

**Processing of speech and non-speech sounds in the language-related cortex
compared between dyslexic and normal-reading adults: fMRI –study**

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ABSTRACT

An open and disputed question concerning dyslexia is whether it is based on an auditory processing deficit or on a more specific speech-related phonological deficit. Here an attempt was made to find out whether (and how) the location and/or function of the neural-level processing of auditory versus phonological discrimination tasks differ between adults with and without dyslexia. Functional magnetic resonance images of the sagittal slices of the temporal cortex of nine dyslexic and ten non-dyslexic adults were compared when participants were listening to sequences of speech and tone stimuli. The tone stimuli differed from the speech stimuli only in their not containing the spectral components of sound specific to speech. In both conditions, the subjects were instructed to report the number of deviant stimuli among 14 subsequent items, 0-3 of which differed from a repeated stimulus. The deviant stimuli differed from the repeated ones only by the duration of a single element of the sound. The repeated speech stimulus was a short bisyllabic pseudoword /ata/ and in the deviant stimulus, the silent gap in the /ata/ was lengthened so that an ordinary listener perceived it as /atta/. The results revealed that adults with dyslexia showed activation exceeding that of the controls in the left middle temporal areas (middle STG, PT) during the speech sound discrimination task and in the left anterior temporal (anterior STG) and inferior frontal (IFG, preCG) areas in the analogous non-speech task. Additionally, dyslexic subjects showed less activation in the left posterior Sylvanian areas (posterior SF) in both conditions. The results suggest that the processing of both speech and non-speech auditory material in the brain of dyslexic readers employs the language-related cortical networks differently from non-impaired readers. Compared to non-impaired readers, dyslexic adults seem to employ more the regions within the middle superior temporal areas, especially for speech-related discrimination, the anterior temporal to inferior frontal areas, especially for tone-related discrimination, and less the posterior language areas independent on the speech vs. non-speech content of the task.

Keywords: dyslexia; fMRI; planum temporale; sound discrimination

TIIVISTELMÄ

Dysleksia-tutkimuksen yksi keskeisimmistä kysymyksistä tällä hetkellä on, johtuvatko havaitut kuulonvaraisen fonologisen prosessoinnin heikkoudet erityisesti puheäänelle ominaisten piirteiden hahmotus- tai käsittelyongelmasta vai yleisemmästä, kaiken auditorisen materiaalin käsittelyn ongelmasta. Tämän tutkimuksen tarkoituksena oli selvittää, eroaako neuraalisen tason prosessointi auditorisen ja fonologisen diskriminaatio-tehtävän aikana normaalisti lukevilla ja dysleksiasta kärsivillä aikuisilla. Tutkimukseen osallistui 9 dyslektikkaa ja 10 normaalisti lukevaa aikuista, joiden kielelliseen prosessointiin erikoistunutta aivokuorta kuvattiin funktionaalisella MRI:lla heidän suorittaessaan kahdentyypisiä diskriminaatiotehtäviä, epäsanojen ja sini-aalto -äänien erottelua. Ainoa ero ärsykkeiden välillä oli, että sini-aalto -äänissä ei ollut puheelle ominaisia spektrimuotoja. Kummankin ärsykeen kohdalla koehenkilöiden tehtävänä oli erottaa 14 peräkkäisen ärsykeen joukosta 0-3 poikkeavaa ärsykettä. Toistettu puhe-ärsyke oli lyhyt kaksitavuinen epäšana /ata/ ja poikkeava ärsyke epäšana /atta/, joka muodostettiin pidentämällä keskellä olevaa taukoa (konsonanttia) niin, että se erosi toistettavasta epäsanasta. Tulokset osoittivat, että dysleksiasta kärsivillä aikuisilla aivojen aktivaatio vasemman hemisfäärin temporaalilohkon ylimmässä poimussa (superior temporal gyrus), erityisesti sen keski-osissa sekä planum temporalen alueella, oli suurempi kuin kontrollihenkilöillä puhe-äänteiden diskriminaatiotehtävän aikana. Analogisen sini-aalto -äänien diskriminaatiotehtävän aikana vasemman hemisfäärin temporaalilohkon ylimmän poimun etuosat sekä inferiorisen frontaalilohkon osat aktivoituivat dyslektikoilla kontrolleja enemmän. Lisäksi dysleksiasta kärsivien aikuisten vasemman temporaalilohkon ja parietaalilohkon liitoskohdan alueella, Sylviuksen uurteen taka-osissa, aktiivisuus oli kontrollihenkilöitä vähäisempää molempien tehtävien aikana. Yksinkertaisen puhe-äänien ja sini-aalto -äänien erottelu näyttää siis aktivoivan eri tavoin kielen käsittelyyn erikoistunutta aivokuorta dyslektikoilla verrattuna normaaleihin lukijoihin. Dysleksiasta kärsivillä henkilöillä prosessointi näyttää painottuvan enemmän kielellisen aivokuoren keski- ja etuosiin ja vähemmän sen takaosiin, normaalilukijoihin verrattuna.

