to the experiment, with the constraint that only one flash would appear in any one column or row per presentation. Patterns were then recorded, so that all subjects received identical stimuli. Except as described below (in "different" trials), stimuli always appeared in the order left to right across the matrix. After a 2 s delay, a second pattern of four sequential light flashes was presented. In this task, the pattern of flashes was always identical, as were the first and last flashes shown, but the order in which the two intermediate flashes appeared was different in half of the trials. The subject's task was to determine whether the two patterns had appeared in the same, or a different order, and to press the appropriate key ("s" or "d") on the keypad accordingly, using his/her dominant hand. Six practice trials were given to each subject. Practice trials could be repeated if necessary. Twenty trials at each of three ISI's were then presented. Duration of flashes was 100 ms in each condition. In the fast condition, the ISI between flashes was 50 ms, in the medium condition the ISI was 100 ms, and in the slow condition, the ISI was 250 ms. Fast, medium and slow conditions were presented randomly, and there was an equal number of same or different order of presentation at each speed. Reaction times (recorded from the onset of the second series in each pair) and responses were recorded. Reaction times of less than 150 ms were not included in calculations, as it was felt that such responses must have been made before the second series of stimuli could have been seen. The subject's score was the number of correct decisions made. The mean reaction time for all correct responses was calculated.

(iv) Pattern matching task (simultaneous): The fourth visual task was similar to the third, except that the four light flashes appeared simultaneously, rather than sequentially. Each pattern remained on the screen for either 100 ms (fast condition) or 400 ms (slow condition). After a 2 s delay, a second pattern of light flashes appeared, remaining on the screen for the same time as the first pattern. Following practice, forty trials in all were presented (20 at each speed, in random order), with inter-trial intervals of 3 s. Half of the trials contained identical pairs of patterns, and half contained different pairs. An equal number of same and different pairs were presented at each speed. Again, the subject was required to make same or different judgments. Responses and reaction times were recorded and scored as in the sequential matching task above.

Results

Group comparisons

All analyses were carried out using an SPSS statistical package. Analyses of variance were performed on the data for each task. Repeated measures analyses of variance were used where appropriate. Evaluation of interactions was carried out by tests of simple main effects. Where significant differences were indicated, non-orthogonal planned comparisons were executed, in the manner suggested by Keppel & Zedeck (1989), and using the mean square error term from the overall F test. The reported probabilities from the analyses are unadjusted for multiple comparisons.

1) Reading tests and phonemic awareness tasks

Mean scores and standard deviations for all three groups on the WRAT-R reading test are shown in Table 1, and for the Word Attack test are shown in Table 2[3]. Scores on the three phonemic awareness tasks (odd-one-out, rhyming words, and auditory analysis) are also shown in Table 2.

a) WRAT-R

Median grade equivalent reading levels for the three groups have already been reported. Since the AM group had completed the Level II test, it was not possible to compare their raw scores with those of the DYS and RM groups, who had taken the Level I test. Therefore the grade equivalent scores were converted to numerical data by assigning the following values: B = 0.2, M = 0.5, and E = 0.8. Thus a grade equivalent of 3B was assigned the numerical value of 3.2. An analysis of variance was then performed using these values, to verify that the reading level of the younger control group was indeed equivalent to that of the dyslexics, as planned in subject selection. This analysis indicated a significant main effect for group ($F_{2,57} = 81.12$, $p<.001$). Planned comparisons indicated that the reading levels of the DYS and RM groups were not significantly different ($F<1$), but the level of the AM group was significantly higher than that of the other two groups ($F_{1,57} = 164.23$, $p<.01$).

b) Word Attack

The maximum score which can be made on this test is 45. Analysis of variance of the Word Attack test scores indicated a main effect for group ($F_{2,57} = 16.00$, $p<.001$). Planned comparisons showed that the performances of the DYS and RM groups on this test did not differ ($F_{1,57}=1.49$), but that the DYS group scored significantly lower than the AM group ($F_{1,57}=30.19$, $p<.01$).

c) Odd-one-out

The maximum score which can be made on this task is 18. Analysis of variance of the results of the odd-one-out phonemic awareness task indicated that there was a significant Group effect ($F_{2,57} = 4.116$, $p=.021$). Comparisons were carried out as planned, and indicated that the DYS group scored significantly lower than both the RM group ($F_{1,57} = 5.07$, $p<.05$), and the AM group ($F_{1,57} = 7.11$, $p<.01$).

d) Rhyming words

There is no maximum score on this task. There was a significant effect for group on this task ($F_{2,57} = 6.27$, $p=.003$). Planned comparisons indicated that there was no difference between the scores of the RM and DYS groups ($F<1$), but that the AM group were significantly better than the DYS group at producing rhyming words ($F_{1,57} = 11.16$, $p<.01$).

e) Auditory analysis

The maximum score which can be made on this task is 20. There was a significant effect for group on this task also ($F_{2,57} = 6.039$, $p=.004$). Planned comparisons indicated that the scores of the RM and DYS groups did not significantly differ ($F_{1,57}=1.12$), but that the AM group scored significantly higher than the DYS group ($F_{1,57} = 11.53$, $p<.01$).

2) Auditory tasks

a) Click fusion

Analysis of variance on the ISI's needed to hear two clicks indicated that there was a significant effect for Group on this task ($F_{2,57} = 4.08$, $p=.022$). Comparisons were carried out as planned. These indicated that the mean ISI of the DYS group was considerably longer than that of both the RM group ($F_{1,57} = 4.08$, $p<.05$), and of the AM group ($F_{1,57} = 7.61$, $p<.01$). Data are illustrated in Figure 1.

Following the method of adjustment to determine the ISI needed to perceive two clicks, a series of trials was presented, consisting of either one or two clicks, to assess response bias. In this signal detection portion of the task, both hits (correct response when two clicks were presented) and false alarms (incorrect response when one click was presented) were recorded by the computer and subsequently analysed, to provide an independent assessment of sensitivity and response bias in the click fusion task. Analysis of variance on the number of hits on this task revealed that the group effect for hits approached significance ($F_{2,57} = 2.91$, $p=.063$), but planned comparisons indicated that neither the difference between the RM and DYS groups ($F_{1,57}=2.36$) nor between the AM and DYS groups ($F<1$) approached significance. There were no differences among the three groups for false alarms ($F<1$). Mean ISI's, false alarms, and hits for the three groups on this task are given in Table 4. Also given in Table 4 are the mean d' and beta values for each group. Values for d' were calculated using the table of Green and Swets (1966). An analysis of variance performed on these data revealed that there were no significant differences among the groups ($F_{2,57} = 2.54$, $p=.09$). Values for beta were calculated using the method of Hochhaus (1972) as follows:

$$\text{Beta} = A/B$$

where A is the ordinate value of the standardized normal distribution for the hit rate, and B is the ordinate value of the standardized normal distribution for the false alarm rate. The means shown in Table 4 reflect the values for beta for each group obtained in this way. However, distribution of these data was extremely skewed, as the values calculated range from 0 to infinity, with 1 as a mid-point. In order to normalize distribution for analysis, the following transformations were used:

If A/B $\geq$ 1, then beta = 1-(B/A)

If A/B < 1, then beta = 1-(A/B)

The transformed values ranged from 0 to 1. Means (and standard deviations) of the transformed values were as follows: DYS = 0.55 (0.40), AM = 0.38 (0.42), and RM = 0.37 (0.44). An analysis of variance performed on the transformed values revealed no significant differences among groups ($F_{2,57} = 1.24$, p=.30).

The lack of a significant difference among the d' values suggests that the longer ISI needed by the DYS group to segregate clicks may in fact be an indication of response bias in the self-administered method of adjustment, rather than a sensitivity difference. That is, the dyslexics may have been more conservative in their judgment of whether two clicks were being presented in the earlier portion of the task. As a further check on this, a correlational analysis was carried out on the values for d' and ISI selected for each group. It was reasoned that a significant correlation between these data points would suggest that the ISI's recorded were in fact an indication of the sensitivity of the subjects, rather than a response bias. Correlation coefficients for each group were as follows: DYS = .04, AM = -.36, RM = -.45. The correlation for the RM group was significant (p<.05), but that for the other two groups was not. Thus it is not possible to assert with confidence that the difference in ISI recorded for the DYS group is an indication of their sensitivity in detecting two clicks, as the possibility that the longer ISI is a result of their response bias can not be ruled out.

b) Temporal order judgment - tones

It was anticipated that the dyslexics (and possibly the reading-matched controls) would have more difficulty determining the order of stimuli that were different (i.e., HL or LH tones) than when they were the same (i.e., HH or LL tones), because in that situation there was no possibility of mistaking the order, assuming the identity was recognized. Therefore the condition, same or different (SD), was entered into the analysis as a variable. The analysis performed was thus a 3 x 3 x 2 (Group x ISI x SD) repeated measures analysis of variance. Results of the overall analysis showed a main effect for Group ($F_{2,57} = 7.27$, p=.002), for ISI ($F_{2,57} = 12.26$, p<.001), and for SD ($F_{1,57} = 15.49$, p<.001). The Group x SD interaction was significant ($F_{2,57} = 4.24$, p=.019), but no other interaction approached significance. Group means for percentage of overall correct order judgments at each ISI are shown in Table 5, together with group means for percentages of correct judgments for same and different stimuli at each ISI. It will be noted that the variance for the DYS group (and to some extent the RM group) was extremely large. Perusal of individual data revealed that on some tasks the range of scores went from 0 to 100 per cent correct. It was clear that some subjects in the DYS group had no difficulty with this task, while others had considerable difficulty. Variance for the AM group was much smaller, with most subjects in this group performing very well, and no subject having more than minor difficulty. The data over all stimulus conditions are illustrated in Figure 2. Figures 3 and 4 show the results when stimuli were the same, or different, respectively.

Because both ISI and SD were predicted to have an effect, analyses of both main effects by group were carried out as planned. Analysis of variance on the effect of ISI on the overall scores showed there was a significant difference for the RM group ($F_{2,38} = 10.00$, p<.001), but not for the DYS or AM groups (p>.05 in both cases). In order to explore this result further, the difference in percentage of correct responses for the fastest and slowest ISI's (360 ms and 40 ms) was calculated for each group. Analyses were then performed to see how the groups compared on this new variable. Results indicated that the DYS group differed from neither the AM nor the RM group on this variable ($F<1$ in both cases).

The effect of SD was then explored. When stimuli were the same, there was no difference in performance among the groups ($F_{2,57} = 2.63$, $p=.08$), although the trend was for the DYS group to have fewer correct responses than the other two groups. However, when stimuli were different, analysis of variance indicated a main effect for group ($F_{2,57} = 8.12$, $p=.001$). Planned comparisons revealed that there was no difference in performance of the RM and DYS groups with different stimuli, but that the AM group gave significantly more correct responses than the DYS group ($F_{1,57} = 15.15$, $p<.01$).

The effect of ISI when stimuli were the same, and when they were different, was then explored. When stimuli were the same, there was no difference in performance at the various ISI's for any group. When stimuli were different, there was an effect of ISI for the RM group ($F_{2,38}= 7.85$, $p=.001$), but not for the DYS or AM groups. However, the effect of ISI approached significance for the DYS group ($F_{2,38}=2.92$, $p=.066$)

Thus, as expected, temporal order judgments were harder for the dyslexics (and the reading-matched controls) when different stimuli were required to be ordered. When no ordering was required (when stimuli were the same), both the DYS and RM groups were as good as the AM group at recognizing the stimuli. However, contrary to expectations, an effect of ISI was only seen for the RM group, and not for the dyslexics also, although the trend was in this direction. As can be seen from Figure 2, all groups did do better as ISI increased, but not significantly so in the case of the DYS and AM groups.

c) Tone sequence matching

The mean percentage of correct responses for each group when tone sequence sets were the same, and when they were different, are given in Table 6. The data are illustrated in Figures 5 and 6. A 3 x 3 x 2 (Group x ISI x SD) repeated measures analysis of variance revealed that the effect for Group did not reach significance ($F_{2,57} = 2.11$, $p=.13$), but that the main effects for SD ($F_{1,57} = 55.29$, $p<.001$) and for ISI ($F_{2,114} = 52.31$, $p<.001$) were significant. There was a significant ISI x SD interaction ($F_{2,114} = 59.60$, $p<.001$), and a Group x SD interaction which approached significance ($F_{2,57} = 3.09$, $p=.053$). This latter interaction was explored by looking at simple main effects, but no effect for group was found. Perusal of the data suggests that the fact that the SD difference is greatest for the RM group may have contributed to this interaction.

3) Visual tasks

a) Flash fusion

Mean ISI's needed to see two flashes from the method of adjustment procedure, and mean numbers of false alarms and hits from the signal detection task procedure, are shown in Table 7 for each group. Analysis of variance on the ISI's indicated that there was no effect for group ($F_{2,57} = 1.75$, $p=.183$). Analysis of variance on the number of false alarms (responding two flashes when one had been presented) and on hits (responding two flashes when two had indeed been presented) revealed no group differences ($F_{2,57} = 1.29$, $p=.284$ for hits; $F<1$ for false alarms). Table 7 also gives the means of d' and beta for each group. These were derived in the same way as for the click fusion task. Analyses of variance revealed no differences among the three groups for either d' or beta ($F<1$ in both cases). As was done for the click fusion task, the correlation coefficients for d' and ISI were calculated for this task. None was significant (DYS: $r = -.13$; AM: $r = .24$; RM: $r = -.10$). Thus, as with the click fusion task, the data from the signal detection portion of the task would seem to indicate that response bias could not be ruled out when considering the results of this task.

b) Temporal order judgment - symbols

As with the auditory TOJ task, it was anticipated that the dyslexics (and possibly the reading-matched controls) would have more difficulty when the symbols presented were different than when they were the same. A 3 x 3 x 2 (Group x ISI x SD) repeated measures analysis of variance was thus performed. Group means at each ISI for overall correct responses and for both same and different stimuli are shown in Table 8. Data for overall correct responses are illustrated in Figure 7; those for same and different stimuli are illustrated in Figures 8 and 9 respectively. There was a significant main effect for ISI ($F_{2,114} = 5.95$, p=.003), for SD ($F_{1,57} = 8.86$, p=.004), and for Group ($F_{2,57} = 3.61$, p=.033). Although none of the interactions approached significance, in order to provide comparability the same analyses (i.e., investigation of the effects of ISI and SD for each group) were performed as for the auditory TOJ task. Analysis of variance on the overall scores for each group across ISI showed that the effect of ISI for the DYS group was significant ($F_{2,38} = 3.40$, p=.044), but the difference for the other two groups did not approach significance. (The actual mean differences across ISI were largest for the RM group, but presumably the larger variances for this group precluded any significant findings.) In order to explore this result further, the difference in percentage of correct responses for the fastest and slowest ISI's (250 ms versus 50 ms) were calculated for each group, as was done for the analogous auditory task. Analyses were then performed on this new variable. Results indicated that there were no significant differences among the groups on this variable (F<1). The effect of SD was then explored. When stimuli were the same, the difference among the groups was significant ($F_{2,57} = 4.42$, p=.016). However, planned comparisons indicated no significant differences between the RM and DYS or DYS and AM groups. Thus the difference found was clearly due to the performance of the AM group versus the performance of the RM group. When stimuli were different, there was no difference in performance among the groups ($F_{2,57} = 1.87$, $p=.163$).

c) Pattern matching - sequential presentation

Mean correct responses for each group at the three ISI's for both same and different order presentations are shown in Table 9, and are illustrated in Figure 10. A 3 x 3 x 2 (Group x ISI x SD) repeated measures analysis of variance was performed. The main effect for Group was significant ($F_{2,57} = 7.51$, $p=.001$), but there was no significant effect for SD ($F<1$) or for ISI ($F_{2,57} = 2.03$, $p=.136$). Only one interaction was significant, that for ISI x SD ($F_{2,144} = 4.33$, $p=.015$). The effect for Group was explored. Planned comparisons revealed no difference between the performances of the RM and DYS groups ($F_{1,57} = 2.18$, $p>.05$), but the difference between the AM and DYS groups was significant ($F_{1,57} = 5.60$, $p<.05$)

d) Pattern matching - simultaneous presentation

Mean correct responses for each group at the two stimulus durations, for both same and different stimulus sets, are given in Table 10, and are illustrated in Figure 11. A 3 x 2 x 2 (Group x Duration x SD) repeated measures analysis of variance was performed. There was no signficant main effect for SD ($F<1$), but the effects for Group ($F_{2,57} = 3.63$, $p=.033$) and for Duration ($F_{1,57} = 6.86$, $p=.011$) were significant. There were no significant interactions. The effect for Group was explored by planned comparisons, which indicated that there was no significant difference between the RM and DYS groups ($F<1$), but that the AM group gave significantly more correct responses than the DYS group ($F_{1,57} = 6.33$, $p<.05$).

Reaction times

Analyses of variance were performed on the reaction times for the various tasks, to investigate whether the groups varied in any consistent way. Repeated measures analyses of variance were used where appropriate, and interactions of interest were evaluated by tests of simple main effects. Planned comparisons were used to investigate significant differences in the manner outlined above for group comparisons. It should be noted that reaction times for two-stimulus tasks (the auditory and visual temporal order judgment tasks) were calculated from the offset of the second stimulus. It was possible, however, that subjects might begin to initiate their response before this time, as soon as the first stimulus had been seen. For multi-stimulus tasks (the tone sequence and pattern matching tasks), reaction times were measured from the onset of the second series of stimuli. This was because decisions as to whether these series were different could be made as early as the perception of the second stimulus of the second series. In practice, most subjects did not respond until both series were completed. Thus reaction times for multi-stimulus tasks reflect the longer time of presentation at the longer ISI's.

a) Temporal order judgment - tones

Reaction times (RT's) on this task for the various groups are shown in Table 11. RT's are shown for both responses (first and second stimuli).[4] A 3 x 3 (Group x ISI) repeated measures analysis of variance indicated main effects for Group ($F_{2,56} = 14.51$, $p<.001$), and for ISI ($F_{2,112} = 17.77$, $p<.001$). The interaction was not significant. Planned comparisons on the Group effect revealed that the difference between the AM and DYS groups was marginal ($F_{1,56} = 3.314$, $p>.05$), and that between the DYS and RM groups did not approach significance ($F<1$).

b) Tone sequence matching

Reaction times on this task for the three groups at each ISI, for same and different trials, are given in Table 12. A 3 x 3 x 2 (Group x ISI x SD) repeated measures analysis of variance was performed, and indicated main effects for Group ($F_{2,57} = 4.47$, p=.016), for ISI ($F_{2,114} = 609.11$, p<.001), and for SD ($F_{1,57} = 12.12$, p=.001). Only the ISI x SD interation was significant ($F_{2,114} = 5.42$, p=.006). The effects involving ISI were not unexpected, as noted earlier. The main effect for Group was explored by planned comparisons, which revealed no significant differences between the RM and DYS groups or the AM and DYS groups (F<1 in both cases).

c) Temporal order judgment - symbols

Reaction times on this task for the three groups at each ISI, for both first and second responses, are given in Table 13. A 3 x 3 (Group x ISI) repeated measures analysis of variance revealed main effects for Group ($F_{2,57} = 15.87$, p<.001), and for ISI ($F_{2,114} = 22.07$, p<.001). The interaction was not significant. The Group effect was investigated by means of planned comparisons, which indicated that there were no significant differences between the RM and DYS groups (F<1), or the AM and DYS groups ($F_{1,57} = 2.26$, p>.05).

d) Pattern matching - sequential presentation

Table 14 gives the reaction times on this task for the three groups at each ISI, for both same and different trials. A 3 x 3 x 2 (Group x ISI x SD) repeated measures analysis of variance was performed, which indicated main effects for Group ($F_{2,57} = 18.85$, p<.001), for ISI ($F_{2,114} = 121.14$, p<.001), and for SD ($F_{1,57} = 14.42$, p<.001). The only significant interaction was that of ISI x SD ($F_{2,114} = 8.64$, p<.001). Effects involving ISI were not unexpected, as discussed earlier. The effect for Group was explored by planned comparisons, which revealed that there were no significant differences between the RM and DYS groups ($F_{1,57} = 2.811$, $p>.05$), or between the AM and DYS groups ($F<1$).

e) Pattern matching - simultaneous presentation

Reaction times on this task for each group at each duration, for same and different trials, are given in Table 15. A 3 x 2 x 2 (Group x Duration x SD) repeated measures analysis of variance was performed, which indicated main effects for Group ($F_{1,57} = 13.37$, $p<.001$), for Duration ($F_{1,57} = 6.11$, $p=.016$), and SD ($F_{1,57} = 10.15$, $p=.002$). None of the interactions approached significance. Again, the different durations were reflected in the RT's, which were calculated from the onset of the second stimulus set. Planned comparisons were carried out to explore the Group effect, and these revealed that there was no significant difference between the RM and DYS groups ($F_{1,57} = 2.205$, $p>.05$), or between the AM and DYS groups ($F_{1,57} = 1.188$, $p>.05$).

Thus for all tasks where RT's were recorded, the pattern was similar, with the RM group having the slowest reaction times, the DYS somewhat faster, and the AM group having the fastest RT's. However, in no case did the difference between the DYS group and either of the other groups reach significance. Thus the Group effects indicated for each task had to be attributable to the difference in each case between the RM and AM groups. It is clear, therefore, that the DYS group were not in any case trading accuracy for speed. That is, in those tasks where their performance was inferior to that of the AM group, this could not be attributed to their faster response times, as in no case were the RT's for the DYS group faster than those for the AM group.