Avainsanat: Dysleksia; fMRI; planum temporale; äänen diskriminaatio

TABLE OF CONTENTS

1	INTRODUCTION	6
1.1	Dyslexia as a cognitive deficit	6
1.2	Neural level phenomena associated with dyslexia	8
2	METHODS.....	16
2.1	General methods	16
2.2	Subjects.....	16
2.3	Experimental design	17
2.4	Procedure	19
2.5	Differentiating the signal from noise.....	19
2.6	Defining the regions of interest	20
2.7	Quantification of the activation in the regions of interest	21
2.8	Hypothesis Testing	25
3	RESULTS.....	26
3.1	Differences in the task performance	26
3.2	General activation.....	27
3.3	Differences between groups.....	28
4	DISCUSSION.....	35
5	REFERENCES	43
6	APPENDIXES.....	51

ABBREVIATIONS

AG	angular gyrus
arSF	ascending ramus of Sylvian fissure
hrSF	horizontal ramus of Sylvian fissure
IFG	inferior frontal gyrus
MTG	middle temporal gyrus
postCG	postcentral gyrus
postCS	postcentral sulcus
preCG	precentral gyrus
preCS	precentral sulcus
PP	planum parietale
PT	planum temporale
SF	Sylvian fissure
SMG	supramarginal gyrus
STG	superior temporal gyrus
STS	superior temporal sulcus
TTG	transverse temporal gyrus
fMRI	functional magnetic resonance imaging

1 INTRODUCTION

1.1 Dyslexia as a cognitive deficit

Dyslexia is a brain-based developmental disorder in which reading ability is much lower than expected on the grounds of other cognitive abilities (Diagnostic and Statistical Manual of Mental Disorders, 4th edit, 1994). Although the behavioral and cognitive outcomes of dyslexia are rather widely characterized in the research literature, little is known of the brain processes affected in dyslexia. One of the central issues in dyslexia study today is the level of auditory processing where the impairment occurs; whether it covers all the auditory processing or only the processing of speech-related sounds. Although intensive debate has taken place on the subject at the behavioral and cognitive levels, only few studies so far have challenged the question at the neural level of processing.

It is commonly agreed that dyslexia is associated with impaired phonological skills and phonological awareness (Bradley & Bryant, 1979; Fletcher et al., 1994; Shankweiler et al., 1995; Shaywitz et al., 1998; Stanovich & Siegel, 1988). Phonological processing refers to the processing of speech sound, comprising sub-word level lexical units, down to phonemes, the smallest meaningful constituents of speech. Phonological ability is, however, not a homogenous body of capacity, but is constructed of a relatively heterogeneous set of different components (Lyytinen, 1997; Lyytinen, Leinonen, Nikula, Aro, & Leino, 1995; Wagner & Torgeson, 1987). It employs perceptive functions, memory functions, motor functions etc. Therefore it is reasonable to assume that more specific deficits cause the phonological impairments in dyslexia. In the Finnish language, one of the features of sub-word processing which is difficult for individuals with dyslexia seems to concern the discrimination and manipulation of the quantitative (duration-related) information. The length of vowels and consonants, which are highly distinctive (and occur without confounding stress or pitch variation) in the Finnish language, seem to be difficult to manipulate accurately, both in reading and spelling among Finnish dyslexic children and adults (Lyytinen et al., 1995).