Correlations

Correlational analyses were carried out to determine Pearson product-moment correlation coefficients. Ten variables were selected for a correlation matrix, to ascertain the relationships among scores on the various types of task. For the reading and phonemic awareness tasks, these variables were as follows: READLEV (the numerical score derived from the grade equivalent level on the WRAT-R, as described earlier in this section); WATT (the raw score on the Word Attack sub-test); and PHONAWAR (a composite phonemic awareness score, calculated by computing the average for each subject of z-scores derived from scores on the three tasks Odd-one-out, Rhyming words, and Auditory analysis). This latter variable was thus a measurement of general phonemic awareness, or ability to discriminate or manipulate the sounds within words. One score from each of the three auditory and four visual tasks comprised the remaining variables. The following variables were used for the auditory tasks: CISI (the inter-stimulus interval on the click fusion task); ATOJD (the mean score on the temporal order judgment task, for different stimuli only); and TS, the mean score on the tone sequence matching task. On the TOJ task, it was the trials where different stimuli were presented that were of interest here, and where group differences were expected to be seen. For the visual tasks, FISI (the inter-stimulus interval on the flash fusion task) was used, as was VTOJD (the mean score on the TOJ task, different stimuli only). This latter variable was used employing the same rationale as for ATOJD. For the two matrix tasks, the variables used (MATSIM and MATSEQ) were the mean scores for the simultaneously and sequentially presented matrix tasks respectively.

a) Relationship with IQ/CAT scores

It could be argued that accuracy on the tasks in this study might reflect intellectual ability in general, rather than a perceptual sensitivity to stimuli based on temporal processing ability. Thus, before a correlation matrix was produced, the relationship of intellectual level with the 10 variables selected was explored. It will be recalled that the for the DYS group Performance IQ (PIQ) scores were used for subject selection and matching, while for the AM and RM group scores were generally CAT scores assessing overall ability, or (for the younger children) scaled scores on the Block Design sub-test of the WISC-R. As can be seen from the list of correlation coefficients in the first part of Table 16, none of the correlations approached significance. Correlation coefficients were also calculated for each group, to see if IQ/CAT score was consistently related to the 10 variables. As can be seen from the latter part of Table 16, there were isolated instances of correlations which were significant at the .05 or .01 level. For the DYS group, PIQ was positively correlated with FISI (the higher the PIQ, the longer time needed to separate flashes). For the AM group, IQ/CAT scores were positively correlated with READLEV, WATT, and MATSEQ. Since for the majority of this group the measure used was one of overall cognitive ability and achievement, the relationship with reading level and non-word decoding was not unexpected. For the RM group, IQ/CAT scores were negatively correlated with CISI (the higher the IQ/CAT level, the smaller the interval needed to separate clicks). However, there were no other significant correlations within the three groups, and it was concluded that IQ/CAT scores were not consistently related to the variables of interest.

Because the IQ variable for the DYS group was based on performance tasks only, and Verbal IQ (VIQ) scores were available for this group, the relationship of VIQ to the ten variables was also explored. Since Verbal IQ is affected by reading ability and experience (Stanovich, 1989), then VIQ should be correlated to some extent with the reading and phonemic awareness tasks. The scores on tests of intelligence and those measuring phonological awareness, while not highly correlated, do show some degree of relationship (Mann, 1993; Stanovich, 1989). It was further hypothesized that if a temporal processing deficit in the auditory modality is basic to the phonemic difficulties that contribute to dyslexics' impaired reading ability and thus reduced reading experience, then VIQ might also be correlated with scores on the auditory tasks in this study. Of interest was whether VIQ would also be correlated with performance on the visual tasks.

Correlation coefficients for VIQ with READLEV, WATT and PHONAWAR did not in fact reach significance ($r = .113$, .253, and .200 respectively, $p>.05$ in all cases). However, VIQ was significantly correlated with two of the three auditory tasks (for CISI, $r = .455$, $p<.05$, and for ATOJD, $r = .474$, $p<.05$). The correlation with TS did not approach significance ($r = .233$, $p>.05$). Surprisingly, the relationship with CISI was a positive one (the higher the VIQ score, the longer the interval needed to separate clicks). No obvious explanation for this positive correlation is apparent. It is conceivable that, given the possibility of a differing response bias for the DYS group, this relationship may reflect the tendency of higher Verbal IQ dyslexics to be more conservative on the click fusion task. This could also explain the positive relationship of PIQ with FISI for the DYS group noted above. None of the correlations with visual tasks approached significance.

b) Overall correlations

A correlation matrix for the 10 variables of interest was then generated. The correlation coefficients, both overall and for each group, are listed in Tables 17 to 20. The additional power available in the overall correlation matrix enables us to see relationships among variables that might not be apparent in individual groups, with their reduced numbers of subjects. The correlation matrices for individual groups enable us to see whether these relationships hold for different types of readers, or whether the patterns of relationships differ over groups.

As can be seen from Table 17, when all subjects were considered, the three variables which tapped reading ability and phonemic awareness (READLEV, WATT and PHONAWAR) were all highly inter-related. These three variables were also significantly correlated with scores on all the auditory and visual tasks, with the exception of FISI. None of the three reading/phonemic awareness variables was significantly correlated with FISI, but all three showed the expected negative correlation with CISI (the inter-stimulus interval required on the click fusion task). It had been hypothesized that performance on all three auditory tasks would be inter-related, as would that on the three visual tasks involving temporal processing, and that there would also be significant correlations across modalities on the temporal processing tasks. Although not all individual correlations were significant, the pattern was very much as expected, with the exception of the flash fusion task. As will be seen in Table 17, the variable FISI was not significantly correlated with any other variable, with the exception of its analogous task in the auditory modality, CISI. FISI was positively correlated with CISI, possibly meaning that overall, subjects who required longer separations of visual stimuli to judge that two were presented also needed longer separations of auditory stimuli. Given the data from the signal detection portion of each task, however, the alternative interpretation, that the positive correlation reflects a similar response bias for each task, must be borne in mind. CISI was significantly correlated (negatively, as expected) with ATOJD, and with all of the visual tasks, but not with TS.

It had been hypothesized that the matrix task involving sequential presentation, MATSEQ, would be significantly correlated with other tasks involving temporal processing, but it had not been expected that MATSIM would be significantly correlated with such tasks. As will be seen, the correlations for MATSIM were not as high as those for MATSEQ, but nevertheless they were significant in every case overall (with the above -noted exception of FISI). Possible reasons for this will be discussed when within-group correlations are discussed below.

When correlation matrices were produced for each group, the number of correlation coefficients which reached significance was, not unexpectedly, lower than for the groups combined, because of the smaller n in each case, but the patterns showed a tendency to be similar.

c) DYS group correlations

Correlation coefficients for the DYS group are given in Table 18. For the DYS group, the three variables READLEV, WATT, and PHONAWAR were highly inter -related, as expected. However, for the auditory and visual tasks, none of the correlation coefficients for CISI and FISI with any other variable reached significance. Performance by the dyslexics on the ATOJD task was significantly correlated with two of the variables tapping reading and phonemic awareness, WATT and PHONAWAR, and also with the matrix matching task with sequential presentation, MATSEQ. TS, the tone sequence matching task, was significantly correlated with READLEV, WATT, and PHONAWAR, and with the three visual tasks, VTOJD, MATSEQ, and MATSIM. Performance on TS was not, however, correlated with that on any other auditory task. In addition to its significant relationship with WATT and PHONAWAR, the visual temporal order judgment variable, VTOJD, was significantly correlated with TS and the two matrix pattern matching tasks, but not with its auditory analogue, ATOJD. Both MATSEQ and MATSIM were significantly correlated with most of the other variables except READLEV, CISI and FISI, and highly correlated with each other. The only difference was that MATSEQ was correlated with ATOJD, whereas MATSIM was not.

d) AM group correlations

Correlation coefficients for the AM group are shown in Table 19. The expected relationship of PHONAWAR with the two reading-task variables was not seen with this group. In fact, PHONAWAR was not significantly correlated with any other variable. It is possible that this was because of the ceiling effect on the odd-one-out and auditory analysis tasks for these age-matched controls. To explore this suggestion further, the relationships of READLEV and WATT with the individual phonemic awareness variables was explored for this group. No significant correlations were found. Thus it would appear that level of phonemic awareness was not related to reading level, or performance on other tasks, for this group. This does concur with the observation that phonemic awareness is more closely related to reading level in the early years of reading acquisition, but that in later grades it is general cognitive ability that is more highly correlated with reading level (Adams, 1990). For this group, CISI showed the expected negative correlation with the other two auditory tasks, ATOJD and TS, and also with WATT. ATOJD and TS were also significantly correlated with each other, and TS was significantly correlated with its visual analogy, MATSEQ, but not with MATSIM, as anticipated. FISI was not significantly correlated with most of the other variables, but it was significantly (negatively) correlated with MATSIM. It may be that the lack of variability of performance on these two tasks by this group may have contributed to this anomalous result. Of 20 AM subjects, 16 scored 90 or 100% on MATSIM, and 18 of 20 chose a flash fusion ISI of 30 or 40 ms. MATSIM was not correlated with any other variable. However, MATSEQ was significantly correlated with both reading tasks, WATT and READLEV, and with the other visual task VTOJD, as well as with TS, its auditory analogy, as mentioned above. Unlike the DYS group, the correlation coefficient for MATSEQ and MATSIM did not reach significance.

e) RM group correlations

The correlation coefficients for the RM group are shown in Table 20. As can be seen, the trends were very much as anticipated. READLEV, WATT, and PHONAWAR were all highly inter-related for this group, as expected. READLEV was significantly correlated with the two temporal order judgment tasks and with MATSEQ, as was WATT. PHONAWAR was significantly correlated with every other variable except MATSIM, as expected. The correlations with CISI and FISI were negative, also as expected. Apart from their relationship with PHONAWAR, CISI was significantly negatively correlated with only MATSEQ, and FISI was significantly negatively correlated with both MATSEQ and TS. ATOJD was significantly correlated with the other auditory task, TS, with its visual analogy, VTOJD, and with MATSEQ. Apart from the correlations already mentioned, TS was not related to any other variable, although its correlation with MATSEQ did approach significance ($r = .372, p<.06$). In addition to its (almost significant) relationship with TS, MATSEQ was significantly correlated with all other variables except MATSIM. Unlike the DYS group, the RM group's performance on MATSIM was not significantly related to their performance on any other task.

Discussion

The questions of interest in this study were a) whether deficits in the various aspects of temporal processing delineated would be found in adolescent dyslexics; b) whether auditory and visual temporal processing deficits would be found to co-exist in these students, giving support for the suggestion of a more general temporal processing deficit which might underlie reading difficulties; and c) whether any temporal processing deficits found would in fact be related to reading and phonemic awareness level. Of further interest was whether dyslexics would be impaired relative to reading-matched, as well as age-matched, controls.

The findings in this study indicated that a) the adolescent dyslexics studied were impaired versus their age-matched controls on some, but not all of the temporal processing tasks, as well as on the task involving simultaneous presentation; b) impairments were found on both auditory and visual tasks, and performances on tasks in both modalities were correlated for all subjects in many instances; and c) performance on reading tasks for both words and non-words, and performance on the phonemic awareness tasks, was highly correlated with performance on many of the auditory and visual tasks in this study. Further, the dyslexics' performance on the various tasks was almost always at the same level as their reading-matched controls, even when it was significantly impaired compared to their age-matched controls.

The dyslexic group were impaired on two of the three auditory tasks. On the click fusion task, they required longer ISI's than either the age-matched or the reading-matched controls before they could discern that two clicks had been presented. This was the only visual or auditory task in which the DYS group's performance was worse than that of the RM group. Perusal of the data revealed that 5/20 (25%) of the DYS group had required ISI's of 10 ms or more on this task, whereas only 1/20 (5%) of the AM group and 2/20 (10%) of the RM group had required ISI's in this time frame. Even when these "outliers" are disregarded, the remaining DYS subjects required longer than the other two groups to discern two clicks (mean ISI for DYS = 3.60 ms, mean ISI for AM = 2.53 ms, mean ISI for RM = 2.83 ms). Only 3/20 (15%) of the DYS subjects could perform with ISI's of 1 or 2 ms, whereas 10/20 (50%) and 8/20 (40%) of the AM and RM subjects, respectively, performed with ISI's of 1 or 2 ms. Every effort was made during the administration of this task to ensure that the subjects understood the requirements of the task, and that they selected an interval which truly reflected their sensitivity. After each subject indicated that the ISI had been selected, the experimenter reduced the ISI by 1 ms by pressing the left arrow key once, with the words "So, if I go down one more, it sounds like one click. Is that right?" If the subject agreed, the experimenter pressed the right arrow key, and said "And if I go back up to where you were, it sounds like two clicks. Is that right?" This ISI was selected if the subject agreed. If the subject did not agree to either question, he/she was asked to continue adjusting the ISI until the appropriate point had been reached. The above procedure was then repeated. In approximately 20% of cases, mostly with the RM group, the subject did not agree with the first question, and continued to adjust the ISI, usually resulting in a lower ISI.

The results of the click fusion task in this study are consistent with what few data there are in the literature with similar tasks. The ISI's in this study were somewhat longer than those required by learning disabled students and controls in the Haggerty and Stamm

(1978) study, but in that study the clicks were presented to different ears, either simultaneously or with one ear leading. The results of the present study are more consistent with what might be expected given the findings of Auerbach et al. (1982), that normal adult subjects need ISI's of 1-3 ms on a click fusion task. The adolescent age -matched controls in the present study needed ISI's at the upper end of this range, and the younger reading-matched controls needed slightly longer. The longer interval needed by the dyslexics could be interpreted to indicate that they were indeed having difficulty perceptually segregating the two clicks.

However, notwithstanding the evidence of the longer ISI's needed by the dyslexics on the first portion of this task, the lack of a significant difference in d' among groups on the signal detection portion of the task is counter to the hypothesis that the difference in groups occurs at the perceptual level rather than at the decision level. It will be recalled that d' is a bias-free measure of sensitivity, but of course is confined to sensitivity at the levels (or intervals) predetermined by the experimenter. It is possible that the dyslexics were simply more conservative in making judgments regarding the perception of two clicks as oppposed to one. Of course, this possibility is present in any fusion task which does not control for response bias.

In an attempt to cast further light on this question, the individual data for the dyslexics were studied. If indeed the dyslexics' longer ISI on the click fusion task was a reflection of their perceptual difficulties, then those subjects in the DYS group with the longest ISI's, considerably above the 4 ms ISI used in the signal detection portion of the task, should have performed at or near chance level on this latter portion. Of the five dyslexics who selected ISI's equal to or greater than 10 ms, two had indeed made false alarms (FA) and hits (H) as expected (45% FA/50% H and 30% FA/70% H). However, the remaining three scored only 10% false alarms each, with 95-100% hits. Of the three subjects in the other two groups who selected ISI's equal to or greater than 10 ms, all made false alarms or hits at or near the chance level (the one AM subject scored 60% FA/75% H; the two RM subjects scored 45% FA/65% H and 58% FA/60% H). A comparison was then made between the mean percentages of false alarms for those subjects in each group who had selected ISI's of 4 ms or higher in the first portion of the task, and those who had selected lower ISI's (4 ms being the ISI in the signal detection portion). In each case, the mean proportion of false alarms was higher for subjects selecting longer ISI's than for those with shorter ISI's (DYS: 20.83% [n=12] versus 10.13% [n=8]; AM: 20.00% [n=5] versus 8.47% [n=15]; RM: 40.80% [n=10] versus 11.20% [n=10]).

These data are suggestive, but not convincing, evidence that some of the dyslexics (and a very small number of subjects in the other groups) may have had perceptual difficulties in segregating the two clicks. However, the signal detection task findings would suggest that the differences in CISI among groups may have been due to a response bias on the part of the dyslexics subjects. It is possible that both explanations contribute to the results. Within the DYS group, there may have been subjects who had perceptual difficulties in temporal processing, and/or were more conservative than the members of the other groups in reporting hearing two clicks. To further test this possibility, an investigation was made of the correlation between d' for each group and the three reading and phonemic awareness variables (READLEV, WATT, and PHONAWAR). As will be recalled, d' is a measure of the sensitivity of the observer, and while no significant differences were found among the groups for d' itself, it was of interest to see if there was a different pattern of correlations involving d' for each group. For the DYS group, d' for the click fusion task was significantly correlated with both WATT ($r = .49$, $p<.05$) and PHONAWAR ($r = .39$, $p<.05$), but not with READLEV ($r = .05$). For the AM group, d' was significantly correlated with READLEV ($r = .55$, $p<.01$), but not with PHONAWAR ($r = .09$). The correlation with WATT approached significance (r = .38, p<.06). For the RM group, none of the correlations was significant, although all three approached significance (READLEV: r = .37; WATT: r = .36; PHONAWAR: r = .36). Of interest here is the presence, for the DYS group, of a correlation between sensitivity on the click fusion task and performance on the non-word reading and phonemic awareness tasks, but the total absence of a correlation with reading level itself. In contrast, the age-matched group's sensitivity was correlated with reading level, but not at all with performance on the phonemic awareness tasks. One might tentatively conclude that the ability to discriminate rapid temporal sounds does indeed contribute to the ability to segment words into sounds early in reading acquisition. However, the lack of a significant difference among groups for d' does not allow us to draw any firm conclusions. Before finally laying this argument to rest, however, one more piece of evidence may be in order. The data of the nine DYS subjects who did most poorly on the auditory temporal order judgment task (lowest scores on any condition from 0-50%) were examined for their performance on the click fusion task. Performance on the ATOJ task did not appear to be related to the ISI selected on the click fusion task, as only two of the nine selected an ISI greater than 4 ms. However, perusal of the data suggested that performance on the signal detection portion of the task did bear more of a relationship to ATOJ scores. The nine dyslexics who performed the most poorly on the ATOJ task had false alarm rates ranging from 0 to 70% (mean = 29%), and hit rates from 50 to 70% (mean = 62%). In contrast, the remaining 11 dyslexics had false alarm rates ranging from 0 to 25% (mean = 6.3%), and hit rates ranging from 85 to 100% (mean = 93.6%). Furthermore, d' for the click fusion task was found to have a significant correlation with performance on the auditory TOJ task when stimuli were different for both the DYS group (r = .72, p<.01) and the RM group (r = .44, p<.05), but not for the AM group (r = .33). This would suggest that perhaps a forced choice task with appropriate ISI levels may be a more accurate measure of sensitivity than the selection method utilized in the first portion of the click fusion task, and in many other studies.

The dyslexics in this study were also impaired on the auditory TOJ task. This task was modelled on the rapid perception task used by Tallal (1980), and the results may thus be said to support the findings of Tallal. The results of the current study were analyzed to see if they differed depending on the type of stimulus pair to be ordered. When stimuli were different (HL or LH tones), the explicit order of the stimuli had to be recorded; when stimuli were the same (LL or HH tones), no ordering was required. In this case, it was sufficient that the subject perceive that both tones were the same, and that he/she be able to identify whether these same-frequency tones were high or low. It was not expected that the dyslexics would have any difficulty with these latter requirements, although it was hypothesized that the dyslexics would be impaired when temporal ordering was necessary. These expectations were borne out, as the DYS group performed at the same level as the two control groups when stimuli were the same, but were impaired compared to the age-matched controls when stimuli were different.

The hypothesis that the DYS group would be impaired on the auditory TOJ tasks was thus supported by the results of this study, and that regarding the click fusion task received tentative support. However, it was also speculated that performance on these two tasks might be significantly (negatively) correlated. When CISI and ATOJD are considered, this was only true in the case of the AM group. The correlation did not approach significance for either the DYS or RM groups, although it did when all groups were considered together. Since the DYS group was impaired on both tasks (and assuming that the click fusion results reflected a sensitivity difference for at least some of the dyslexics), the lack of a relationship might suggest the possibility of (at least) two different types of temporal processing deficit: one for perceptual segregation of two rapidly presented stimuli, and one for the ordering of two rapidly presented stimuli.

These two types of deficit would not necessarily co-exist in any dyslexic subject. In fact, only the variable measuring the latter (ATOJD) correlates with word attack and phonemic awareness skills for the DYS group. That for the former (CISI) does not correlate with these variables, although, as noted earlier, the measure of sensitivity on the click fusion task (d') did correlate significantly with WATT and PHONAWAR for the dyslexics. However, it is not unreasonable to speculate that there may exist, probably in the auditory association areas, different areas of the brain specialized to respond to different processing requirements of auditory stimuli. It is well-known that the visual association areas have subareas that respond to different processing requirements, such as varying line orientations, movement of stimuli, borders of objects, form integration, etc. One might speculate that the auditory association areas might also consist of subareas specializing in distinct types of information processing, and a dysfunction in any one subarea could lead to a very specific deficit. However, the fact that scores on tasks tapping these two abilities were negatively related in the older controls suggests that there normally exists some relationship between the two abilities, at least in older subjects. Thus it would seem that those older normal readers who have good ability to perceptually segregate two auditory stimuli presented close together in time, also have good ability to perceive the correct order of two temporally close auditory stimuli. The lack of a significant correlation between the CISI and ATOJD scores, assumed to tap these two abilities, for the younger normal readers and dyslexics, suggests that one, or both, of these abilities might not yet be fully developed. Alternatively, the lack of a significant correlation could be due to the inadequate sensitivity of one or both tasks. This latter possibility is suggested by the significant relationship between d' and ATOJD for both the DYS and RM groups.

The final auditory task required subjects to determine whether two sequences of four high and low tones were the same, or different. On this task, the dyslexics performed as well as both control groups. It is possible that ceiling effects masked any differences that might have been found, but this seems unlikely, given the results at the fastest ISI when stimulus pairs were different. Under this condition, all groups performed less well, but the performances of the DYS and AM groups were almost identical. These results do not appear to be consistent with much of the evidence from other studies which used similar types of tasks. However, as noted earlier, sequence matching tasks using non-linguistic auditory stimuli generally involved long ISI's (500 -750 ms in the Bryden, 1972, study; 428 ms in the Tallal & Piercy, 1973, study; 500 ms in the Tallal et al., 1981, study). It is possible that with these long ISI's, subjects were able to produce verbal labels such as high or low, long or short, for the tones used as stimuli. Thus any deficit seen for dyslexic or language-impaired children might have been the result of a phonemic deficit which prevented these subjects from rapidly producing such verbal labels.