Because of the multiple symptoms found in dyslexia at the behavioral level, some authors have suggested that dyslexia would be better explained by different sub-syndromes with distinctive core deficits than by one coherent syndrome (Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996; Ridder, Borsting, Cooper, McNeel, & Huang, 1997).

There are different views concerning the cognitive nature of the core deficit (or deficits) in the brain processes underlying dyslexia. The symptoms are mainly seen in language-related behavior and the idea of a specific language-based deficit in dyslexia has a long history. However, a growing body of research is also eliciting support for the contention that the brain functioning of dyslexic readers differs in more basic auditory processing – not merely in auditory processing specific to speech. This hypothesis of deficit in general auditory processing claims that the organization of the brain is altered so that the ability to process the versatile properties of sounds is somehow impaired (Merzenich, Schreiner, Jenkins, & Wang, 1993; Tallal, Miller, & Fitch, 1993). According to Tallal et al. (1993), the difficulties which manifest in the speech perception of language-impaired (LI) and dyslexic children arise from the inability to process brief acoustic changes in format transitions of consonant-vowel -syllables. Accordingly, language-impaired and reading-impaired (dyslexic) children are unable to establish stable and invariant phonemic representations due to their basic deficit in the perception of temporal features of auditory information. This affects reading acquisition due to difficulties in accurately perceiving speech and sub-word segments of a word. Tallal et al. believe that the underlying deficit is general in nature and also affects other sensory modalities (e.g. visual and somatosensory)(Tallal et al., 1993).

Tallal et al. (1993) suggest that the left hemisphere is specialized in the manipulation of rapid events; Belin et al. (1998) have recently published support for this contention showing left lateralized processing of rapid acoustic transitions. Fitch, Miller, and Tallal (1997) suggest that a disruption of the mechanism in the left hemisphere (in primary and secondary auditory cortices), which reflects the processing of rapid acoustic changes in either speech or non-speech auditory stimuli, leads to the phonological disorders seen in developmental language disorders, including dyslexia. For dyslexic children, the theory of a basic temporal perception deficit has gained support from e.g. Hari and Kiesilä (1996) and Stein and Walsh (1997).

Mody, Studdert-Kennedy, and Brady (1997) pose a counter-argument to Tallal's hypothesis by reporting that the difficulties in the identification of temporal changes stem from a deficit in discriminative capacity, not in temporal processing of acoustic phenomena in general (see also Studdert-Kennedy & Mody, 1995). According to the language specific deficit hypothesis, the central units at the basis of the language (consonant-vowel syllables) cannot be reduced to pure auditory signals at a cognitive or neural level. The deficits are suggested to be in a more specific ability to discriminate or segment different sounds in language. The fuzziness or lack of specificity of the representations, i.e. an innate deficit of speech perception produces impaired processing of

these representations (Mody et al. 1997). According to Mody et al. (1997), the deficit in dyslexia is domain-specific and reflects difficulties in identifying the phonological categories of speech sounds that resemble one another.

A third attempt to understand deficits causing impairments in reading is based on a motor theory of speech. According to this theory, the mental representations of articulatory gestures are thought to be necessary for both the production and comprehension of speech (Heilman, Voeller & Alexander, 1996; Liberman & Mattingly, 1985) because accessing articulatory representations is necessary for phonetic judgements. This aspect of speech processing is believed to involve neural circuits that especially include Broca's area (Zatorre, Evans, Meyer & Gjedde, 1992).

Heilman et al. (1996) introduced a hypothesis of a motor-articulatory feedback deficit as one possible underlying cause of dyslexia. According to Heilman et al. (1996), the awareness of the position of articulators is impaired in some dyslexic children and an inability to associate these positions with speech sounds may impair the adequate development of phonological processing ability. The awareness of correspondence between speech utterances and articulatory gestures is automatically learned in the childhood language environment. The acquisition of phonemic awareness - which is required to learn the correspondences between graphemes and phonemes - is difficult if one is unable to acquire an awareness of the fine movements in different articulatory gestures. Lacking awareness of the articulatory gestures may stem from impaired functioning of feedback and may lead to difficulties in reading (Heilman et al., 1996). This theory would thus predict a speech perception related disorder, which is associated to fine motor functions, as the basis of dyslexia.

1.2 Neural level phenomena associated with dyslexia

As reviewed recently by Lyytinen and Leppänen (in press), the knowledge concerning brain functions associated with reading is growing fast, but the differences related to dyslexia are less well known. It however, seems clear that the areas activated for phonological processing – regions in the temporal and inferior parietal cortices and the inferior frontal cortex – often reveal differences (Brunswick, McCroy, Price, Frith, U., & Frith, C., 1999; Frost, Binder, Newby, & Hammeke, 1997; Rumsay et al., 1992; Rumsay, Nace, et al., 1997; Shaywitz et al., 1998). Based on many functional brain-imaging studies of normal readers, the tentative roles of more and more specific regions in these language-related cortices are becoming uncovered. The knowledge about

the normal functioning of the specific regions is important when trying to find the functional differences connected to the dyslexic syndrome.

Activation in the temporal lobe, mostly centered on the superior temporal gyrus (STG), is almost always present when the task includes some sort of phonological analysis (e.g. Binder et al., 1994; Celsis et al., 1999; Demonet et al., 1992; Liu, Lantos, Shafer, Knuth, & Vaughan, 1997). Especially, it has been suggested that it is connected to speech-related processing. Binder et al. (1994) shows how the processing of different speech stimuli (words, pseudowords, narrative text) induce significantly more widespread activation in the STG than a white noise stimulus, which activated mainly the Heschl's gyrus. Celsis et al. (1999) and Liu et al. (1997) also detected activation in the STG during passive listening to phonemic stimuli. However, there is a strong suggestion that activation is also seen anteriorly near Broca's area during phonological processing. Recently, Pugh et al. (1996) suggested a more multi-functional role for the temporal language areas in language processing (reflecting semantic, phonological and orthographic processing) and, based on his findings and previous studies, proposed the inferior frontal cortex to be more specifically devoted to phonological processing.

Broca's area and the surrounding inferior frontal cortex are traditionally connected to speech production (e.g. Petersen, Fox, Poster, Mintum, & Raichle, 1989). However, activation in this area has recently been discovered also during speech perception, especially during active listening to phonemic stimuli (Binder et al., 1997; Celsis et al., 1999; Demonet et al., 1992, Demonet, Price, Wise, & Frackowiak, 1994; Pugh et al., 1996; Shaywitz et al., 1997; Zatorre et al., 1992). Activation in the inferior frontal gyrus (IFG) has been shown during tasks requiring sub-vocal rehearsal (Paulesu et al., 1993), complex phonetic discrimination, and the sequencing and rehearsing of phonemes (Demonet et al., 1992, 1994; Zatorre et al., 1992). Zatorre et al. (1992) has proposed that Broca's activation represents part of the articulatory component in phonetic perception. In his study, the discrimination of the phonetic structure of a stimulus increased activity in Broca's area of the left hemisphere, while only passive listening to speech syllables activated the secondary auditory cortices bilaterally. According to Demonet et al. (1992), the activation in Broca's area is consistent with the motor theory of speech presented by Liberman and Mattingly (1985) (see above, Heilman et al., 1996). The discrimination of different phonemes from changing phonetic flow requires the sub-articulatory functions of the frontal language cortex. Demonet et al. (1994) also reported activation in the inferior parts of the left motor cortex during phonological tasks. This was suggested to reflect the articulator aspect of inner speech.