In the present study, the longest ISI used (360 ms) was somewhat shorter than those in the above-mentioned studies. The ISI's used were chosen in an attempt to ensure that verbal coding would not be used. Given that, it was still expected that dyslexics would perform worse on this task, if they were required to order the stimuli in order to compare pairs of sequences. This expectation was not met. One possible explanation for this result may be that the dyslexics were not specifically processing the order of the tone sequences in order to compare sequences, but had adopted an alternative strategy for doing this task. This strategy may have involved the processing of each stimulus set as a temporal pattern, rather than a sequence of discrete elements. Evidence in support of such a speculation can be found in a study by Ben-Dov and Carmon (1984). These researchers presented subjects with pairs of sequences of 2-5 flashes, with either same or different time intervals between flashes (resulting in same or different rhythms for each pair). The stimuli were presented in either the left or right visual fields. When reaction times were analyzed, a significant visual field by rhythm length interaction was apparent. As the number of stimuli increased, processing of the stimulus sets appeared to be shifting from the left to the right hemisphere. Since the left hemisphere's superior ability for temporal analysis has been demonstrated for both visual and auditory stimuli (Nottebohm, 1979), Ben-Dov and Carmon (1984) interpreted their results as indicating that subjects preferentially use analytic processing for short sequences, but shift to holistic processing when sequences are longer.

If dyslexics do have difficulty with analytic processing of temporal sequences, they may well adopt a holistic processing approach, perhaps at a shorter sequence length than would normal readers. If the dyslexics in the current study were comparing tone sequences as holistic patterns rather that sequentially processing them, they may well have performed at the same level as the controls.

Support for this suggestion of the utilization of a different processing strategy by the DYS group may be gleaned from the pattern of correlations seen in Tables 18-20. Performance on the tone sequence matching task (represented by TS) was significantly correlated with that on the auditory TOJ task (ATOJD), for both the AM and RM groups. The correlation did not reach significance, however, for the DYS group. TS was significantly correlated with CISI (negatively, as expected) for the AM group, but not for the other two groups. Thus there appeared to be somewhat of a relationship between the sequence matching task and the other auditory tasks for the AM and RM groups, but not for the DYS group. Given that the DYS group may have adopted a different strategy (i.e., holistic processing) to deal with this tone sequence matching task, as speculated above, this pattern of correlations is not surprising. Further evidence from the pattern of correlations for a different processing strategy by the DYS group may be seen from the difference in the relationships of MATSIM with the other variables in the various groups. For the DYS group, MATSIM was highly correlated with MATSEQ and with VTOJD and TS, suggesting that this group may have been using similar strategies in these tasks.

Apart from its negative relationship with FISI in the AM group, MATSIM was not related to any other variable in either control group.

Thus the results of the current study lend some support to the hypothesis that dyslexics have a temporal processing deficit in the auditory modality. Since the stimuli used in the auditory tasks in this study were clicks or tones, it is evident that this deficit does not have a linguistic basis, but rather, as Tallal (1984) has argued, is a more general temporal processing deficit for auditory stimuli presented rapidly in sequence. It might be argued that there was a possibility for verbal coding of the stimuli in the TOJ task, but given the short ISI's involved it is unlikely that this strategy could be employed. Even if it had been, with only two stimuli, the processing and memory requirements associated with verbal coding should not have affected accuracy to any degree, but would rather have affected only reaction times for the dyslexics who had difficulty with phonological coding. Further, if verbal coding had been a possible strategy in the auditory TOJ task, it should also have been a possible strategy in the tone sequence matching task. As noted above, the dyslexics were not significantly impaired on this latter task.

It had been hypothesized that deficits would be seen for the DYS group on visual tasks that were analogous to the auditory tasks, but not on the pattern matching task where stimuli were presented simultaneously. However, the only visual task involving sequential processing on which the dyslexics were impaired relative to their age-matched controls was the sequence matching task (MATSEQ). The performance of the DYS group was not significantly different from that of the controls on either the flash fusion or the visual TOJ task. However, contrary to expectations, the dyslexics were impaired relative to the age-matched controls on the simultaneously presented pattern matching task (MATSIM). Before discussing this latter finding, the possible reasons for the former findings will be discussed.

The failure to find evidence for a temporal processing deficit on two of the three tasks where such evidence was expected, could result from one of three possible situations: a) there is not, and never was, a temporal processing deficit in the visual modality in these dyslexics; b) there was a temporal processing deficit in the visual modality in these adolescent dyslexics, but it has been resolved by this stage of their development; or c) there still is a temporal processing deficit in the visual modality in these dyslexics, but the tasks employed in this study were not sensitive enough to find evidence for it.

The first possibility seems unlikely for several reasons. First, the dyslexics in this study were significantly impaired on one of the visual sequential tasks, that requiring sequence matching. Second, although the difference was not statistically significant, the dyslexics as a group selected a longer ISI (43.5 ms) to perceptually segregate two flashes than either of the control groups (38.5 ms and 38.0 ms for the AM and RM groups respectively). In the DYS group, 13/20 (65%) of the subjects could segregate two flashes when the ISI was 40 ms or less, whereas 19/20 (95%) and 18/20 (90%) of the AM and RM groups, respectively, could segregate the two flashes when the ISI's were in this time frame. Again, the dyslexics' performance on the visual TOJ task was not statistically significantly different from the other two groups. However, as will be seen from Figures 8 and 9, there was a trend for the dyslexics to make fewer correct responses when the stimuli were different (particularly at the shorter ISI's), but not when the stimuli were the same. This is the same pattern that was seen in the auditory TOJ task, where the dyslexics were significantly less accurate than their age-matched controls. Third, the evidence from the studies reviewed earlier indicates that generally dyslexics are impaired on tasks of numerosity judgments or temporal integration of form. None of the studies reviewed employed precisely the same methodology as the current study, but two (O'Neill & Stanley, 1976; Di Lollo et al., 1983) employed a similar method (two straight lines as the stimuli which had to be segregated). For all these reasons, the explanation that there never was a temporal processing deficit in the visual modality in these dyslexics seems unlikely.

The second possible explanation, that there was a temporal processing deficit which has since been ameliorated, has more plausibility, given the evidence in the literature for such an amelioration in the visual modality in dyslexic children. Tallal and her colleagues (Stark & Tallal, 1981; Tallal et al., 1981) did find that only their younger subjects (five to six years old) were impaired on visual TOJ tasks, although, similar to the results of the current study, the older subjects were impaired on visual sequence ordering tasks. Badcock and Lovegrove (1981) speculated that their results suggested "a trend toward normal functioning" (p.500) some time between the ages of 8 and 14 years. However, since their data were not longitudinal, but gathered from two different age groups, their results are inconclusive. Di Lollo et al. (1983) studied a group of dyslexics containing subjects ranging in age from 8 to 14 years. Overall, the group was impaired on temporal integration tasks compared to age-matched controls. Di Lollo et al. plotted ISI's for the tasks against age for both groups: there was no significant trend over age change for the controls, but a clear trend in the dyslexic group for the ISI to decrease as age increased. Di Lollo et al. noted that scores for the older dyslexics were very similar to those of the controls, and suggested that the perceptual deficit evidence in the younger dyslexics "had all but vanished by age 11 or 12" (p.932). Again, the data were not longitudinal, but together with the previously cited evidence, are suggestive of a developmental trend. A more recent study has shown that for both dyslexic and retarded readers, there is a linear decrease in the temporal integration and gap detection thresholds on visual tasks as age increases from 7 to 14 years (Martos & Marmolejo, 1992). Thus it seems reasonable to speculate that any temporal processing deficit which might have been present in the visual modality could have resolved for the dyslexics in the current study, who were aged between 12 and 15 years. This possibility had been considered when subjects were selected, but was considered unlikely because of the severity of the reading disability in these subjects. Dyslexic subjects in the Di Lollo et al. (1983) study were reading on average three grade levels below their controls; dyslexic subjects in the current study were reading on average 5-6 grade levels below their age-matched controls. Furthermore, in a previous study (Farmer & Bryson, in preparation), evidence of a visual temporal processing deficit was found in a group of dyslexics of a comparable age to those in the current study. However, there remains the possibility that resolution of a previously existing temporal processing deficit in the visual modality had taken place in some of the dyslexics in this study.

The third possibility must now be discussed: that some of the tasks used in this study were not sensitive enough to find evidence of a still-existing temporal processing deficit in the visual modality. In the case of the flash fusion task, this may well be true. The range of ISI's (0 to 150 ms) was chosen to encompass the ISI's found to be required by dyslexics on tasks involving numerosity or temporal integration of form reported in the literature. Within this range, steps of 10 ms were selected. In practice, however, the highest ISI selected during the current study was 90 ms, the lowest 20 ms. The vast majority of subjects selected ISI's of either 30 or 40 ms, and most subjects had no difficulty in deciding on the ISI, being quite clear that only one flash could be seen one step lower, while two were clearly seen at the ISI selected. This was not true in the click fusion tasks, where all subjects listened very carefully at various intervals before deciding on the critical ISI. Thus it may be that the range chosen was too broad, and the steps too gross, in the flash fusion task. Possibly with smaller steps, the difference in ISI required by the dyslexics would have reached significance. The issue is not quite so clear with the visual TOJ task. The ISI's were selected to encompass those reported for TOJ tasks in the literature. The three ISI's used were chosen in an attempt to demonstrate that the dyslexics (and probably the RM group also) were able to produce more correct responses as the ISI became longer. While there was no statistically significant interaction between Group and ISI, it will be seen from Figure 9 that there was a trend for both the DYS and RM groups to be less impaired compared to the AM group as the ISI lengthened, when stimuli were different and explicit ordering was required. As was done with the auditory TOJ task, the effect of ISI on VTOJD was explored, but in all cases the results were not significant. As with other tasks in this study, ceiling effects may have played a part in obscuring differences between groups, and it may be that increasing the difficulty of the task by reducing the ISI's employed, perhaps to 30, 60, 90, and 120 ms, would result in significant differences between groups. It may also be, however, that more trials at each ISI might have resulted in a significant difference being found for the DYS group, given that on half of the trials presented, where stimuli were the same, no group differences were expected. This left only 12 trials for each subject (four at each ISI) where differences were expected, and so this task may not have been sensitive enough to detect the temporal processing deficit hypothesized. If indeed there was some amelioration of a visual temporal processing deficit in some of these dyslexics, in spite of their apparent severe reading disability, then the visual tasks employed would need to be particularly sensitive to find evidence of any remaining temporal processing deficit.

The only visual task involving sequential presentation on which the DYS group was significantly impaired was the sequence matching task (MATSEQ). These results were consistent with other sequence matching tasks reviewed earlier, but in particular with the results of Farmer and Bryson (in preparation), which was one of very few studies employing rapid presentation of visual stimuli. However, unlike the Farmer and Bryson study, the dyslexics in the present study also were impaired relative to the AM group when the stimuli were presented simultaneously (the MATSIM task). It had been hypothesized that the dyslexics would be expected to process such a simultaneously presented pattern of stimuli as a visual whole, and thus should not be impaired on this task, if in fact dyslexics are more reliant on visual processing, as indicated by such studies as those of Gordon (1984) and Rack (1985). The unexpected results of the present study raise the possibility: a) that the dyslexics in this study had a deficit in visual processing of patterns, as well as the hypothesized temporal processing deficit; and b) that as a result of such a deficit, the dyslexics in this study were attempting to sequentially process the simultaneously presented patterns, at least on some of the trials.

At first blush the possibiity of a visual pattern processing deficit might seem reasonable, given the severe reading disability of these students, and thus their presumed inability to develop or utilize a reliable sight vocabulary. However, the students in the current study were selected based on Performance IQ/Verbal IQ discrepancies, with all students having PIQ higher than VIQ, and within the average or above average range. If these dyslexics did have a deficit in visual processing of patterns, it seems unlikely that they would have Performance IQ scores in the normal range. Furthermore, the dyslexic subjects in the Farmer and Bryson (in preparation) study were just as severely reading disabled, and they performed as well as their controls with simultaneous presentation of the stimuli. However, there are some minor methodological differences between the two studies which could contribute to the discrepant results. In the Farmer and Bryson study, the stimuli (four letters) were presented in a 4 x 4 matrix, as in the current study. However, in the Farmer and Bryson study, only one set of four stimuli was presented, and rather than having to be compared to a second set, the pattern of the single set had to be reproduced with cards on a board. It may be that severely reading disabled children are able to process a single visual pattern well enough to reproduce it, but when two visual patterns have to be processed for comparison, the dyslexics may have difficulties with the task. Possibly the dyslexics were unable to retain the first pattern presented sufficiently well or long enough to compare it to the second pattern. Some (albeit weak) support for this argument may be found in the results for the MATSIM task. At the faster stimulus duration, both the AM and RM groups gave more correct responses when the stimulus sets were the same than when they were different, but the opposite was true for the DYS group - they gave more correct responses when the stimulus sets were different. One possible explanation is that when the second stimulus set was clearly different from the first, there was no necessity to make a detailed comparison, but when similarity or difference was not obvious, the two patterns had to be matched more carefully visually. The dyslexics may have had more difficulty in retaining both images than the other groups, and may have had to resort to an attempt to match square by square. Whatever strategies they were using for the MATSIM task seem to be related to the strategies they were using for the MATSEQ task, given the high correlation between the variables MATSIM and MATSEQ for the DYS group ($r = .854$, $p<.01$). The correlation between these two variables was not significant for the other two groups, indicating that the controls may have been using different strategies for the two tasks.

The question that arises, of course, is why the dyslexics were not able to process either of the MATSIM or MATSEQ patterns holistically as a temporal pattern, rather than as sequential discrete elements, as was speculated for the tone sequence matching task. It will be recalled that the study by Ben-Dov and Carmon (1984), on which such speculation was based, involved visual stimuli (light flashes), and that with an increase in the number of flashes, processing appeared to shift from the left to the right hemisphere. One major difference between the stimulus sets used in the Ben-Dov and Carmon study and the present study is that the light flashes in the former experiment were presented with varying time intervals between flashes, resulting in a rhythmic pattern, with no spatial element. In the current study, there was no distinctive rhythm associated with the different stimulus sets, as the temporal intervals were the same for each pair of sequences. The patterns varied only in spatial placement (with simultaneous presentation) or the order of sequencing (with sequential presentation). The shift to holistic processing may be easier and more likely for stimulus sets involving rhythm than for patterns involving spatial variables, at least for the dyslexics in the current study. One explanation for this may be that the dyslexics may have had difficulty processing the pattern holistically at the speeds presented because of the extended visual angle employed in the two matrix tasks. The matrix subtended a visual angle of 11.07 degrees. This is comparable to the matrix used in the Solman and May (1990) study, where poor readers were found to have difficulty identifying the location of stimuli presented as distance from the fixation point increased. It will be recalled from the Klein et al. (1990) study, that all subjects had more difficulty identifying stimuli as eccentricity increased. In the present study, there was no requirement to remain fixated at a central spot, but the DYS group may have experienced difficulty in correctly locating stimulus components in the periphery at the faster rate of presentation. Even where the slower rate of presentation allowed eye movements, the performance of the dyslexics might have been impaired because of their longer visible persistence, as discussed earlier.

The pattern matching and sequence matching tasks were designed in an attempt to replicate the results of the Farmer and Bryson (in preparation) study, but using non-linguistic stimuli. The matrices for the two studies had been generated by the same procedure. However, in the Farmer and Bryson study, an Apple IIc monitor had been used when collecting data in the schools. Because that monitor was slightly smaller than the Apple III monitor used in the present study, the visual angle subtended by the matrix in the Farmer and Bryson study would have been closer to 7 degrees. This difference in visual angles may have contributed to the difference in performance by the dyslexics on the simultaneous pattern matching tasks in the two studies.

An alternative version of this task might employ two series of low and high blocks in a horizontal line (subtending a visual angle of 7^{o} or less), for which a same/different response is required. This task would have the advantage of more closely resembling the skills required in reading, in that the envelope of the stimulus sets would roughly resemble the envelope that could be encountered for words. It may be that dyslexics who are severely reading disabled have not been able to fully develop a visual strategy for whole word recognition, and may have difficulty with more complex patterns such as those in a matrix. However, these dyslexics may have been able to develop their visual/spatial strategies enough to recognize word shapes or envelopes (at least when these do not subtend too great a visual angle), and it is possible that they will perform such a task as well as age-matched controls. Certainly less severely disabled dysphonetic dyslexics, those who have been able to utilize a visual strategy to develop a sight vocabulary, might have no difficulty with such a task when stimuli within such sets are presented simultaneously, but may well have difficulty with sequential presentation.

Reaction times for the DYS group were in all cases slower than those for their age-matched controls, although in no case was the difference significant As noted earlier, the fact that the DYS group were not performing their responses faster than the AM group suggests that they were not sacrificing accuracy for speed. In other words, on tasks where their performance was inferior to that of the AM group, the difference could not be attributed to a speed-accuracy trade-off. Indeed, at no time was any indication given to the subjects that speed of responses was of import, nor were they told that reaction times were being measured. On the rare occasions when subjects asked if they had to respond as fast as they could, they were simply told that speed did not matter, they should just try to get the response right. Therefore it seems unlikely that any one group was intentionally attempting to respond as quickly as possible, at the expense of accuracy.

The finding that the dyslexics were consistently (if not significantly) slower than their age-matched controls could be interpreted as evidence that they were slower to process the stimuli presented. However, it could equally be taken as evidence that they were slower to generate the motor movements necessary to make the required responses.

A third possibility is that the temporal lag occurred in the decision-making process. The fourth, and perhaps most likely explanation, is that the dyslexics were generally somewhat slower than their peers because of a combination of the above suggestions, either within the group or within subjects. It is not possible to determine the reasons for the trend to slower performance based on the data from this study.

It had been hypothesized that performance on the various reading and phonemic awareness tasks, on the auditory tasks, and on the visual tasks (except MATSIM), would be inter-related. The correlation matrix derived from the 10 variables which were chosen to represent these tasks supported this hypothesis to a large degree, but not entirely. When all three groups were considered together, the two reading tasks were significantly correlated with all of the visual and auditory tasks involving sequential processing except the flash fusion task. The phonemic awareness variable was also related to all of the auditory and visual tasks except flash fusion. The analogous fusion task variables, CISI and FISI, were significantly correlated, as were the analogous TOJ task variables. In addition, the two analogous sequence matching task variables were significantly related for the groups as a whole, and MATSEQ was significantly correlated with all the other visual and auditory tasks except flash fusion. Contrary to expectations, MATSIM was also significantly correlated with all other variables except FISI, although in no case were the correlations as high as were those for MATSEQ. Moreover, as will be described below, the correlations involving MATSIM only hold true for the DYS group, and not for the AM and RM groups. Within modalities, neither fusion task was related to all other tasks, but CISI was related to the auditory TOJ task. Both TOJ tasks were significantly correlated with the same-modality sequence matching task.

When the correlation matrix for only the subjects in the DYS group is considered, the hypotheses for inter-relatedness are not as fully supported, however. The three reading and phonemic awareness task variables are highly correlated with each other, and performances on the word attack task and phonemic awareness tasks are significantly correlated with all other variables except the two fusion tasks. Neither of the two fusion tasks is significantly correlated with any other variable. The two sequence matching tasks (and the simultaneous matching task) are significantly correlated, and within the visual modality the hypothesis is supported, with the exception of FISI. This is not so for the auditory tasks. Thus there is good evidence within the DYS group that the visual and auditory tasks are related, with non-word reading and phonemic awareness tasks, and to some degree with each other, but the hypotheses are not fully substantiated for this group.

Perhaps what is most informative from the correlational data, however, are the differences in correlational patterns across groups which suggest qualitative differences in performance on the various tasks. For instance, the relationship of d' on the click fusion task is quite different for the DYS group (correlated with WATT and PHONAWAR) than it is for the AM group (correlated with READLEV). In addition, the high correlation of MATSIM with MATSEQ (and with TS) for the DYS group, is not seen at all for the other two groups. The differing patterns of correlations suggest that the DYS group has developed different strategies whenever possible for processing rapidly presented stimuli than have the normal readers studied. This suggests that caution must be used when interpreting the results of studies where reading-matched groups have been used as controls for dyslexics. Where these two groups are found to have performed at the same level on tasks, it can not be assumed that this is indicative of a developmental lag on the part of dyslexics. Clearly it is important to investigate the qualitative performance, as well as the quantitative outcome, of the subjects involved.

Experiment 2

Method

Subjects

The 20 university-level subjects (the UNIV group) were all enrolled in an introductory psychology course. All were volunteers recruited from class, and were awarded course credit for participating in the experiment. Mean age of the UNIV group was 20.7 years (range = 17-32 years). Median reading level as measured by the WRAT -R was 12+ (range = 7E to 12+), and mean reading rate grade equivalent as measured by the Nelson-Denny Reading Test (Brown, Nelson, & Denny, 1976) was 13.11 (range = 9.2 to 15.0). Reliability and validity of the Nelson-Denny make this a suitable test for screening and predictive uses. Split-half reliability coefficients in the .80's and .90's, and test-retest reliability coefficients ranging from .78 to .97 are reported; concurrent validity has been demonstrated with moderately high correlations with scholastic aptitude tests (Brown et al., 1976). Intellectual level was not measured for this group.

Procedure

The procedure was essentially the same for the university-level subjects as for the younger subjects, except that testing took place in a small testing room in the university. The same tasks were administered as for the school-age subjects, with the addition of the Nelson-Denny Reading Test, Form D (Comprehenson and Rate). Tasks were administered during a single session, which took approximately two hours. A short break was scheduled in the middle of the session.