The association of the inferior parietal cortex to short-term memory functions has gained strong support in functional brain imaging studies (Demonet et al., 1994; Paulesu et al., 1993). Demonet et al. (1994) found significant activation in the inferior part of the supramarginal gyrus (SMG) during task, which required to briefly store phonological sequences in short-term storage. Also in Paulesu et al. study (1993), a short-term memory task (storing different consonants for later use) showed specific activation in the SMG. The area of the temporoparietal junction is also considered as a polysensory region (Kolb & Whishaw, 1996), which probably participates in the processing of more complex aspects of speech and language.

As Rumsey, Horwitz, et al. (1997) concludes, rather than being subserved by a single localized mechanism within the brain, phonological processes differentially engage various regions within a large-scale language network. Different aspects of phonological tasks emphasize differentially localized functions.

Neuroimaging studies have reported deviations both in the structure and in the function of the brains of dyslexic subjects (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Leonard et al., 1993). The clearest structural difference found in previous research is increased abnormal symmetry, or even reversed asymmetry of the secondary auditory cortex, planum temporale (PT), among dyslexic readers (Hynd, Semrud-Clikeman, Lorys, Novey, & Eliopoulos, 1990; Larsen, Hoiem, Lundberg, & Odegaard, 1990; Leonard et al., 1993; Rumsey, 1996). The studies of structural differences were followed by functional brain-imaging studies of dyslexia. The functional aberrations at the neural level have been emphasized in tasks which require phonological processing, while for example, activations during syntactic or semantic processing seem, for the most part, to be normal (Rumsey et al., 1994, Rumsey, 1996).

A number of studies have reported that the brain of dyslexics has a dysfunctional posterior phonological system. Compared to normal-reading controls, dyslexics have shown a paucity of activation in the posterior temporal and parietal regions during rhyme detection (Rumsey, 1996), phonological decision making (Rumsey, Nace, et al., 1997), pseudoword presentation (Brunswick et al., 1999), discrimination, and tasks related to phonological working memory (Frost et al., 1997). In Rumsey et al.'s study (1994), dyslexics showed diminished activation in the left parietal cortex, near the SMG and angular gyrus (AG) also while resting. Thus, the symptoms of dyslexia can reflect a general dysfunction in cognitive functioning or even a slight structural anomaly in this posterior parietal region (Rumsey, 1996). Rumsey, Nace, et al. (1997) reported normal activation in the left inferior frontal cortex during phonological tasks, so his study

suggests a dysfunction of the left cortical language areas restricted to posterior language regions.

However, in addition to diminished activation in the posterior region, Frost et al. (1997) showed paucity of activation also in the IFG. This was shown specifically during phonological working memory task where the subjects' task was to mentally delete certain sounds from a shown word, and respond as to whether the result matched with a second given word. During a phonological discrimination task (responding to the occurrence of certain letters in a series of consonant-vowel-syllables), the normal-reading subjects showed increased activation of the STG in comparison to working-memory tasks. Dyslexics failed to show this specialization and the activation of the STG was equally high in the two tasks. The diminished activation in the SMG was present both during a discrimination and a working-memory task. Frost et al. (1997) suggested that in the brain of dyslexic readers, the SMG reaches the limits of its functional capacity and compensates by shifting neural resources to the STG, which was activated normally and was even over-activated during the tasks.

Recently, Shaywitz et al. (1998) also demonstrated this diminished activation for dyslexics in posterior areas (Wernicke's area, AG, striate cortex) but, contrary to Frost et al's. (1997) results, also *excessive* activation for dyslexics in the anterior areas (IFG) compared to controls during tasks, which placed progressively greater phonological demands.

Brunswick et al. (1999) reported decreased activation in addition to the posterior parietal areas also in the temporal areas during a visual feature detection task of real words, pseudowords and false-font strings. Rumsey, Nace, et al. (1997) found reduced activation in the STG during a pronunciation task. Rumsey (1996) concluded that during rhyme detection tasks, a decrease in the activation of the left posterior language regions including the left temporoparietal and superior temporal cortex is seen. As shown in reported studies, the results concerning the temporal and anterior regions, are more contradictory than the clear paucity of activation in posterior regions.

Because of the methodological differences in the presented studies, many of the results are non-comparable. However, the theoretical dilemma surrounding whether dyslexia is a language-based or more general auditory-based disorder (Tallal versus Studdert-Kennedy) poses the question as to whether the deficits mentioned above reflect pure auditory (non-speech) deficits or more specifically, a deficit restricted to language-related functions. To answer this, it is necessary to differentiate between these functions on a neural level.

Traditionally, the differences between speech and non-speech processing have been

connected to the distinction between hemispheres. The areas important for non-speech auditory processing have been reported to be dominating in the right hemisphere (Celsis et al., 1999; Demonet et al., 1992, 1994; Zatorre et al., 1992). Samson and Zatorre (1994) also showed musical timbre perception to be associated with the right temporal lobe (also Zatorre, Evans, & Meyer, 1994). The activation for speech stimuli has been suggested to occur predominantly in the left hemisphere (Celsis et al., 1999; Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Demonet et al., 1992, 1994; Price et al., 1992).

The distinction between the two hemispheres is not, however, so unambiguous. For example tasks engaging phonological functions often reflect bilateral and symmetrical processing (Binder et al., 1994). Binder et al. (1994) also claim that some specific regions are activated unilaterally in the right hemisphere, e.g. certain regions in the right frontal cortex during different speech stimuli (text, words, and non-words). On the other hand, some studies claim that the left hemisphere dominates during both speech and non-speech discrimination tasks (e.g. Liu et al., 1997).

Another distinction concerning the speech - non-speech dimension has been made within the left hemisphere between the anterior and posterior areas. The processing of speech stimuli have been noticed to activate spatially wider areas than the processing of non-speech stimuli (Binder et al., 1994), but additionally, the speech-specific areas have been reported as situated anterior to non-speech areas (Berry et al., 1995; Binder et al., 1994; Zatorre et al., 1992).

However, rather than reflecting the differences between speech and non-speech processing, the differences between the anterior and posterior areas in the left hemisphere are probably more specific. According to Carr and Posner (1995), the anterior areas are devoted to articulator and syntactic functions while the posterior areas reflect more perceptual, receptive and semantic functions. First presented by Luria (1966, 1976), the idea of distributed localization of specific functions holds both posterior and anterior language areas as connected to the perception (and the production) of speech with differential functional roles. According to Luria, frontal regions are connected to the fluent processing of language, middle temporal regions to memory functions, inferior parietal regions for auditive discrimination and identification of speech sounds etc. The processing of language at the neural level is a network of functionally differentiated brain regions, and auditory vs. linguistic processing can be seen as a characteristic connected to this entire network. Thus, the question concerning dyslexia on this occasion is whether this network shows deviations from normal processing only in response to speech-related sounds, or also to other

auditory sounds. The regions concerned are naturally the auditory-processing regions within the temporal, parietal and inferior frontal cortices and especially the regions showing aberrations from normal functioning in dyslexic subjects.

One of the most interesting temporal areas in the context of dyslexia is the secondary auditory cortex, PT, because of the anatomical differences shown between individuals with reading problems or not. Whether the functional nature of this area is associated to general non-speech auditory processing or more to language-related processing, would give important information about the nature of the core deficit in dyslexia.