Results

Mean scores and standard deviations obtained by the UNIV group on the Word Attack and phonemic awareness tasks are given in Table 21. Results on the two fusion tasks are given in Table 22, and results on the remaining auditory and visual tasks are given in Table 23. As can be seen, the mean performance of the UNIV group was generally in the same range as the performance of the AM group. Ceiling effects were noted on many tasks. The one notable exception was the click fusion task, where the UNIV group's performance was more in line with that of the DYS group.

Reaction times for the auditory and visual tasks, where measured, are given in Table 24. Reaction times were generally faster for the UNIV group than for any other group. As noted earlier, no statistical comparisons were made because this group was in no way selected to be matched to the other groups, and because minor methodological differences in task administration precluded any direct comparison. The major interest here was the within-group correlations on the various tasks.

The variables were selected for the correlation matrix in the manner described in Experiment 1. The correlation matrix for the UNIV group is shown in Table 25. As can be seen from this table, fewer of the relationships among the variables reached significance than was so for the other groups studied. The ceiling or close-to-ceiling scores obtained by many subjects on a number of the tasks may have contributed to the dearth of significant correlations. There were some relationships of note, however. As expected, READLEV, WATT, and PHONAWAR were all highly correlated. However, only one of these variables, PHONAWAR, was significantly correlated with performance on the two auditory tasks ATOJD and TS, and with performance on the simultaneous pattern matching task, MATSIM. The auditory temporal order judgment task, ATOJD, was significantly correlated with both the auditory pattern matching task (TS) and the flash fusion task, FISI. This latter was, unexpectedly, a positive correlation. That is, the longer the ISI needed to perceptually segregate two flashes, the better the performance on the auditory TOJ task. The visual order judgment task (VTOJD) also shared a significant positive relationship with FISI, and also was significantly correlated with both MATSEQ and MATSIM, the other two visual tasks. As with the DYS group, these latter two variables also were significantly correlated.

Discussion

As expected, the three reading and phonemic awareness variables were highly inter-related. However, the pattern of correlations among the other variables was not quite as expected. The auditory TOJ task variable was correlated, as expected, with the tone sequence matching task variable, indicating that these older subjects had perhaps employed a sequential analytic strategy for comparing tone sequences, rather than a holistic matching strategy as proposed for the DYS group. ATOJD was not, however, significantly correlated with its analogous visual task, the TOJ task for symbols. However, perusal of the data indicates that some 16/20 subjects scored 100% at the fastest ISI on the visual TOJ task (13/20 subjects scored 100% at all ISI's on this task), and thus ceiling effects may well have contributed to the lack of significant correlations evident for this group. Ceiling effects may also explain the lack of significant correlations among other variables which were expected for this group. They do not explain, however, the significant positive correlation between performance on the flash fusion task and both the auditory and visual TOJ tasks. Thus the higher the ISI chosen in the flash fusion task, the more correct responses on the two TOJ tasks. As a whole, the UNIV group's mean ISI was the lowest of the four groups, and in the range of the AM and RM groups' ISI. There was little variation in the ISI's selected by the UNIV subjects, with the vast majority (18/20) selecting ISI's between 30-50 ms. It may be that the positive correlations seen between these ISI's and the TOJ tasks may reflect a more conservative approach by these older subjects. Those subjects who conservatively chose the higher step when in doubt may also have been those who were more careful in responding on the TOJ tasks, and thus made fewer errors through carelessness. If this was so, however, it was not reflected in higher reaction times for these subjects on the temporal order judgment tasks, as the correlations between CISI and FISI, and reaction times on the TOJ tasks, did not approach significance.

The high ISI selected by the UNIV group on the click fusion task, in the range of that selected by the DYS group, may also reflect a more conservative approach to this task. However, an additional contributing factor may be that the majority of these subjects were tested by a different experimenter, who did not institute the additional instructions to ensure that the click fusion ISI chosen was the most indicative of sensitivity. Perusal of the individual data adds credence to this supposition, as the variability in the ISI's chosen was quite large. Two subjects chose the maximum ISI of 20 ms, another six chose ISI's of 6 ms or above, and two chose ISI's of 0 ms. Those subjects who did select a shorter ISI on this task tended to be those who did better on the auditory TOJ task, as indicated by the almost significant negative correlation coefficient between ATOJD and CISI. This evidence converges with that pertaining to the AM group, and provides some supporting evidence for the earlier suggestion that older normal readers who have good perceptual ability for segregating temporally close auditory stimuli generally also have good ordering ability for sequentially presented auditory stimuli. Also providing supporting evidence for this suggestion (but in contrast to the AM group) was the finding of a very strong relationship between d' on the click fusion task and ATOJD ($r = .93$, $p<.01$). D-prime was also significantly related to READLEV ($r = .40$, $p<.05$) and to PHONAWAR ($4 = .48$, $p<.05$), but not to WATT. Since d' is a measure of sensitivity, its relationship with these other variables suggests that the ability to segregate two rapidly presented auditory stimuli is related to reading ability and other aspects of auditory temporal processing. It further suggests that the threshold measurement used in the first part of the click fusion task was not the optimum method of measuring sensitivity. On the flash fusion task, the relationship of d' with VTOJD was not significant. Its relationship with both READLEV and PHONAWAR approached significance ($r = .37$ and $r = .38$, respectively, $p<.06$), and that with WATT was not significant.

Of interest is the observation that, in contrast to the older normal readers (the AM group), the UNIV group's performance on the phonemic awareness tasks was correlated with several other variables. It was argued earlier that perhaps the lack of a relationship for PHONAWAR to reading level and performance on other tasks for the AM group was due to the decreasing relationship of phonemic awareness and reading level in the later grades. However, if this were so, one would expect this lack of a relationship to hold for university-age subjects. One possible explanation for the difference between the UNIV and AM groups in this respect lies in subject recruitment. The age-matched controls were selected to have no indication of reading problems. In contrast, the university subjects were recruited on a volunteer basis. One might assume that university students should have few difficulties with reading. However, during the study, two of the UNIV subjects volunteered the information that they had been diagnosed as dyslexic during their school years. In fact, five of the 20 UNIV subjects received WRAT-R grade equivalent scores of between 7E and 10B, somewhat lower than might be expected for university students. It may be that it was students who had at one time experienced difficulty with reading who were inclined to volunteer for this study. Such students might well contribute to a higher correlation between phonemic awareness performance and other variables for this group, compared to the AM group.

Overall, however, the pattern of correlations seen for this group adds little to our knowledge of a possible temporal processing deficit in dyslexics. These tasks were relatively simple for these older subjects, in the majority of cases. It may be that a more challenging set of tasks, incorporating basically the same processing strategies, would result in a more informative pattern of correlations. An alternative approach would be to select older subjects who were reading disabled, and examine their results on these tasks to see if the pattern of performances was comparable to that of younger dyslexics.

General Discussion

As indicated in the review of the literature presented earlier, there is clear evidence that a majority of dyslexics have impaired phonemic awareness or phonological knowledge. Several studies have shown that this phonemic deficit is predictive of difficulties learning to read (Goswami, 1990; Mann & Brady, 1988; Share et al., 1984; Stanovich et al., 1984), and longitudinal studies of language-impaired children have shown that the vast majority of language-impaired children later are identified as reading disabled (Tallal & Curtiss, in press). The putative contribution of auditory temporal processing difficulties to phonemic deficits was discussed. The evidence for a general auditory temporal processing deficit rather than a deficit specific to linguistic stimuli, was reviewed. It was suggested that an auditory temporal processing deficit is particularly likely to be evident with linguistic stimuli because of the very rapid changes in speech sounds, especially the stop consonants. Of note is the evidence from Werner et al. (1992) that some infants begin to approach adult performance on gap detection tasks with nonverbal auditory stimuli, at approximately 12 months of age. This is similar to the age at which Werker (1989) and Kuhl (1992) have shown that infants have learned to categorize their native language phonemes, and lose the ability to discriminate other phonemes. One might speculate that a disordered or delayed temporal processing system during this critical time would make it extremely difficult for children to discriminate/categorize language sounds, and would lead to the sorts of phonemic discrimination and phonemic awareness difficulties that are seen in language and reading impaired children. Even though the temporal processing deficit may ameliorate to some extent with development, these children may evidence persistent language difficulties (Bernstein & Stark, 1985; Bishop, 1992).

In addition to the evidence presented for a phonemic (and perhaps general auditory temporal processing) deficit in a majority of dyslexics, evidence was also presented for a visual temporal processing deficit. Increased visible persistence, as evidenced by longer ISI's on gap detection and integration of form tasks, was reported to have been found in some two-thirds of the dyslexics studied. Increased visible persistence has not been shown to be causal to reading difficulties, but it is interesting to note that the percentage of reading disabled children affected coincides with the figure reported anecdotally to have visual stability difficulties, although no good evidence exists at present to link these two observations.

Obviously more research is needed to provide a firmer link between the visual temporal processing deficit in dyslexics with actual reading tasks. However, the evidence that a majority of dyslexics have a phonemic deficit, which very likely is a general auditory temporal processing deficit, taken together with the evidence for a visual temporal processing deficit in a majority of dyslexics, is tantalizing. Such evidence can not be dismissed as mere coincidence. A more parsimonious explanation is that a general temporal processing deficit underlies the deficits apparent in each modality.

The current study attempted to provide evidence for a general temporal processing deficit, manifested in both the visual and auditory (nonverbal) modalities, in adolescent dyslexics. No clear evidence of such a link was found, but the pattern of results, and in particular the correlational pattern, is suggestive. It would clearly be premature to dismiss the claim for a general temporal processing deficit. Hopefully future research studies will clarify the picture, and chart the developmental course of such a deficit, as expressed in each modality.

If indeed most dyslexics have both a visual and an auditory temporal processing deficit, at least at an early developmental stage, what could be the underlying mechanism which contributes to such a deficit? Recent anatomical and physiological studies of the brains of dyslexics and normal readers have revealed numerous differences. Structural differences in the size of the plana temporale in the two groups have been shown, with the tendency being for the dyslexics to have symmetrical plana, rather than the L > R seen in most normal readers (Galaburda, 1988; Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985). Evidence suggests that in normal brains the initial symmetry during fetal development is changed as involution occurs and the right planum temporale experiences neuronal loss (Galaburda, Corsiglia, Rosen, & Sherman, 1987). This involution does not appear to have happened in some dyslexic brains. In recent reports of adolescent dyslexics (Larsen, Hoien, Lundberg, & Odegaard, 1990; Lundberg & Hoien, 1989), symmetry of the planum temporale, determined by magnetic resonance imaging, was linked to performance on phonological tasks.

These are not the only structural differences that have been found, however. Polymicrogyria and focal dysplasias have been found, mainly in the left temporal region (Galaburda, 1988), but also in the left and right frontal regions (Hynd & Semrud -Clikeman, 1989), and in the thalamus (Galaburda et al., 1985). Physiological studies have also revealed differences in brain activity between dyslexics and normal readers (Segalowitz, Wagner, & Menna, 1992; Tallal, Sainburg, & Jernigan, 1991; Wood, Flowers, Buchsbaum, & Tallal, 1991). Suggested mechanisms for a temporal processing deficit, based on such physiological findings, include an impairment in the ability to adequately recruit attentional resources (Segalowitz, et al., 1992), perhaps resulting in a failure to automatize some processes, such as phoneme discrimination (Robin, Tomblin, Kearney, & Hug, 1989; Wood et al., 1991). Automatization of skills is acquired more slowly by dyslexics, with the time increasing exponentially as task complexity increases (Nicolson & Fawcett, 1992).

It has been suggested that some dysphasics and dyslexics may have impaired thalamic gating mechanisms, which have been described as acting to sharpen the edges of stimuli in the visual and auditory systems (and for the tactile system), and thus providing a perceptual "window" for stimulus resolution (Tallal et al., 1991). An impairment in this system would result in poor temporal processing. In turn, poor temporal processing and resolution of stimuli would greatly inhibit the automatization of categorization and recognition skills. If this impairment was present at the stage when infants were learning to perceive and produce speech sounds, this lack of automaticity could have far-reaching effects.

What is currently known about the gating mechanisms in the visual and auditory systems makes the suggestion for their impairment in dyslexics plausible, and consistent with the anatomical findings. As noted earlier, there is evidence for an impaired visual magnocellular pathway in dyslexics (Chase & Jenner, in press; Lehmkuhle, Garzia, Turner, Hash, & Baro, 1993; Livingstone et al., 1991). The magnocellular neurons are involved in motion analysis and in analysis of the relative locations of objects (Berne & Levy, 1988), and as noted earlier, are involved in rapid information processing (Livingstone et al., 1991). The magnocellular pathway (like the parvocellular pathway) is routed from the retinal ganglion cells through the optic nerve and optic chiasm to the dorsal lateral geniculate nucleus (LGN) of the thalamus. The auditory neuronal pathway is routed from the cochlea through the cochlear nuclei, the superior olivary nuclei, and the inferior colliculus to the medial geniculate nucleus (MGN) of the thalamus. From the LGN and MGN the visual and auditory pathways are routed to the visual and auditory cortex, respectively. At the level of the thalamus, however, both the visual and auditory system axons (and those of the somatosensory system) have connections to the reticular nucleus of the thalamus (RNT), with feedback to the originating nuclei (Berne & Levy, 1988; Tallal et al., 1991). These "relay" cells involve the neurotransmitter gamma aminobutyric acid (GABA), and are thus presumed to be inhibitory. In the auditory system, afferent inhibition acts to sharpen frequency discriminations, and it has analogous effects in both the visual and somatosensory systems (Berne & Levy, 1988). Thus feedback from the RNT may be involved in the gating mechanism which ensures fine discriminations, and interference with the system could lead to difficulties in the automaticity of discrimination and categorization of stimuli involving rapid temporal changes.

Models have been proposed for both speech perception (Wickelgren, 1979) and reading (Seidenberg & McClelland, 1989), which invoke the parallel processing of sets of speech sounds or letters. Thus what is perceived is not a series of individual phonemes or letters, but sets consisting of a phoneme or letter in the context of the phonemes or letters flanking it. Each set activates a particular pattern of excitation in the brain, and temporal order is determined by the particular activation of transitional, context-dependent patterns (Wickelgren, 1979), with the strength of the excitatory patterns being influenced by the frequency with which similar patterns have been perceived in the past. In turn, the strength of activation influences the speed with which future patterns will be correctly identified. This parallel processing of sets of context-dependent stimuli enables the cognitive system to rapidly process incoming stimuli such as speech. While it may seem that such a system would mean a huge increase in the number of possible activational patterns over those required for individual phonemes or letters, the constraints of our phonemic and orthographic systems limit the number of possible combinations (Adams, 1990). This still leaves a large number of patterns which must be activated and then learned, however, if understanding (and later, production) of speech and acquisition of fluent reading is to be attained. For such learning to proceed, it is necessary that the organism is able to discriminate among the various stimuli perceived. Thus before patterns of stimuli can be discriminated, it is necessary that the subject can easily and automatically recognize the individual units, such as letters. Letters themselves are made up of various individual parts (straight and/or curved lines) juxtaposed in particular patterns. Individual phonemes are also made up of spectral changes in set relationships with each other. Thus the patterns for letters and phonemes must be learned before these can contribute in a meaningful way to the stimulus sets which have to be learned. It will be recalled that dyslexics do more poorly than good readers on tasks which require rapid and automatic naming of letters, for instance. If the units within a stimulus are not clearly and rapidly discriminable, then no precise or clearly replicable pattern will be activated. Thus perception of speech units (or perception of letter units, and the association of the two types) will not be easily and automatically acquired. If indeed it is the gating mechanisms associated with the RNT described above which contribute to precise discrimination of auditory and visual stimuli, and thus stimulus sets, then abnormalities in the thalamus might well contribute to difficulties in language and reading.

Given the complexity of the differences found to date in brain structure and activity between dyslexic and normal readers, and the heterogeneity of reading problems identified, it will obviously be some time before we are able to define the precise ways in which brain anomalies contribute to reading problems. The picture may never be entirely clear, because of the degree of interaction, in the developing child, of sub-systems which may have achieved some degree of modularity in the adult (Hulme & Snowling, 1992). Readers who share similar genotypical profiles may show quite disparate phenotypical expression (Elbert & Seale, 1988). Continued efforts to classify dyslexics (and other poor readers) on the basis of behavioural variables may be the most practically useful in the meantime. A temporal processing deficit in dyslexics could be the result of a variety of contributory brain anomalies.

While continued investigation of brain differences is important, a crucial need is for the development of diagnostic techniques to identify types of reading disability which might be helped by different forms of remediation. For instance, reading levels have been shown to be improved by phonemic awareness training (Bradley & Bryant, 1983), particularly where this includes metalevel instruction in how and where to apply the skills learned (Adams, 1990; Cunningham, 1990). However, for those dyslexics who have a temporal processing deficit which has not resolved to the point where they can discriminate or segregate basic speech sounds, or for those dyslexics in whom the reading disability is not related to a phonemic deficit, such remediation in phonemic awareness skills might not be at all effective. Identification of the underlying behavioural expression of various skill deficits is the first step to designing remediation programmes which will be effective for each individual. In the case of a temporal processing deficit, should this be shown to be basic to many reading impairments, identification of the developmental course will be essential to target appropriate remediation programmes at the optimal times.

Conclusions

The results of these experiments provide qualified support for Tallal's (1984) suggestion that the phonemic deficit evident in so many dyslexics is a symptom of a more general underlying temporal processing deficit for any rapidly perceived sequential sounds. The dyslexics were impaired relative to their age-matched controls on two of the three auditory tasks, click fusion and temporal order judgment for two tones. Since both tasks involved non-linguistic stimuli, this evidence for a deficit with non-speech sounds (but nevertheless sounds in the same time frames as speech sounds) supports the theory of a general auditory temporal processing deficit. This conclusion has to be tempered, however, by the possibility that the impaired performance on the click fusion task might be indicative of a response bias on the part of some subjects, rather than a difference in sensitivity.

The evidence for a visual temporal processing deficit was ambivalent. The dyslexics were impaired on one of the three visual tasks involving sequential presentation, but they were also impaired on the pattern matching task, when stimuli were presented simultaneously. Given the severe reading disabilities of these particular subjects, this may indicate that their deficits are many. That is, it is possible that they have deficits for both visual temporal processing and for processing patterns as a whole. This latter deficit may explain why they have failed to develop an adequate sight vocabulary that would enable them to perform reading tasks more functionally.

The failure to elicit evidence for a visual temporal processing deficit on the flash fusion and visual TOJ tasks could have occurred because a visual temporal processing deficit is more likely to have resolved by the age of the dyslexic subjects in this study. This would not explain, however, their impaired performance on the sequence matching task. Another possible explanation is that the tasks in this study were not refined enough to adequately measure any visual temporal processing deficit that had not resolved. Further research using more refined visual tasks, and including younger dyslexics, is needed to determine whether either of these two explanations, or a combination of the two, may be true.

The evidence for an auditory temporal processing deficit in at least some aspects of auditory processing of non-verbal stimuli, particularly determining the order of rapidly presented stimuli, and the links found among reading and phonemic awareness tasks, and various auditory and visual temporal processing tasks, suggest that researchers should focus attention on a more general processing deficit in some dyslexics, rather than one for linguistic stimuli only. Further evidence that a visual temporal processing deficit may also be apparent in some dyslexics, particularly in conjunction with an auditory temporal processing deficit, will necessitate that attention be focussed on the possible underlying causes for such a general temporal processing deficit, and on possible avenues for identification of and remediation for such dyslexics.

Footnotes

1 In the studies described in this review of the literature, many different terms have been used to describe the reading disabled subjects (e.g, dyslexics, poor readers, specific reading disabled children, etc.). Many of these subjects would undoubtedly meet the criteria for dyslexia, but this may not be so in all cases. To avoid misrepresentation, the term used in the specific study under discussion has been used when referring to the subjects in that study.

2 Tasks requiring separation of events over time which involve many identical stimuli are known as auditory flutter or visual flicker tasks. It might be considered that flicker and flutter tasks involve more complex instances of numerosity judgments (visual flash fusion occurs at ISI's of approximately 16-20 ms, similar to tasks involving two flashes [Ripps & Weale, 1976]). However, it is not clear that such tasks fall within the scope of this discussion as it is possible that when many events occur close together decisions might be based on a detection of change in intensity over time. Dyslexics may well show the same deficits on flicker and flutter tasks as they do on numerosity tasks (and it is assumed that Tallal's hypothesis predicts that they should). However, because such tasks may be solved on the basis of a quality other than discreteness of events, they are not included here. A discussion of the performance of dyslexics on flicker tasks may be found in Martin and Lovegrove (1988).

3 In order to avoid any possible experimenter bias in the scoring of these two tests, both the WRAT-R reading test and the Word Attack test were also scored by a second rater who was blind to group membership. Inter-rater agreement was high. Pearson product -moment correlations of the scores from the two raters were generally above .95, and

were significant at the $p<.01$ level for each test both overall and within each group. The correlations are presented in Table 3. In cases of disagreement, the decision of a third rater (who was also blind to group memberhsip) was accepted.

[4] Because of equipment failure the reaction times for one dyslexic subject on this task were not available.

Table 1.

Mean age and IQ/CAT scores, and median reading levels for each group (standard deviations in parentheses)

Group	N	Age	IQ/CAT scores	Reading level
DYS	20	14.07 (1.01)	114 (7.94)	3B
AM	20	14.10 (0.98)	113 (8.88)	8E
RM	20	8.8 (1.37)	-	3B

Table 2.

Mean scores for each group on reading and phonemic awareness tasks. (Standard deviations are in parentheses)

Group	Word Attack (max: 45)	Odd-one-out (max: 18)	Rhyming words -	Auditory analysis (max: 20)
DYS	20.60 (8.31)	14.70 (3.50)	17.00 (5.32)	12.45 (4.93)
AM	33.10 (4.84)	16.95 (2.37)	22.90 (7.15)	17.10 (4.50)
RM	23.85 (8.08)	16.60 (1.88)	18.15 (3.76)	13.90 (3.48)

Table 3.

Inter-rater reliabilities for the WRAT-R and Word Attack reading tests

Group	WRAT-R	Word Attack
DYS	.986	.975
AM	.982	.957
RM	.990	.974
Overall	.978	.977

Table 4.

Click fusion task: mean ISI's, percentage of false alarms, and percentage of hits for each group. (Standard deviations in parentheses)

Group	ISI	Hits	False alarms	d'	Beta
DYS	6.50 (5.52)	83.45 (19.25)	20.60 (17.30)	2.35 (1.57)	11.91 (28.31)
AM	2.95 (2.21)	88.65 (16.24)	19.00 (25.68)	3.12 (1.65)	10.21 (32.59)
RM	3.90 (3.78)	74.00 (22.43)	23.10 (18.77)	1.98 (1.69)	12.45 (35.61)

Table 5.

Auditory temporal order judgment: mean percentage correct (overall and for same and different stimuli) at each ISI. (Standard deviations in parentheses)

Group		ISI			
		40 ms	120 ms	360 ms	Mean
DYS	Overall	75.85 (22.95)	82.00 (21.26)	83.25 (21.50)	80.37 (21.90)
	Same	86.27 (22.18)	88.75 (20.64)	86.25 (24.97)	87.09 (22.60)
	Different	65.00 (30.78)	75.00 (31.41)	80.00 (24.79)	73.33 (28.99)
AM	Overall	93.85 (9.44)	97.60 (4.93)	98.20 (4.40)	96.55 (6.26)
	Same	95.00 (10.26)	96.25 (9.16)	97.50 (7.70)	96.25 (9.04)
	Different	92.50 (16.42)	98.75 (5.60)	98.75 (5.60)	96.67 (9.21)
RM	Overall	80.75 (15.36)	87.10 (14.81)	93.30 (10.16)	87.05 (13.44)
	Same	91.25 (16.77)	95.00 (13.08)	96.25 (9.14)	94.17 (13.00)
	Different	70.00 (27.63)	78.75 (30.65)	90.00 (14.96)	79.58 (24.41)

Table 6.

Tone sequence matching: percentage correct at each ISI for same and different stimuli sets. (Standard deviations in parentheses)

Group		ISI			
		40 ms	120 ms	360 ms	Mean
DYS	Same	93.50 (9.33)	90.00 (12.57)	93.00 (9.79)	92.17 (10.56)
	Different	72.00 (21.67)	90.50 (11.46)	90.00 (12.14)	84.17 (15.09)
AM	Same	98.00 (5.23)	97.00 (5.71)	96.00 (6.81)	97.00 (5.92)
	Different	72.85 (21.58)	94.50 (8.26)	95.45 (8.29)	87.60 (12.71)
RM	Same	97.00 (4.70)	95.95 (8.25)	96.00 (5.98)	96.32 (6.31)
	Different	63.00 (18.95)	86.45 (16.30)	89.50 (10.99)	79.65 (15.41)

Table 7.

Flash fusion task: mean ISI's, percentage of false alarms and percentage of hits per group. (Standard deviations in parentheses)

Group	ISI	Hits	False alarms	d'	Beta
DYS	43.50 (8.13)	98.25 (2.45)	4.75 (5.25)	4.11 (0.77)	5.67 (15.70)
AM	38.50 (13.49)	98.50 (4.62)	7.25 (11.18)	4.20 (0.94)	3.15 (11.40)
RM	38.00 (8.34)	96.45 (5.57)	6.10 (6.91)	3.89 (1.01)	8.31 (18.64)

Table 8.

Visual temporal order judgment: mean percentage correct (overall and for same and different stimuli) at each ISI. (Standard deviations in parentheses)

Group		ISI			
		50 ms	100 ms	250 ms	Mean
DYS	Overall	90.15 (13.18)	93.85 (10.99)	95.75 (9.13)	93.25 (11.10)
	Same	95.00 (10.26)	98.75 (5.59)	97.50 (7.70)	97.08 (7.85)
	Different	85.00 (20.52)	88.75 (22.18)	93.75 (17.91)	89.17 (20.20)
AM	Overall	94.50 (8.48)	98.20 (4.40)	96.95 (6.77)	96.55 (6.55)
	Same	96.25 (9.16)	100.00 (0.00)	98.75 (5.59)	98.33 (4.92)
	Different	92.50 (14.28)	96.25 (9.16)	95.00 (10.26)	94.58 (11.23)
RM	Overall	82.70 (24.41)	90.15 (13.08)	91.40 (14.02)	88.08 (17.17)
	Same	86.25 (23.61)	93.75 (13.75)	90.00 (17.01)	90.00 (18.12)
	Different	78.75 (30.65)	86.25 (20.64)	92.50 (16.42)	85.83 (22.57)

Table 9.

Sequential matrix matching: mean correct responses for same and different order at each ISI. (Standard deviations in parentheses)

Group		ISI			
		50 ms	100 ms	250 ms	Mean
DYS	Same	87.50 (17.43)	89.00 (13.34)	86.00 (17.59)	87.50 (16.12)
	Different	85.50 (17.61)	92.00 (15.08)	94.00 (9.40)	90.50 (14.03)
AM	Same	95.50 (6.86)	97.00 (5.71)	96.00 (9.40)	96.17 (7.32)
	Different	94.00 (7.54)	97.50 (5.50)	96.50 (5.87)	96.00 (6.30)
RM	Same	86.50 (13.49)	90.00 (10.26)	83.50 (14.97)	86.67 (12.91)
	Different	83.00 (17.20)	79.00 (15.86)	85.50 (14.32)	82.50 (15.79)

Table 10.

Simultaneous matrix matching: mean correct responses for same and different sets at each duration. (Standard deviations in parentheses)

Group		Duration		
		100 ms	400 ms	Mean
DYS	Same	87.50 (12.93)	91.00 (18.33)	89.25 (15.63)
	Different	93.00 (8.01)	94.00 (9.95)	93.50 (8.98)
AM	Same	98.00 (4.10)	97.00 (6.57)	97.50 (5.34)
	Different	93.00 (9.23)	98.50 (3.66)	95.75 (6.45)
RM	Same	93.00 (6.57)	92.50 (10.20)	92.75 (8.39)
	Different	88.50 (10.40)	95.00 (6.88)	91.75 (8.64)

Table 11.

Mean reaction times on the auditory temporal order judgment task for same and different stimuli at each ISI. (Standard deviations in parentheses)

Group	Response	ISI 40 ms	120 ms	360 ms	Mean
DYS	1st	1.511 (.481)	1.366 (.573)	1.225 (.523)	1.367 (.526)
	2nd	1.929 (.541)	1.787 (.627)	1.711 (.558)	1.809 (.575)
AM	1st	0.902 (.388)	0.735 (.243)	0.646 (.185)	0.761 (.272)
	2nd	1.273 (.423)	1.158 (.304)	1.095 (.222)	1.175 (.316)
RM	1st	1.560 (.547)	1.404 (.445)	1.300 (.478)	1.421 (.490)
	2nd	1.971 (.631)	1.820 (.513)	1.808 (.554)	1.866 (.566)

Table 12.

Mean reaction times on the tone sequence matching task at each ISI for same and different stimuli sets. (Standard deviations in parentheses)

Group		ISI			
		40 ms	120 ms	360 ms	Mean
DYS	Same	1.347 (.278)	1.571 (.383)	2.116 (.259)	1.678 (.307)
	Different	1.462 (.569)	1.536 (.277)	2.277 (.287)	1.758 (.378)
AM	Same	1.236 (.273)	1.403 (.249)	2.129 (.185)	1.589 (.236)
	Different	1.444 (.426)	1.469 (.241)	2.174 (.323)	1.696 (.330)
RM	Same	1.459 (.346)	1.674 (.448)	2.383 (.390)	1.839 (.395)
	Different	1.726 (.398)	1.735 (.324)	2.444 (.363)	1.968 (.362)

Table 13.

Mean reaction times on the visual temporal order judgment task for same and different stimuli at each ISI. (Standard deviations in parentheses)

Group	Response	ISI			
		50 ms	100 ms	250 ms	Mean
DYS	1st	1.087 (.400)	0.939 (.266)	0.811 (.242)	0.946 (.301)
	2nd	1.489 (.462)	1.348 (.324)	1.251 (.290)	1.363 (.359)
AM	1st	0.723 (.180)	0.671 (.171)	0.600 (.242)	0.665 (.198)
	2nd	1.066 (.235)	1.029 (.230)	0.988 (.189)	1.028 (.218)
RM	1st	1.221 (.303)	1.072 (.274)	1.059 (.298)	1.117 (.292)
	2nd	1.576 (.345)	1.461 (.349)	1.465 (.335)	1.501 (.343)

Table 14.

Mean reaction times on the sequential matrix matching task for same and different order at each ISI. (Standard deviations in parentheses)

Group		ISI			
		50 ms	100 ms	250 ms	Mean
DYS	Same	1.624 (.462)	1.701 (.392)	2.196 (.512)	1.840 (.455)
	Different	1.597 (.465)	1.561 (.326)	1.929 (.378)	1.696 (.390)
AM	Same	1.426 (.293)	1.484 (.274)	1.869 (.325)	1.593 (.297)
	Different	1.353 (.291)	1.410 (.339)	1.639 (.370)	1.467 (.333)
RM	Same	2.020 (.344)	2.204 (.482)	2.731 (.598)	2.318 (.475)
	Different	2.118 (.614)	2.126 (.671)	2.490 (.710)	2.245 (.665)

Table 15.

<u>Mean reaction times on the simultaneous matrix matching task for same and different sets at each duration. (Standard deviations in parentheses)</u>

Group		Duration		
		100 ms	400 ms	Mean
DYS	Same	1.151 (.329)	1.238 (.326)	1.195 (.328)
	Different	1.286 (.311)	1.325 (.332)	1.306 (.322)
AM	Same	0.951 (.317)	1.030 (.254)	0.991 (.286)
	Different	1.051 (.243)	1.095 (.254)	1.073 (.249)
RM	Same	1.474 (.473)	1.569 (.523)	1.522 (.498)
	Different	1.594 (.445)	1.550 (.272)	1.572 (.359)

Table 16.

Correlations of IQ/CAT scores with the ten selected task variables

Overall -

	r
READLEV	-.104
WATT	.078
PHONAWAR	.054
CISI	-.169
ATOJD	.082
TS	.049
FISI	-.050
VTOJD	-.020
MATSEQ	.080
MATSIM	.003

By group -

	DYS	AM	RM
READLEV	-.137	.550**	-.070
WATT	.195	.430*	.160
PHONAWAR	.000	.011	.322
CISI	.313	-.277	-.518**
ATOJD	.278	.164	.145
TS	-.049	-.016	.312
FISI	.386*	-.058	-.166
VTOJD	-.072	.181	.093
MATSEQ	-.021	.402*	.277
MATSIM	.197	.259	.106

* $p<.05$, ** $p<.01$

Table 17.

Correlation matrix for the 10 selected task variables for all groups combined

	READLEV	WATT	PHONAWAR	CISI	ATOJD	TS	FISI	VTOJD	MATSEQ	MATSIM
READLEV	1.000	.739**	.453**	-.304**	.491**	.386**	-.073	.386**	.534**	359**
WATT	.739**	1.000	.587**	-.321**	.592**	.412**	-.174	.480**	.617**	.375**
PHONAWAR	.453**	.587**	1.000	-.336**	.481**	.475**	-.175	.364**	.490**	.396**
CISI	-.304**	-.321**	-.336**	1.000	-.246*	-.176	.221*	-.294*	-.274*	-.227*
ATOJD	.491**	.592**	.481**	-.246*	1.000	.414**	-.148	.406**	.534**	.253*
TS	.386**	.412**	.475**	-.177	.414**	1.000	-.154	.364**	.522**	.414**
FISI	-.073	-.174	-.175	.221*	-.148	-.154	1.000	.074	-.078	-.065
VTOJD	.386**	.480**	.364**	-.294*	.406**	.364**	.074	1.000	.730**	.531**
MATSEQ	.534**	.617**	.490**	-.274*	.534**	.522**	-.078	.730**	1.000	.640**
MATSIM	.359**	.375**	.396**	-.227*	.253*	.414**	-.065	.531**	.640**	1.000

* $p < .05$

** $p < .01$

Table 18.

Correlation matrix for the 10 selected task variables for the DYS group

	READLEV	WATT	PHONAWAR	CISI	ATOJD	TS	FISI	VTOJD	MATSEQ	MATSIM
READLEV	1.000	.567**	.719**	-.106	-.119	.518**	.128	.345	.359	.318
WATT	.567**	1.000	.770**	-.130	.504*	.407*	-.197	.449*	.686**	.478*
PHONAWAR	.719**	.770**	1.000	-.202	.380*	.630**	-.044	.507*	.616**	.530*
CISI	-.106	-.130	-.202	1.000	-.010	.020	.264	-.367	-.127	-.133
ATOJD	-.119	.504*	.380*	-.010	1.000	.259	-.172	.016	.390*	.210
TS	.518**	.407*	.630**	.020	.259	1.000	-.131	.391*	.560**	.538**
FISI	.128	-.197	-.044	.264	-.172	-.131	1.000	.161	.110	.198
VTOJD	.345	.449*	.507*	-.367	.016	.391*	.161	1.000	.774**	.777**
MATSEQ	.359	.686**	.616**	-.127	.390*	.560**	.110	.774**	1.000	.854**
MATSIM	.318	.478*	.530**	.133	.210	.538**	.198	.777**	.854**	1.000

* $p < .05$

** $p < .01$

Table 19.

Correlation matrix for the 10 selected task variables for the AM group

	READLEV	WATT	PHONAWAR	CISI	ATOJD	TS	FISI	VTOJD	MATSEQ	MATSIM
READLEV	1.000	.685**	-.199	-.314	.339	.230	.098	.605**	.481*	.046
WATT	.685**	1.000	-.128	-.402*	.386*	.231	.075	.405*	.534**	.248
PHONAWAR	-.199	-.128	1.000	-.084	.106	.142	-.048	-.214	-.018	.094
CISI	-.314	-.402*	-.084	1.000	-.423*	-.529**	.050	.069	-.345	-.097
ATOJD	.339	.386*	.106	-.423*	1.000	.531**	.145	.069	.243	.009
TS	.230	.231	.142	-.529**	.531**	1.000	.015	.144	.479*	.293
FISI	.098	.075	-.048	.050	.145	.015	1.000	.291	.133	-.400*
VTOJD	.605**	.405*	-.214	.069	.069	.114	.291	1.000	.586**	.143
MATSEQ	.481*	.534**	.018	-.345	.243	.480*	.133	.586**	1.000	.374
MATSIM	.046	.248	.094	-.097	.009	.293	-.400*	.143	.374	1.000

* $p < .05$

** $p < .01$

Table 20.

Correlation matrix for the 10 selected task variables for the RM group

	READLEV	WATT	PHONAWAR	CISI	ATOJD	TS	FISI	VTOJD	MATSEQ	MATSIM
READLEV	1.000	.643**	.544**	-.207	.383*	.273	-.150	.471*	.546**	.026
WATT	.643**	1.000	.640**	-.199	.397*	.322	-.224	.504*	.421*	-.325
PHONAWAR	.544**	.640**	1.000	-.537**	.646**	.458*	-.423*	.569**	.665**	-.232
CISI	-.207	-.199	-.537**	1.000	-.261	-.210	.194	-.263	-.453*	-.246
ATOJD	.383*	.397*	.646**	-.261	1.000	.499*	-.165	.794**	.595**	-.072
TS	.273	.322	.457*	-.210	.499*	1.000	-.433*	.349	.372	-.127
FISI	-.150	-.224	-.423*	.194	-.165	-.433*	1.000	-.087	-.523**	.023
VTOJD	.471*	.504*	.569**	-.263	.794**	.349	-.087	1.000	.677**	.119
MATSEQ	.545**	.421*	.665**	-.453*	.595**	.372	-.523**	.677**	1.000	.119
MATSIM	.026	-.325	-.232	-.246	-.072	-.127	.023	.119	.119	1.000

* $p < .05$

** $p < .01$

Table 21.

Mean scores (and standard deviations) for the UNIV group on the Word Attack and phonemic awareness tasks

Task	Score
Word Attack	33.42 (4.60)
Odd-one-out	17.50 (0.61)
Rhyming words	17.80 (4.35)
Auditory analysis	17.50 (3.09)

Table 22.

Results of the two fusion tasks (CFUS) and (FFUS) for the UNIV group

	ISI	Hits	False alarms	d'	Beta
Click fusion	5.60 (6.00)	86.25 (28.05)	8.50 (10.65)	3.37 (1.64)	8.26 (18.67)
Flash fusion	37.00 (13.02)	98.25 (3.73)	4.55 (7.35)	4.34 (0.85)	5.84 (15.64)

Table 23.

Results on the auditory and visual TOJ and sequence and pattern matching tasks for the UNIV group

Task		Overall	Same stimuli	Different stimuli
Auditory TOJ	- 40 ms	93.90 (10.18)	100.00 (0.00)	87.50 (20.68)
	- 120 ms	96.35 (7.01)	97.50 (7.70)	95.00 (13.08)
	- 360 ms	96.30 (8.16)	95.00 (13.08)	97.50 (11.18)
	- mean	95.52 (8.45)	97.50 (6.93)	93.33 (14.98)
Tone sequence matching	- 40 ms	-	92.50 (8.51)	81.00 (18.61)
	- 120 ms	-	95.50 (8.26)	95.00 (8.27)
	- 360 ms	-	97.50 (5.50)	95.00 (9.46)
	- mean	-	95.17 (7.42)	90.33 (12.11)
Visual TOJ	- 50 ms	95.70 (10.03)	97.50 (7.70)	93.75 (15.97)
	- 100 ms	98.80 (3.69)	98.75 (5.59)	98.75 (5.59)
	- 250 ms	99.40 (2.68)	98.75 (5.59)	100.00 (0.00)
	- mean	97.97 (5.47)	98.33 (6.29)	97.50 (7.19)
Sequential matrix matching	- 50 ms	-	95.50 (10.50)	98.50 (3.66)
	- 100 ms	-	93.50 (8.13)	99.00 (3.08)
	- 250 ms	-	93.50 (12.68)	97.00 (5.71)
	- mean	-	94.17 (10.44)	98.17 (4.15)
Simultaneous matrix matching	- 100 ms	-	96.50 (6.71)	95.00 (6.07)
	- 400 ms	-	99.00 (3.08)	96.50 (9.33)
	- mean	-	97.75 (4.90)	95.75 (7.70)

Table 24.

Mean reaction times (and standard deviations) for the UNIV group at each ISI on the auditory and visual TOJ and sequence and pattern matching tasks

Task		1st Response	2nd Response
Auditory TOJ	- 40 ms	0.80 (0.35)	1.14 (0.40)
	- 120 ms	0.73 (0.39)	1.05 (0.33)
	- 360 ms	0.66 (0.31)	1.08 (0.34)
	- mean	0.73 (0.35)	1.09 (0.36)
Visual TOJ	- 50 ms	0.69 (0.18)	1.01 (0.21)
	- 100 ms	0.62 (0.15)	0.95 (0.17)
	- 250 ms	0.55 (0.11)	0.90 (0.13)
	- mean	0.62 (0.15)	0.95 (0.17)
		Same stimuli	Different stimuli
Tone sequence matching	- 40 ms	1.25 (0.24)	1.35 (0.40)
	- 120 ms	1.38 (0.31)	1.45 (0.33)
	- 360 ms	2.04 (0.22)	2.08 (0.24)
	- mean	1.56 (0.26)	1.63 (0.32)
Sequential matrix matching	- 50 ms	1.25 (0.26)	1.18 (0.26)
	- 100 ms	1.34 (0.25)	1.24 (0.28)
	- 250 ms	1.72 (0.20)	1.54 (0.31)
	- mean	1.44 (0.24)	1.32 (0.28)
Simultaneous matrix matching	- 100 ms	0.86 (0.20)	1.05 (0.21)
	- 400 ms	0.98 (0.19)	1.09 (0.23)
	- mean	0.92 (0.20)	1.07 (0.22)

Table 25.

Correlation matrix for the 10 selected task variables for the UNIV group

	READLEV	WATT	PHONAWAR	CISI	ATOJD	TS	FISI	VTOJD	MATSEQ	MATSIM
READLEV	1.000	.719**	.704**	-.006	.236	.316	.194	-.247	-.088	-.342
WATT	.719**	1.000	.508*	.184	-.020	.019	.278	-.297	-.121	-.277
PHONAWAR	.704**	.508*	1.000	-.034	.445*	.482*	.216	-.168	-.047	-.386*
CISI	-.006	.184	-.034	1.000	-.319	-.296	.301	.115	.084	.097
ATOJD	.236	-.020	.445*	-.319	1.000	.677**	.511*	.188	.256	.005
TS	.316	.019	.482*	-.296	.677**	1.000	.344	.287	.285	.162
FISI	.194	.278	.216	.301	.511*	.344	1.000	.443*	309	.081
VTOJD	-.247	-.297	-.168	.115	.188	.287	.443*	1.000	.695**	.513*
MATSEQ	-.088	-.121	-.047	.084	.256	.285	.309	.695**	1.000	.662**
MATSIM	-.342	-.277	-.386*	.097	.005	.162	.081	.513*	.662**	1.000

* p < .05

** p < .01

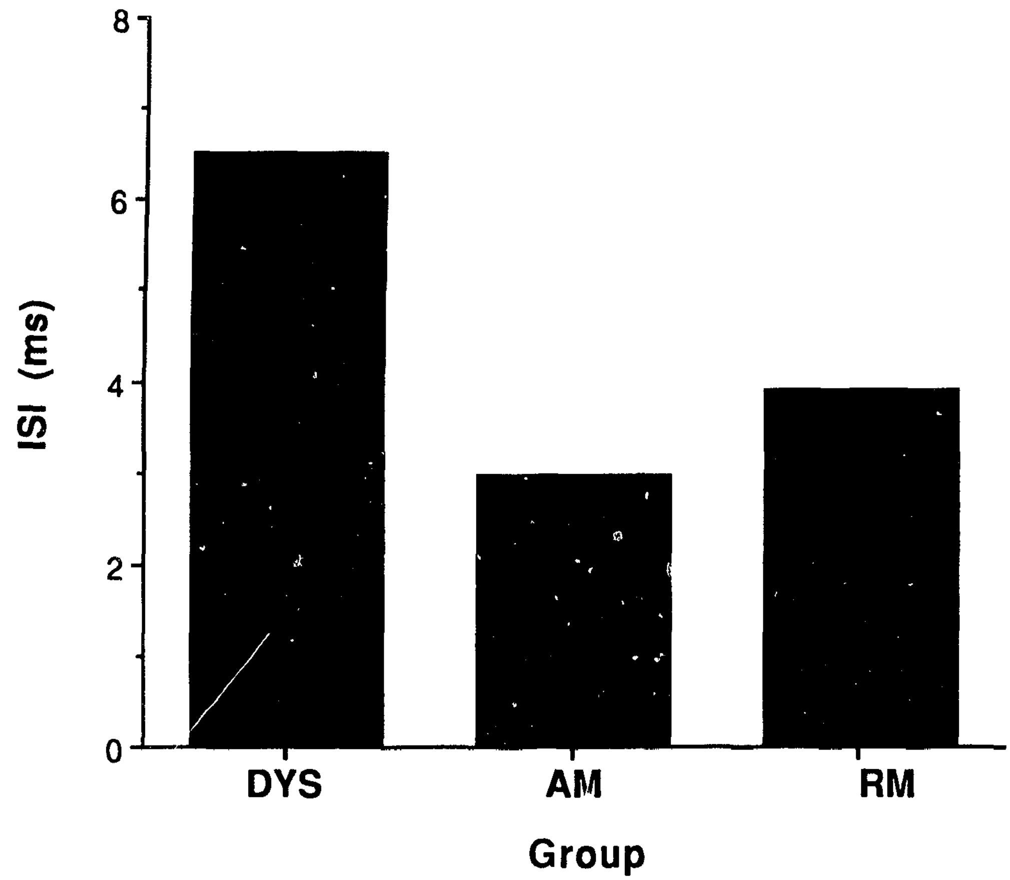

Figure 1. Mean ISI's for each group on the click fusion task

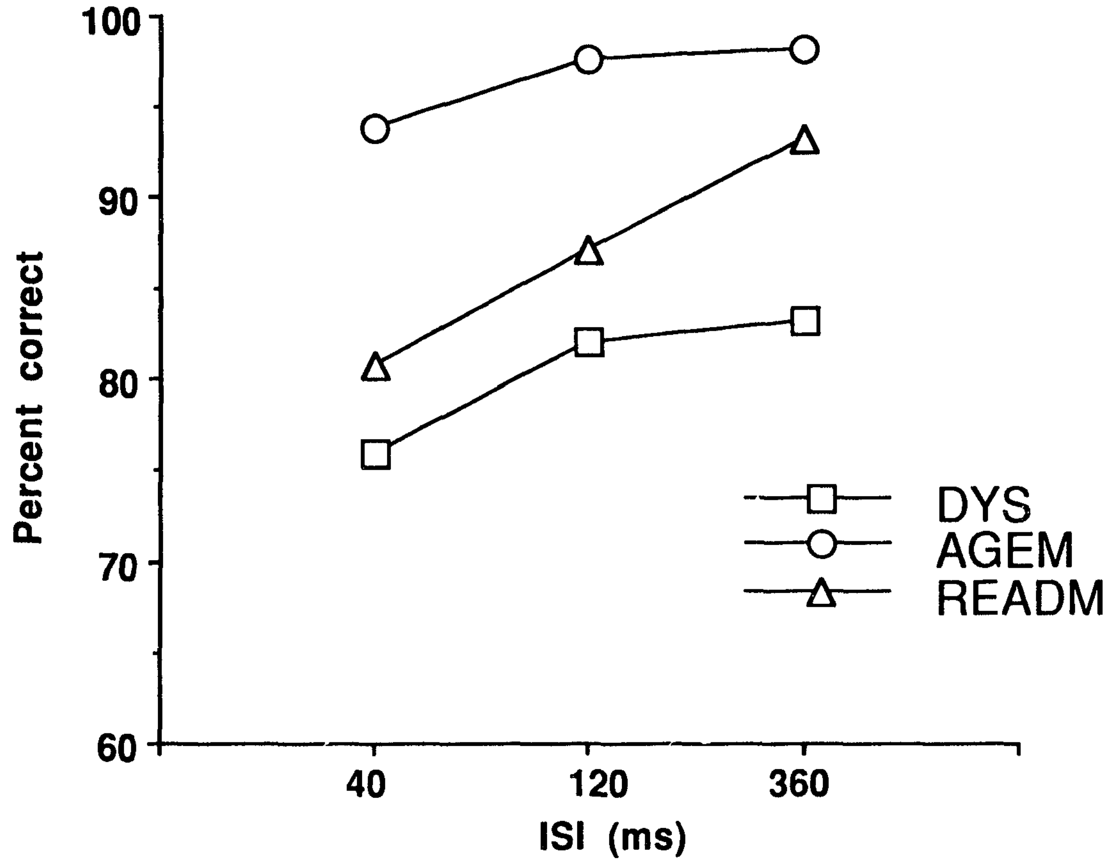

Figure 2. Mean overall correct scores at each ISI for each group on the auditory temporal order of judgment task

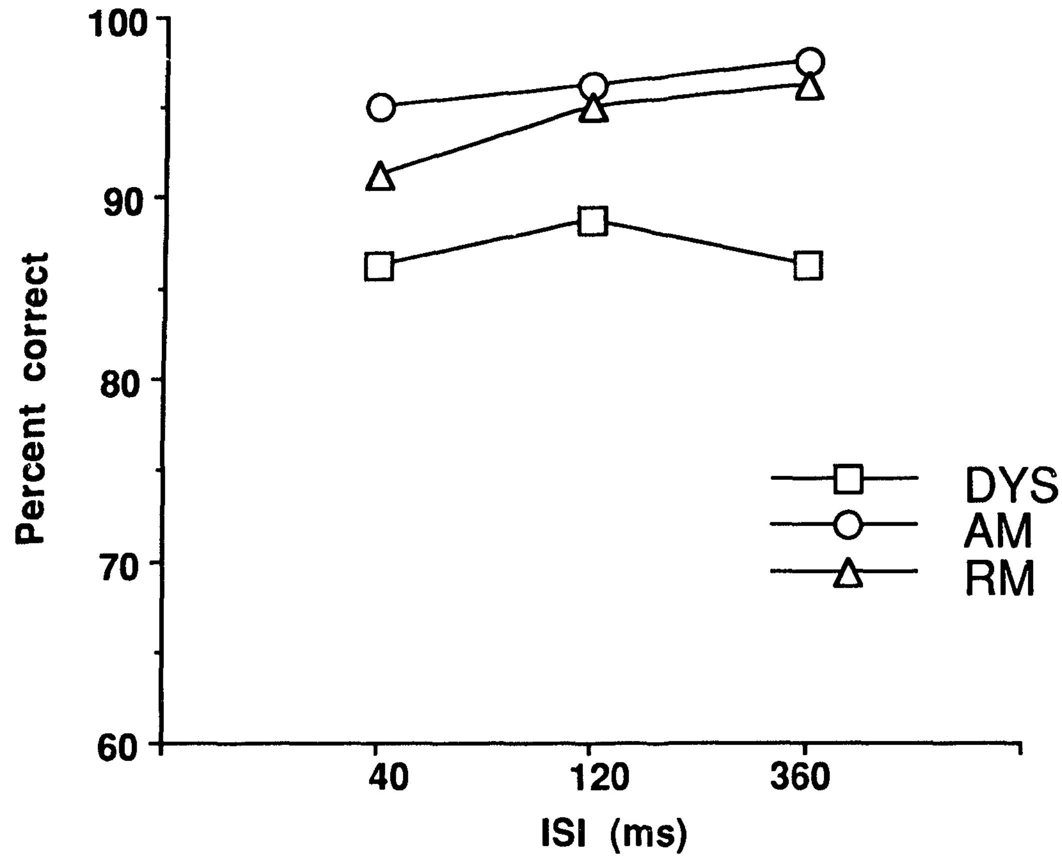

Figure 3. Mean correct scores (same stimuli only) at each ISI for each group on the auditory temporal order of judgment task

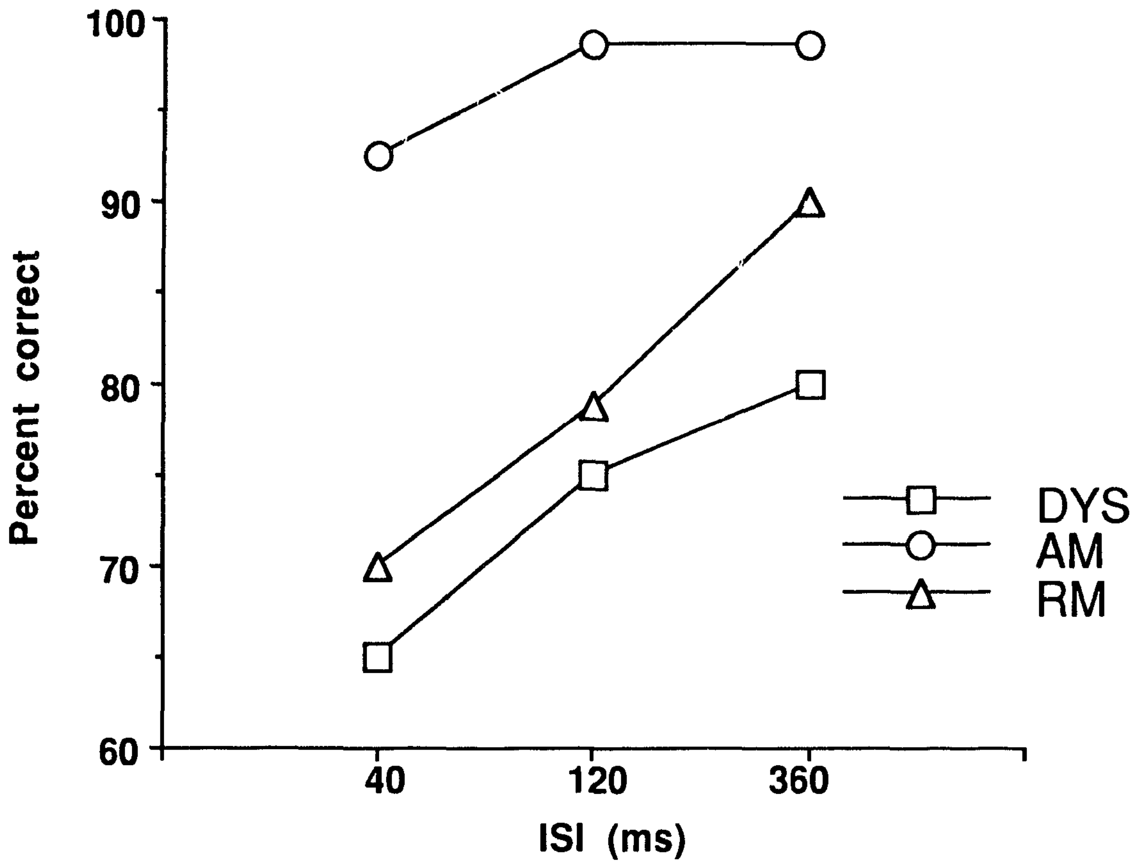

Figure 4. Mean correct scores (different stimuli only) at each ISI for each group on the auditory temporal order of judgment task

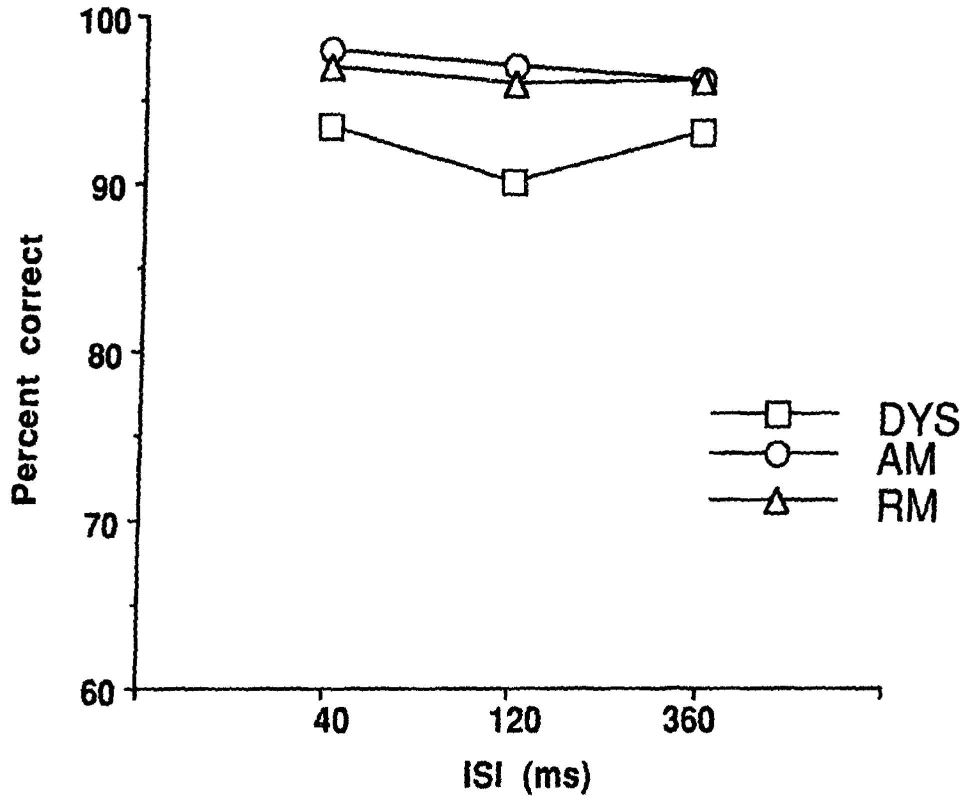

Figure 5. Mean correct scores (same stimuli only) at each ISI for each group on the tone sequence matching task

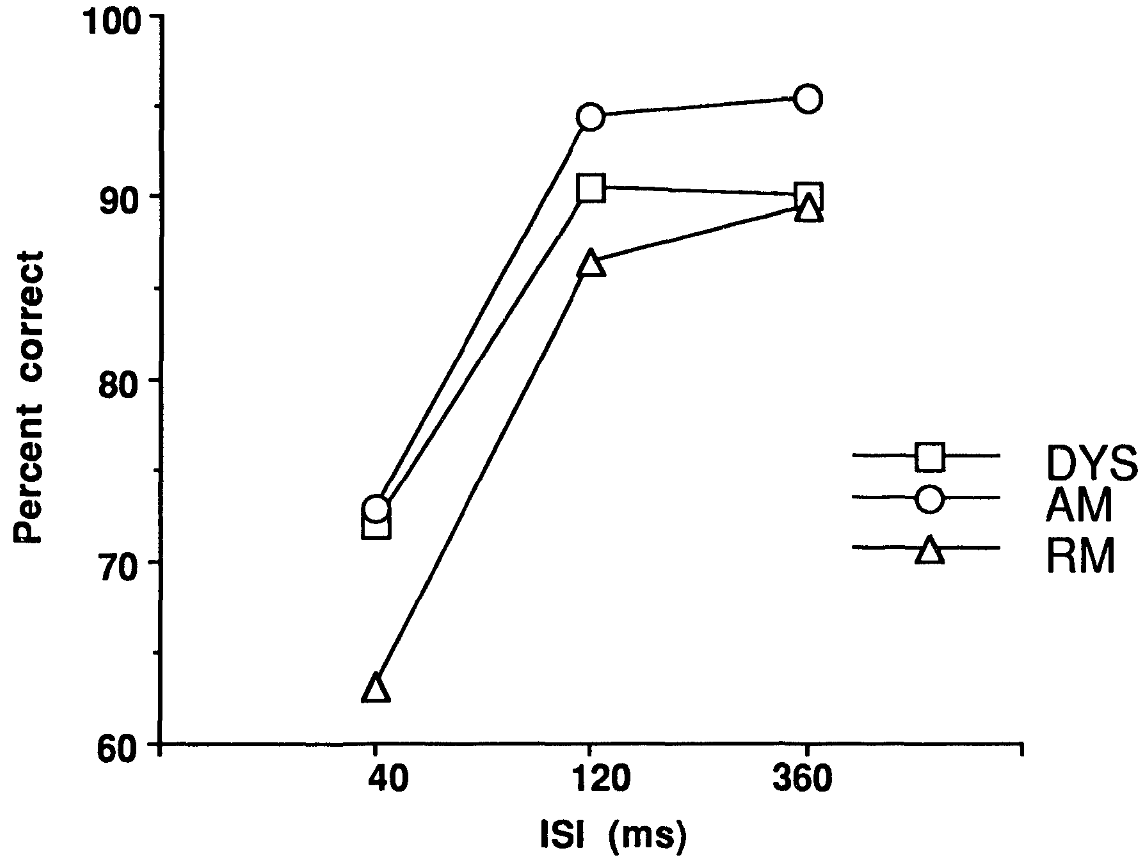

Figure 6. Mean correct scores (different stimuli only) at each ISI for each group on the tone sequence matching task

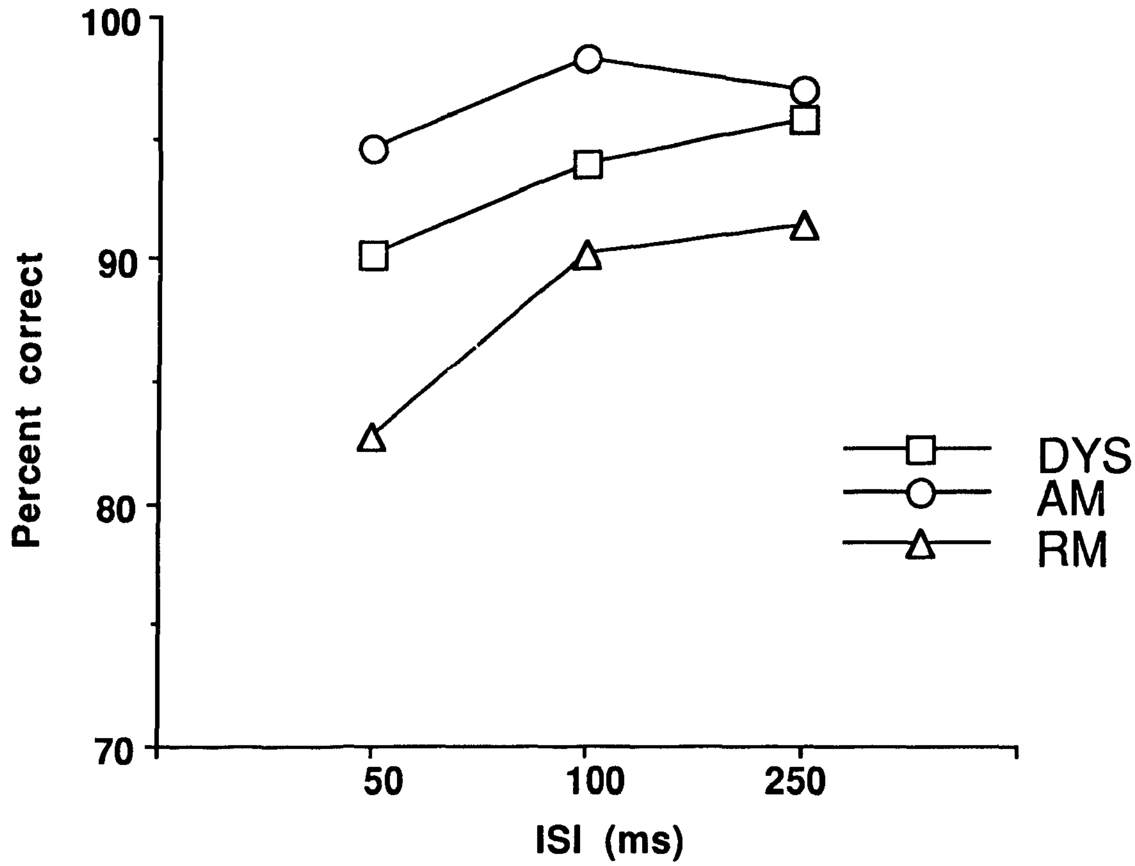

Figure 7. Mean overall correct scores at each ISI for each group on the visual temporal order of judgment task

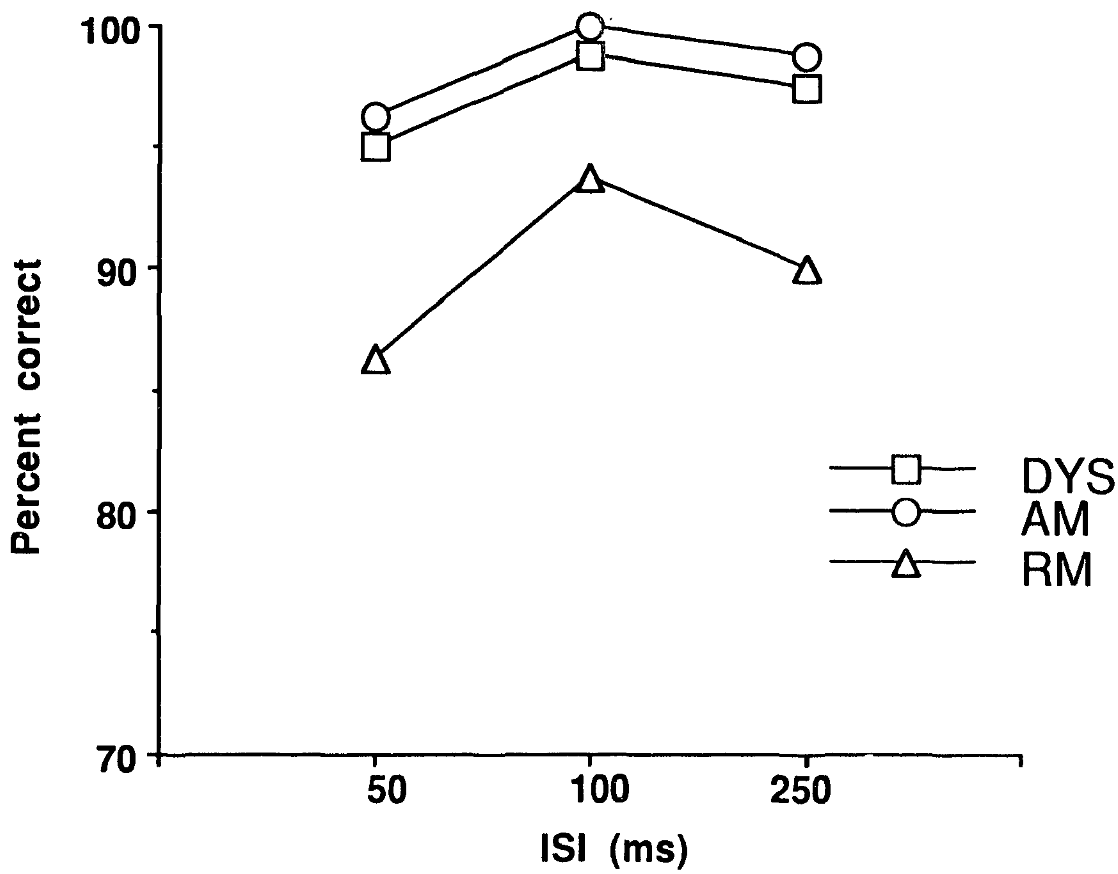

Figure 8. Mean correct scores (same stimuli only) at each ISI for each group on the visual temporal order of judgment task

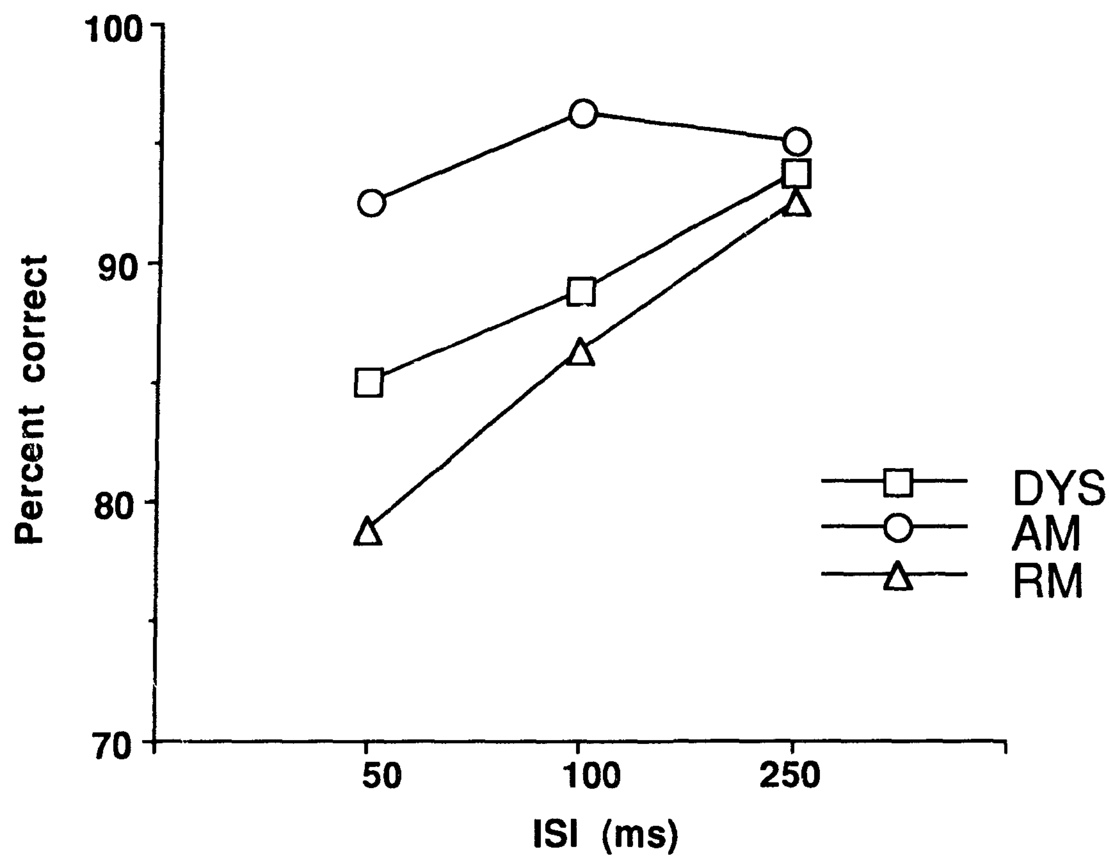

Figure 9. Mean correct scores (different stimuli only) for each ISI for each group on the visual temporal order of judgment task

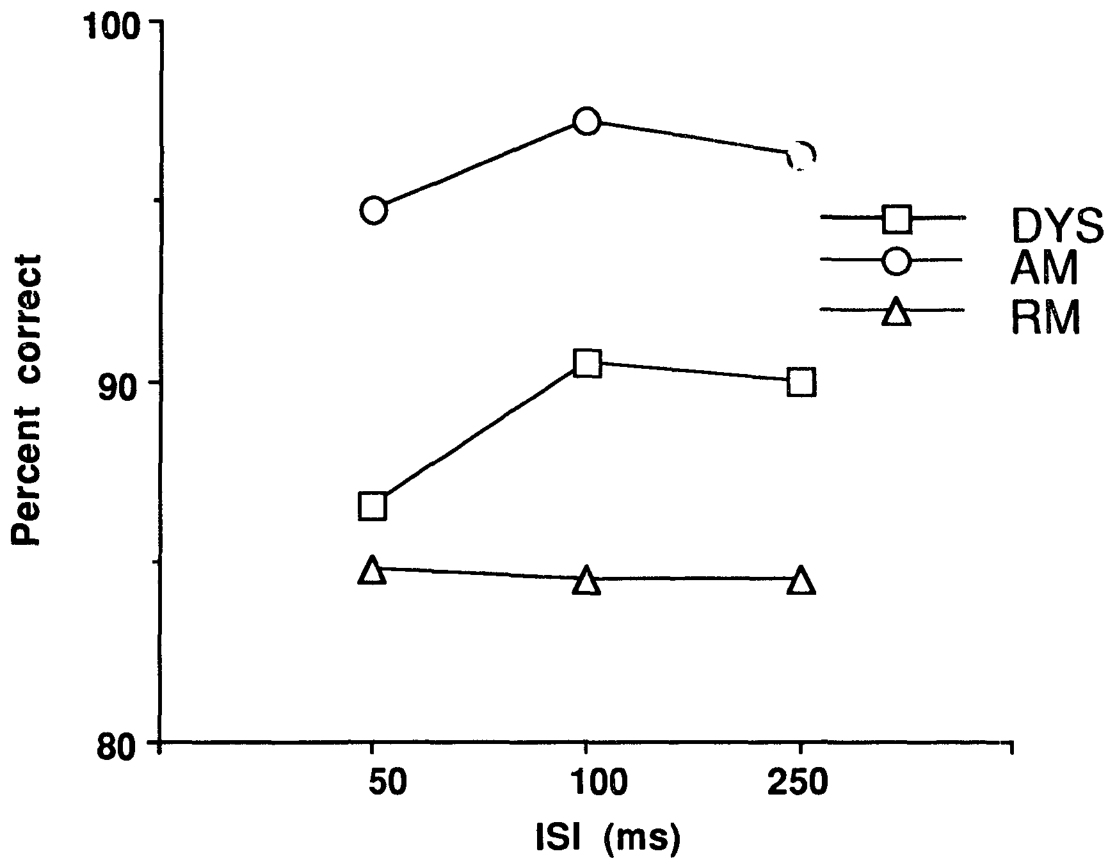

Figure 10. Mean correct scores at each ISI for each group on the visual sequential pattern matching task

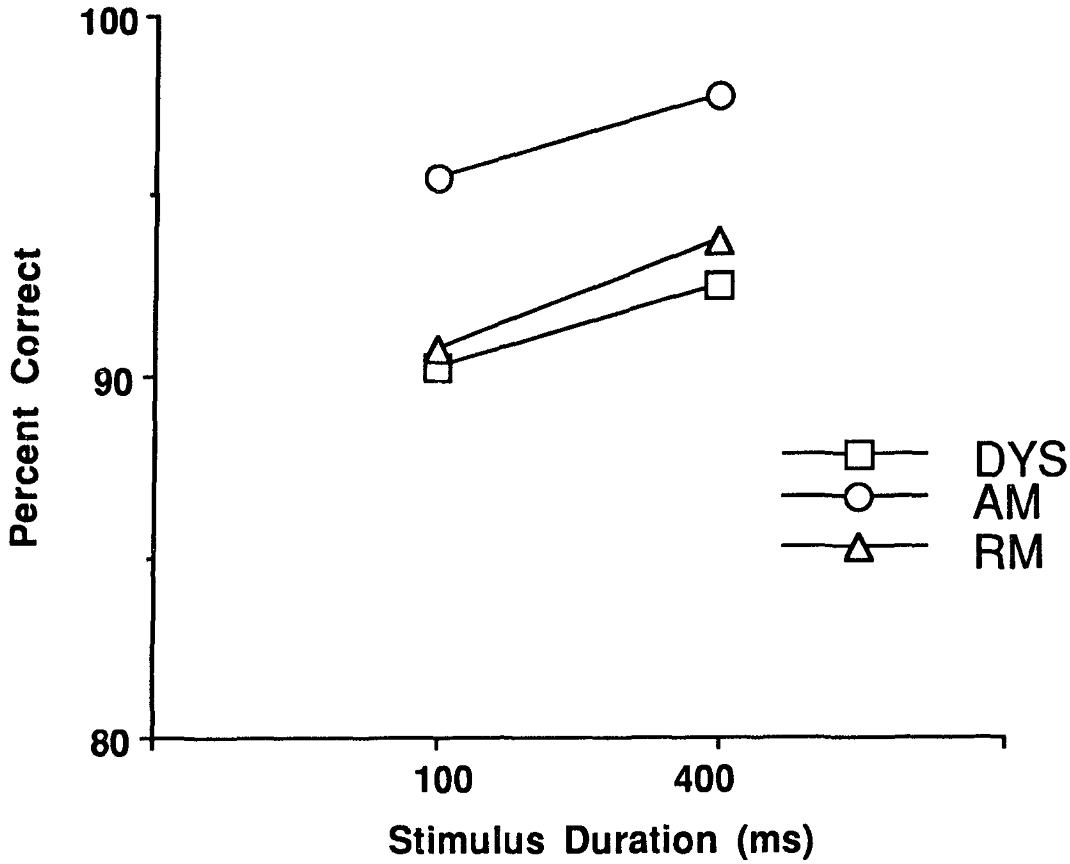

Figure 11. Mean correct scores at each duration for each group on the visual simultaneous pattern matching task

APPENDIX 1

Words used in the odd-one-out phonemic awareness task

a) First phoneme

match	can	caps	cab
bun	bud	bus	rug
pip	pin	hill	pig
sun	see	sock	rag
tent	dell	test	tense
gate	gain	cape	gale

b) Middle phoneme

lot	cot	hat	pot
fun	pin	bun	gun
nod	red	fed	bed
batch	catch	match	witch
joke	bake	poke	soak
toad	seed	reed	deed

c) Last phoneme

pin	win	sit	fin
doll	hop	top	pop
weed	peel	need	deed
bite	white	tide	fight
came	pail	same	game
rush	must	just	dust

APPENDIX 2

Words used in auditory analysis phonemic awareness task

Original word	To be omitted	Correct answer
BELT	/T/	BELL
RODE	/D/	ROE
SOUR	/S/	OUR
LEND	/L/	END
TIME	/M/	TIE
SCOLD	/SK/	OLD
CLIP	/K/	LIP
SMILE	/S/	MILE
PRAY	/P/	RAY
BLOCK	/B/	LOCK
SMELL	/M/	SELL
DESK	/S/	DECK
SHRUG	/SH/	RUG
CREATE	/E/	CRATE
REPRODUCE	/PRO/	REDUCE
SKIN	/K/	SIN
STRAIN	/ST/	RAIN
CLUTTER	/L/	CUTTER
CARPENTER	/PEN/	CARTER
LOCATION	/KA/	LOTION

References

Aaron, P.G. (1985). The paradoxical relationship between intelligence and reading disability. Perceptual and Motor Skills, 61, 1251-1261.

Adams, M.J. (1990). Beginning to read: Thinking and learning about print. Cambridge, Ma: MIT Press.

Albert, M.L., & Bear, D. (1974). Time to understand: A case study of word deafness with reference to the role of time in auditory comprehension. Brain, 97, 373-384.

Anthony, B.J., Zeigler, B.L., & Graham, F.K. (1987). Stimulus duration as an age-dependent factor in reflex blinking. Developmental Psychobiology, 20, 285-297.

Arnett, J.L., & Di Lollo, V. (1979). Visual information processing in relation to age and to reading ability. Journal of Experimental Child Psychology, 27, 143-152.

Auerbach, S.H., Allard, T., Naeser, M., Alexander, M.P., & Albert, M.L. (1982). Pure word deafness. Analysis of a case with bilateral lesions and a defect at the prephonemic level. Brain, 105, 271-300.

Backman, J.E., Mamen, M., & Ferguson, H.B. (1984). Reading level design: Conceptual and methodological issues in reading research. Psychological Bulletin, 96, 560-568.

Badcock, D., & Lovegrove, W. (1981). The effects of contrast, stimulus duration, and spatial frequency on visible persistence in normal and specifically disabled readers. Journal of Experimental Psychology: Human Perception and Performance, 7, 495-505.

Bakker, D.J. (1967). Temporal order, meaningfulness, and reading ability. Perceptual and Motor Skills, 24, 1027-1030.

Bakker, D.J. (1970). Temporal order perception and reading retardation. In D. J. Bakker & P. Satz (Eds.), Specific reading disability: Advances in theory and method. Rotterdam: Rotterdam University Press.

Beitchman, J.H., & Inglis, A. (1991). The continuum of linguistic dysfunction from pervasive developmental disorders to dyslexia. Psychiatric Clinics of North America, 14, 95-111.

Ben-Dov, G., & Carmon, A. (1984). Rhythm length and hemispheric asymmetry. Brain and Cognition, 3, 35-41.

Berne, R.M., & Levy, M.N. (1988). Physiology, 2nd edn. St. Louis, Mi: C.V. Mosby Company, pp.93-134 and 158-178.

Bernstein, L.E., & Stark, R.E. (1985). Speech perception development in language-impaired children: A 4-year follow-up study. Journal of Speech and Hearing Disorders, 50, 21-30.

Bishop, D.V.M. (1992). The underlying nature of specific language impairment. Journal of Child Psychology and Psychiatry, 33, 3-66.

Blackwell, S.L., MacIntyre, C.W., & Murray, M.E. (1983). Information processed from brief visual displays by learning-disabled boys. Child Development, 54, 927 -940.

Boder, E. (1971). Developmental dyslexia: Prevailing diagnostic concepts and a new diagnostic approach. In H. Myklebust (Ed.), Progress in learning disabilities, Vol.2. New York: Grune and Stratton.

Bowers, P.G., & Swanson, L.B. (1991). Naming speed deficits in reading disability: Multiple measures of a singular process. Journal of Experimental Child Psychology, 51, 195-219.

Bradley, L. (1989). Predicting learning disabilities. In J.J. Dumont & H. Nakken (Eds.), Learning disabilities, Vol. 2: Cognitive, social and remedial aspects. Amsterdam: Swets & Zeitlinger.

Bradley, L., & Bryant, P.E. (1978). Difficulties in auditory organisation as a possible cause of reading backwardness. Nature, 271, 746-747.

Bradley, L., & Bryant, P.E. (1983). Categorizing sounds and learning to read - a causal connection. Nature, 301, 419-421.

Brady, S., Mann, V., & Schmidt, R. (1987). Errors in short-term memory for good and poor readers. Memory and Cognition, 15, 444-453.

Brady, S., Shankweiler, D., & Mann, V. (1983). Speech perception and memory coding in relation to reading ability. Journal of Experimental Child Psychology, 35, 345-367.

Brannan, J.R., & Williams, M.C. (1988). Developmental versus sensory deficit effects on perceptual processing in the reading disabled. Perception and Psychophysics, 44, 437-444.

Breedin, S.D., Martin, R.C., & Jerger, S. (1989). Distinguishing auditory and speech-specific perceptual deficits. Ear and Hearing, 10, 311-317.

Breitmeyer, B.G. (1989). A visually based deficit in specific reading disability. The Irish Journal of Psychology, 10, 534-541.

Brown, J.I., Nelson, M.J., & Denny, E.C. (1976). Examiner's Manual: The Nelson -Denny Reading Test. Boston, Ma: Houghton Mifflin Company.

Bryden, M.P. (1972). Auditory-visual and sequential-spatial matching in relation to reading ability. Child Development, 43, 824-832.

Bryson, S.E., & Werker, J.F. (1989). Toward understanding the problem in severely disabled readers. Part I: Vowel errors. Applied Psycholinguistics, 10, 1-12.

Byrne, B., & Shea, P. (1979). Semantic and phonetic memory codes in beginning readers. Memory and Cognition, 7, 333-338.

Canadian Psychology Association. (1988). Canadian code of ethics for psychologists: Companion manual. Quebec, PQ: Canadian Psychological Association.

Chase, C., & Jenner, A.R. (In press). Magnocellular visual deficits affect temporal processing of dyslexics. Annals of the New York Academy of Sciences.

Cohen, S., Glass, D.C., & Singer, J.E. (1973). Apartment noise, auditory discrimination, and reading ability in children. Journal of Experimental Social Psychology, 9, 407-422.

Cunningham, A.E. (1990). Explicit versus implicit instruction in phonemic awareness. Journal of Experimental Child Psychology, 50, 429-444.

Davis, S.M., & McCroskey, R.L. (1980). Auditory fusion in children. Child Development, 51, 75-80.

Denckla, M.B., & Rudel, R.G. (1976). Naming of object-drawings by dyslexic and other learning disabled children. Brain and Language, 3, 1-15.

De Weirdt, W. (1988). Speech perception and frequency discrimination in good and poor readers. Applied Psycholinguistics, 9, 163-183.

Di Lollo, V., Arnett, J.L., & Kruk, R.V. (1982). Age-related changes in rate of visual information processing. Journal of Experimental Psychology: Human Perception and Performance, 8, 225-237.

Di Lollo, V., Hanson, D., & McIntyre, J.S. (1983). Initial stages of visual information processing in dyslexia. Journal of Experimental Psychology: Human Perception and Performance, 9, 923-935.

Doehring, D.G., Trites, R.L., Patel, P.G., & Fiedorowicz, C.A.M. (1981). Reading disabilities: The interaction of reading, language, and neuropsychological deficits. New York: Academic Press.

Eden, G.F., Stein, J.F., & Wood, F.B. (1993). Visuospatial ability and language processing in reading disabled and normal children. In S.F. Wright & R. Groner (Eds.), Facets of dyslexia and its remediation. Amsterdam: Elsevier Science Publishers.

Elbert, J.C., & Seale, T.W. (1988). Complexity of the cognitive phenotype of an inherited form of learning disability. Developmental Medicine and Child Neurology, 30, 181-189.

Farmer, M.E., & Bryson, S.E. (In preparation). Spatial and sequential processing in dyslexic and normal readers.

Fay, W.H. (1966). Temporal sequence in the perception of speech. The Hague: Mouton & Company, pp.24-37.

Foorman, B.R., & Liberman, D. (1989). Visual and phonological processing of words: A comparison of good and poor readers. Journal of Learning Disabilities, 22, 349 -355.

Frith, U. (1986). A developmental framework for developmental dyslexia. Annals of Dyslexia, 36, 69-81.

Galaburda, A.M. (1988). The pathogenesis of childhood dyslexia. In F. Plum (Ed.), Language, communication and the brain. New York: Raven Press.

Galaburda, A.M., Corsiglia, J., Rosen, G.D., & Sherman, G.F. (1987). Planum temporale asymmetry, reappraisal since Geschwind and Levitsky. Neuropsychologia, 25, 853-868.

Galaburda, A.M., Sherman, G.F., Rosen, G.D., Aboitiz, F., & Geschwind, N. (1985). Developmental dyslexia: Four consecutive patients with cortical anomalies. Annals of Neurology, 18, 222-233.

Geiger, G., & Lettvin, J.Y. (1987). Peripheral vision in persons with dyslexia. New England Journal of Medicine, 316, 1238-1243.

Gibbs, D.P., & Cooper, E.G. (1989). Prevalence of communication disorders in students with learning disabilities. Journal of Learning Disabilities, 22, 60-63.

Godfrey, J.J., Syrdal-Lasky, A.K., Millay, K.K., & Knox, C.M. (1981). Performance of dyslexic children on speech perception tests. Journal of Experimental Child Psychology, 32, 401-424.

Gordon, H.W. (1984). Dyslexia. In R.E. Tarter & G. Goldstein (Eds.), Advances in clinical neuropsychology. Vol. 2). New York: Plenum Publishing.

Goswami, U. (1990). A special link between rhyming skill and the use of orthographic analogies by beginning readers. Journal of Child Psychology and Psychiatry, 31, 301-311.

Green, D.M., & Swets, J.A. (1966). Signal detection theory and psychophysics. New York: Wiley.

Gross, K., & Rothenberg, S. (1979). An examination of methods used to test the visual perceptual deficit hypothesis of dyslexia. Journal of Learning Disabilities, 12, 36 -43.

Gross-Glen, K., & Rothenberg, S. (1984). Evidence for deficit in interhemispheric transfer of information in dyslexic boys. International Journal of Neuroscience, 24, 23-35.

Haggerty, R., & Stamm, J.S. (1978). Dichotic auditory fusion levels in children with learning disabilities. Neuropsychologia, 16, 349-360.

Hienz, R.D., & Brady, J.V. (1988). The acquisition of vowel discriminations by nonhuman primates. Journal of the Acoustical Society of America, 84, 186-194.

Hirsh, I.J., & Sherrick, C.E., Jr. (1961). Perceived order in different sense modalities. Journal of Experimental Psychology, 62, 423-432.

Hochhaus, L. (1972). A table for the calculation of d' and beta. Psychological Bulletin, 77, 375-376.

Holmes, D.R., & McKeever, W.F. (1979). Material specific serial memory deficit in adolescent dyslexics. Cortex, 15, 51-62.

Hulme, C. (1988). The implausibility of low-level visual deficits as a cause of children's reading difficulties. Cognitive Neuropsychology, 5, 369-374.

Hulme, C., & Snowling, M. (1992). Deficits in output phonology: An explanation of reading failure? Cognitive Neuropsychology, 9, 47-72.

Hynd, G.W., & Semrud-Clikeman, M. (1989). Dyslexia and brain morphology. Psychological Bulletin, 106, 447-482.

Irwin, R.J., Ball, A.K.R., Kay, N., Stillman, J.A., & Rosser, J. (1985). The development of auditory temporal acuity in children. Child Development, 56, 614 -620.

Jastak, S., & Wilkinson, G.S. (1984). Wide Range Achievement Test - Revised. Wilmington, Delaware: Jastak Associates, Inc.

Johnston, R.S. (1982). Phonological coding in dyslexic readers. British Journal of Psychology, 73, 455-460.

Johnston, R.S., Anderson, M., Perrett, D.I., & Holligan, C. (1990). Perceptual dysfunction in poor readers: Evidence for visual and auditory segmentation problems in a sub-group of poor readers. British Journal of Educational Psychology, 60, 212 -219.

Jorm, A.F. (1983). Specific reading retardation and working memory: A review. British Journal of Psychology, 74, 311-342.

Jusczyk, P.W., Rosner, B.S., Reed, M.A., & Kennedy, L.J. (1989). Could temporal order differences underlie 2-month-olds' discrimination of English voicing contrasts? Journal of the Acoustical Society of America, 85, 1741-1749.

Kamhi, A., & Catts, H.W. (1986). Toward an understanding of developmental language and reading disorders. Journal of Speech and Hearing Disorders, 51, 337-347.

Kamhi, A.G., & Catts, H.W. (1989). Reading disabilities: A developmental language perspective. Boston, Ma: Little, Brown, & Company.

Katz, R.B. (1986). Phonological deficiences in children with reading disability: Evidence from an object-naming task. Cognition, 22, 225-257.

Katz, R.B., Healy, A.F., & Shankweiler, D. (1983). Phonetic coding and order memory in relation to reading proficiency: A comparison of short-term memory for temporal and spatial order information. Applied Psycholinguistics, 4, 229-250.

Katz, R.B., Healy, A.F., & Shankweiler, D. (1984). On accounting for deficiencies in order memory associated with reading difficulty: A reply to Tallal. Applied Psycholinguistics, 5, 170-174.

Katz, R.B., & Shankweiler, D. (1985). Repetitive naming and the detection of word retrieval deficits in the beginning reader. Cortex, 21, 617-625.

Katz, R.B., Shankweiler, D., & Liberman, I.Y. (1981). Memory for item order and phonetic recoding in the beginning reader. Journal of Experimental Child Psychology, 32, 474-484.

Katz, W.F., Curtiss, S., & Tallal, P. (1992). Rapid automatized naming and gesture by normal and language-impaired children. Brain and Language, 43, 623-641.

Keppel, G., and Zedeck, S. (1989). Data analysis for research designs: Analysis of variance and multiple regression/correlation approaches. New York: W.H. Freeman.

Klein, R., Berry, G., Briand, K., D'Entremont, B., & Farmer, M. (1990). Letter identification declines with increasing retinal eccentricity at the same rate for normal and dyslexic readers. Perception and Psychophysics, 47, 601-606.

Kluender, K.R., Kiehl, R.L., & Killeen, P.R. (1987). Japanese quail can learn phonetic categories. Science, 237, 1195-1197.

Kuhl, P.K. (1986). Theoretical contributions of tests of animals to the special -mechanisms debate in speech. Experimental Biology, 45, 233-265.

Kuhl, P.K. (1992). The perception of speech by infants: What is given by nature, what is gained by experience. Paper presented at the New York Academy of Sciences/Rodin Remediation Academy Conference, New York, September 12-15, 1992.

Larsen, J., Hoien, T., Lundberg, I., & Odegaard, H. (1990). MRI evaluation of the size and symmetry of the planum temporale in adolescents with developmental dyslexia. Brain and Language, 39, 289-301.

Lehmkuhle, S., Garzia, R.P., Turner, L., Hash, T., & Baro, J.A. (1993). A defective visual pathway in children with reading disability. The New England Journal of Medicine, 328, 989-996.

Liberman, I.Y. (1983). A language-oriented view of reading and its disabilities. In H. Myklebust (Ed.), Progress in learning disabilities, (Vol. 5). New York: Grune & Stratton, pp.81-101.

Liberman, I.Y. (1989). Phonology and beginning reading revisited. In C. von Euler, I. Lundberg, & G. Lennerstrand (Eds.), Brain and Reading. Stockton, NY: International Rodin Remediation Conference, Uppsala University.

Liberman, I.Y., & Shankweiler, D. (1985). Phonology and the problems of learning to read and write. Remedial and Special Education, 6, 8-17.

Livingstone, M.S., Rosen, G.D., Drislane, F.W., & Galaburda, A.M. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. Proceedings of the National Academy of Sciences, 88, 7943-7947.

Lovegrove, W., & Heddle, M. (1980). Visual persistence as a function of spatial frequency and age. Perception, 9, 529-532.

Lovegrove, W.J., Heddle, M., & Slaghius, W. (1980). Reading disability: Spatial frequency specific deficits in visual information store. Neuropsychologia, 18, 111-115.

Lovegrove, W., Martin, F., & Slaghius, W. (1986). A theoretical and experimental case for a visual deficit in specific reading disability. Cognitive Neuropsychology, 3, 225-267.

Lovett, M.W. (1984). A developmental perspective on reading dysfunction: Accuracy and rate criteria in the subtyping of dyslexic children. Brain and Language, 22, 67 -91.

Lovett, M.W. (1987). A developmental approach to reading disability: Accuracy and speed criteria of normal and deficient reading skill. Child Development, 58, 234 -260.

Ludlow, C.L., Cudahy, E.A., Bassich, C., & Brown, G.L. (1983). Auditory processing skills of hyperactive language-impaired and reading-disabled boys. In E.Z. Lasky & J. Katz (Eds.), Central auditory processing disorders: Problems of speech, language, and learning. Baltimore, Md: University Park Press.

Lundberg, I., & Hoien, T. (1989). Phonemic deficits: A core symptom of developmental dyslexia? The Irish Journal of Psychology, 10, 579-592.

Mann, V.A. (1984). Longitudinal prediction and prevention of early reading difficulty. Annals of Dyslexia, 34, 117-136.

Mann, V.A. (1993). Phoneme awareness and future reading ability. Journal of Learning Disabilities, 26, 259-269.

Mann, V.A., & Brady, S. (1988). Reading disability: The role of language deficiencies. Journal of Consulting and Clinical Psychology, 56, 811-816.

Mann, V.A., Liberman, I.Y., & Shankweiler, D. (1980). Children's memory for sentences and word strings in relation to reading ability. Memory and Cognition, 8, 329-335.

Martin, F., & Lovegrove, W.J. (1988). Uniform-field flicker masking in control and specifically-disabled readers. Perception, 17, 203-214.

Martos, F.J.. & Marmolejo, A. (1992). Visible persistence in developmental dyslexia. Poster presented at the New York Academy of Science/Rodin Remediation Foundation conference, New York, September 12-15, 1992.

Mason, M. (1980). Reading ability and the encoding of item and location information. Journal of Experimental Psychology: Human Perception and Performance, 6, 89-98.

May, J.G., Williams, M.C., & Dunlap, W.P. (1988). Temporal order judgements in good and poor readers. Neuropsychologia, 26, 917-924.

McCroskey, R.L., & Davis, S.M. (1976). Auditory fusion: Developmental trends. Scientific Exhibit, National Convention American Speech and Hearing Association, Houston. Reported in McCroskey & Kidder, 1980.

McCroskey, R.L., & Kidder, H.C. (1980). Auditory fusion among learning disabled, reading disabled, and normal children. Journal of Learning Disabilities, 13, 18-25.

McGivern, R.F., Berka, C., Languis, M.L., & Chapman, S. (1991). Detection of deficits in temporal pattern discrimination using the Seashore Rhythm Test in young children with reading impairments. Journal of Learning Disabilities, 24, 58-62.

Morrongiello, B.A. & Trehub, S.E. (1987). Age-related changes in auditory temporal perception. Journal of Experimental Child Psychology, 44, 413-426.

Muller, F., & Bakker, D.J. (1968). Temporal order perception and reading ability. Unpublished report, Pedological Insitute Research Department, Amsterdam. Reported in Bakker, 1970.

Nicolson, R.I., & Fawcett, A.J. (1992). Children with dyslexia automatise temporal skills more slowly. Poster presented at the New York Academy of Science/Rodin Remediation Foundation conference, New York, 12-15 September, 1992.

Nottebohm, F. (1979). Origins and mechanisms in the establishment of cerebral dominance. In M.S. Gazzaniga (Ed.), Handbook of behavioral neurobiology. Vol. 2. Neuropsychology. New York: Plenum Press, pp.314-323.

Olson, R.K., Davidson, B.J., Kliegl, R., & Davies, S.E. (1984). Development of phonetic memory in dsiabled and normal readers. Journal of Experimental Child Psychology, 37, 187-206.

Olson, R., Wise, B., Conners, F., Rack, J., & Fulker, D. (1989). Specific deficits in component reading and language skills: Genetic and environmental influences. Journal of Learning Disabilities, 22, 339-348.

O'Neill, G., & Stanley, G. (1976). Visual processing of straight lines in dyslexic and normal children. British Journal of Educational Psychology, 46, 323-327.

Pennington, B.F., & Smith, S.D. (1988). Genetic influences on learning disabilities: An update. Journal of Consulting and Clinical Psychology, 56, 817-823.

Phillips, D.P., & Farmer, M.E. (1990). Acquired word deafness, and the time frame of processing in the primary auditory cortex. Behavioural Brain Research, 40, 85-94.

Pollatsek, A., Lesch, M., Morris, R.K., & Rayner, K. (1992). Phonological codes are used in integrating information across saccades in word identification and reading. Journal of Experimental Psychology: Human Perception and Performance, 18, 148 -162.

Rack, J. (1985). Orthographic and phonetic coding in developmental dyslexia. British Journal of Psychology, 76, 325-340.

Rapin, I., & Allen, D.A. (1988). Syndromes in developmental dysphasia and adult aphasia. In F. Plum (Ed.), Language, communication and the brain. New York: Raven Press.

Rayner, K. (1975). The perceptual span and peripheral cues in reading. Cognitive Psychology, 7, 65-81.

Rayner, K., & Pollatsek, A. (1987). Eye movements in reading: A tutorial review. In M. Coltheart (Ed.), Attention and Performance XII: The psychology of reading. Hove, England: Lawrence Erlbaum Associates.

Reed, M.A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. Journal of Experimental Child Psychology, 48, 270-292.

Ripps, H., & Weale, R.A. (1976). Temporal analysis and resolution. In H. Davison (Ed.), The eye, (2nd edn.). New York: Academic Press.

Robin, D.A., Tomblin, J.B., Kearney, A., & Hug, L.N. (1989). Auditory temporal pattern learning in children with speech and language impairments. Brain and Language, 36, 604-613.

Rosner, J., & Simon, D.P. (1971). The auditory analysis test: An initial report. Journal of Learning Disabilities, 4, 1-15.

Sattler, J.M. (1982). Assessment of children's intelligence and special abilities (2nd edn.). Boston: Allyn & Bacon.

Scarborough, H.S. (1989). Prediction of reading disability from familial and individual differences. Journal of Educational Psychology, 81, 101-108.

Scarborough, H.S. (1990). Very early language deficits in dyslexic children. Child Development, 61, 1728-1743.

Segalowitz, S., Wagner, W.J., & Menna, R. (1992). Lateral versus frontal ERP predictors of reading skills. Brain and Cognition, 20, 85-103.

Seidenberg, M.S., & McClelland, J.L. (1989). A distributed, developmental model of word recognition and naming. Psychological Review, 96, 523-568.

Seymour, P.H.K., & Elder, L. (1986). Beginning reading without phonology. Cognitive Neuropsychology, 3, 1-36.

Shapiro, K.L., Ogden, N., & Lind-Blad, F. (1990). Temporal processing in dyslexia. Journal of Learning Disabilities, 23, 1-36.

Share, D.L., Jorm, A.F., Maclean, R., & Matthews, R. (1984). Sources of individual differences in reading acquisition. Journal of Educational Psychology, 76, 1309-1324.

Share, D.L., & Silva, P.A. (1987). Language deficits and specific reading retardation: Cause or effect? British Journal of Disorders of Communication, 22, 219-226.

Siegel, L.S., & Linder, B.A. (1984). Short-term memory processes in children with reading and learning disabilities. Developmental Psychology, 20, 200-207.

Slaghuis, W.L., & Lovegrove, W.J. (1985). Spatial-frequency-dependent visible persistence and specific reading disability. Brain and Cognition, 4, 219-240.

Snowling, M. (1987). Dyslexia: A cognitive developmental perspective. Oxford: Basil Blackwell.

Snowling, M.J. (1991). Developmental reading disorders. Journal of Child Psychology and Psychiatry, 32, 49-77.

Snowling, M., Stackhouse, J., & Rack, J. (1986). Phonological dyslexia and dysgraphia - a developmental analysis. Cognitive Neuropsychology, 3, 309-339.

Snowling, M., van Wagtendonk, B., & Stafford, C. (1988). Object-naming deficits in developmental dyslexia. Journal of Research in Reading, 11, 67-85.

Solman, R.T., & May, J.G. (1990). Spatial localization discrepancies: A visual deficiency in poor readers. American Journal of Psychology, 103, 243-263.

Spreen, O., & Strauss, E. (1991). A compendium of neuropsychological tests: Administration, norms, and commentary. New York: Oxford University Press, pp.94-116.

Stanley, G., & Hall, R. (1973). Short-term visual information processing in dyslexics. Child Development, 44, 841-844.

Stanovich, K. (1986a). Cognitive processes and the reading problems of learning -disabled children: Evaluating the assumption of specificity. In J. Torgeson & B. Wong (Eds.), Psychological and educational perspectives on learning disabilities. New York: Academic Press.

Stanovich, K.E. (1986b). Matthew effects in reading: Some consequences of individual differences in the acquisition of literacy. Reading Research Quarterly, 21, 360-406.

Stanovich, K.E. (1988a). The right and wrong places to look for the cognitive locus of reading disability. Annals of Dyslexia, 38, 154-177.

Stanovich, K.E. (1988b). Explaining the differences between the dyslexic and the garden-variety poor reader: The phonological-core variable-difference model. Journal of Learning Disabilities, 21, 590-604.

Stanovich, K.E. (1989). Has the learning disabilities field lost its intelligence? Journal of Learning Disabilities, 22, 487-492.

Stanovich, K.E., Cunningham, A.E., & Cramer, B.B. (1984). Assessing phonological awareness in kindergarten children: Issues of task comparability. Journal of Experimental Child Psychology, 38, 175-190.

Stark, R.E., Bernstein, L.E., Condino, R., Bender, M., Tallal, P., & Catts, H. (1984). Four-year study of language impaired children. Annals of Dyslexia, 34, 49-68.

Stark, R.E., & Tallal, P. (1981). Perceptual and motor deficits in language-impaired children. In R.W. Keith (Ed.), Central auditory and language disorders in children. Houston, Texas: College-Hill Press.

Stein, J. (1989). Visuospatial perception and reading problems. The Irish Journal of Psychology, 10, 521-533.

Stein, J., Riddell, P., & Fowler, S. (1989). Disordered right hemisphere function in developmental dyslexia. In C. von Euler, I. Lundberg & G. Lennerstrand (Eds.), Brain and Reading. New York: Stockton Press.

Stuart, M., & Masterson, J. (1992). Patterns of reading and spelling in 10-year-old children related to prereading phonological abilities. Journal of Experimental Child Psychology, 54, 168-187.

Tallal, P. (1976). Rapid auditory processing in normal and disordered language development. Journal of Speech and Hearing Research, 19, 561-571.

Tallal, P. (1978). An experimental investigation of the role of auditory temporal processing in normal and disordered language development. In A. Caramazza & E.B. Zurif (Eds.), Language acquisition and language breakdown: Parallels and divergencies. Baltimore, Md: The Johns Hopkins University Press.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. Brain and Language, 9, 182-198.

Tallal, P. (1984). Temporal or phonetic processing deficit in dyslexia? That is the question. Applied Psycholinguistics, 5, 167-169.

Tallal, F. (1988). Developmental language disorders: Part 1 - Definition. Human Communication Canada, 12, 7-22.

Tallal, P., & Curtiss, S. (In press). Neurological basis of developmental language disorders. In A Rothenberger (Ed.), Brain and behavior in child psychiatry. Heidelberg: Springer-Verlag.

Tallal, P., & Piercy, M. (1973). Developmental aphasia: Impaired rate of non-verbal processing as a function of sensory modality. Neuropsychologia, 11, 389-398.

Tallal, P., Sainburg, R.L., & Jernigan, T. (1991). The neuropathology of developmental dysphasia: Behavioral, morphological, and physiological evidence for a pervasive temporal processing disorder. Reading and Writing, 3, 363-377.

Tallal, P., & Stark, R.E. (1982). Perceptual/motor profiles of reading impaired children with or without concomitant oral language deficits. Annals of Dyslexia, 32, 163 -176.

Tallal, P., Stark, R., Kallman, C., & Mellits, D. (1981). A reexamination of some nonverbal perceptual abilities of language-impaired and normal children as a function of age and sensory modality. Journal of Speech and Hearing Research, 24, 351 -357.

Torgeson, J.K. (1985). Memory processes in reading disabled children. Journal of Learning Disabilities, 18, 350-357.

Vellutino, F.R. (1987). Dyslexia. Scientific American, 256, 34-41.

Vellutino, F.R., & Scanlon, D.M. (1987). Phonological coding, phonological awareness, and reading ability: Evidence from a longitudinal and experimental study. Merrill-Palmer Quarterly, 33, 321-363.

Vellutino, F.R., Steger, J.A., Kaman, M., & De Setto, L. (1975). Visual form perception in deficient and normal readers as a function of age and orthographic -linguistic familiarity. Cortex, 11, 22-30.

Underwood, G., & Boot, D. (1986). Hemispheric asymmetries in developmental dyslexia: Cerebral structure or attentional strategies? Journal of Reading Behavior, 18, 219-228.

Wagner, R.K. (1986). Phonological processing abilities and reading: Implications for disabled readers. Journal of Learning Disabilities, 19, 623-630.

Wagner, R.K., & Torgeson, J.K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. Psychological Bulletin, 101, 192 -212.

Watkins, R.V. (1990). Processing problems and language impairment in children. Topics in Language Disorders, 11, 63-72.

Werker, J. (1989). Becoming a native listener. American Scientist, 77, 54-59.

Werker, J.F., Bryson, S.E., & Wassenberg, K. (1989). Toward understanding the problem in severely disabled readers. Part II: Consonant errors. Applied Psycholinguistics, 10, 13-30.

Werker, J.F., & Tees, R.C. (1987). Speech perception in severely disabled and average reading children. Canadian Journal of Psychology, 41, 48-61.

Werner, L.A., Marean, G.C., Halpin, C.F., Spetner, N.B., & Gillenwater, J.M. (1992). Infant auditory temporal acuity: Gap detection. Child Development, 63, 260-272.

Wickelgren, W.A. (1979). Cognitive Psychology. Eaglewood Cliffs, NJ: Prentice-Hall, pp.114-161.

Winters, R.L., Patterson, R., & Shontz, W. (1989). Visual persistence and adult dyslexia. Journal of Learning Disabilities, 22, 641-645.

Wolf, M. (1986). Rapid alternating stimulus naming in the developmental dyslexias. Brain and Language, 27, 360-379.

Wolf, M., & Obregon, M. (1992). Early naming deficits, developmental dyslexia, and a specific deficit hypothesis. Brain and Language, 42, 219-247.

Wood, F., Flowers, L., Buchsbaum, M., & Tallal, P. (1991). Investigation of abnormal left temporal functioning in dyslexia through rCBF, auditory evoked potentials, and positron emission tomography. Reading and Writing, 3, 379-393.

Woodcock, R.W. (1987). Woodcock Reading Mastery Tests. Circle Pines, Mn: American Guidance Service.

Yaqub, B.A., Gascon, G.G., Al-Nosha, M., & Whitaker, H. (1988). Pure word deafness (acquired verbal auditory agnosia) in an Arabic speaking patient. Brain, 111, 457-466.

Zurif, E.B., & Carson, G. (1970). Dyslexia in relation to cerebral dominance and temporal analysis. Neuropsychologia, 8, 351-361.