This question of auditory vs. linguistic processing in the PT has been challenged in few functional studies trying to reveal the critical neural-level processing difference between auditory stimuli with and without a linguistic content in normal subjects (Binder, Frost, Hammeke, Rao, & Cox, 1996; Liu et al., 1997). Binder et al. (1996) reported that the area of the planum gives no specific responses associated to speech stimuli compared to tones, either in active or passive listening tasks. In landmark-based analysis, the temporal and parietal banks of the planum (PT and PP) actually demonstrated stronger activation during active listening to tones, while many of the other areas in the temporoparietal cortex showed wider activation for speech stimuli. In this study, speech stimuli were normal words, which were semantically manipulated in the active listening task. Tone stimuli were pure sine waves and in the active -task, different pitches were discriminated. Thus, the stimuli in Binder et al.'s study (1996) were highly different and some, other than the target difference (speech – non-speech) within them, could have affected the result. The speech stimuli used were also more complex in their auditory nature than the tone stimuli.

Liu et al. (1997) used stimuli that were highly similar in other respects except the speech-specific content. They reported that activation in the PT and posterior temporoparietal cortex including SMG was specific for native and non-native speech stimuli, when compared to spectrally identical non-speech stimuli during a passive listening task. The results suggest speech-specific processing for the PT.

Functional brain-imaging studies have not been exploited directly to the question as to whether dyslexic subjects' impairments originate from a deficit specific to speech, or from a more general auditory deficit. This question is the focus of the present study.

We measured the differences between activation of the auditory areas of dyslexic and normal-reading adults. This was executed in two discrimination tasks, which differed in terms of whether the stimuli used were speech-related or not. The non-speech stimuli were carefully

produced to resemble the speech stimuli in other respects except that they did not contain any fast spectral component characteristic of speech. The discrimination task refers here to discriminating between different durations of a central sound (consonant) in brief vowel/consonant/vowel syllables. Tallal has argued that language-impaired children (including dyslexic children) are impaired in the discrimination of brief-duration temporal cues within speech, such as the brief formant transitions within stop-consonant/vowel syllables. Lyytinen et al. (1995) have shown one of the central impairments in spelling and reading for Finnish dyslexic children to be difficulty in the perception of duration-related information, the length of vowel and consonant in a word. Thus, we wanted to examine, whether we could also detect this impairment in the processing of duration-related discrimination in neural-level processing, and whether it is specific to speech sound discrimination or present also in more general auditory discrimination. The stimuli were as simple as possible to avoid all other than the target processing in order to elicit the least possible activation in the brain during the discrimination of speech sounds and tones.

The traditional method when counting the response to stimulation is to subtract the control noise from the experimental stimulus or to subtract between two experimental stimuli. However, this method has received some criticism (Price & Friston, 1997). Using subtractions presumes hierarchical and distinct construction of processes, which does not seem to be the case in higher order functions such as language (Demonet et al., 1994; Price & Friston, 1997; Shaywitz et al., 1997). To find a baseline task that shares all other components except for the cognitive process of interest is difficult; even implicit processing beyond the demanded task can be present (Price & Friston, 1997). Another difficulty is that adding new components does not keep the remaining processes unaffected; the difference between tasks represent both the added task component and the interaction between the added and shared components (Price & Friston, 1997; Shaywitz et al., 1997).

Our interest was in the differences between the areas that dyslexic and normal readers have to recruit for speech versus tone tasks. We measured the relative proportion (percentage) of area activated in each region of interest from images counted by Bayesian image-analysis and compared the results between the groups.

First, the overall activation for auditory stimulation in general was examined. With one sagittal slice we acquired image from the temporoparietal and inferior frontal language cortex of both left and right hemispheres. We hypothesised that general activation in this region would be seen in the primary and secondary auditory cortices (primary auditory cortex, temporal and parietal

banks of planum), in STG and Sylvian Fissure, in inferior frontal language cortex and in SMG and AG. According to the latest functional brain imaging studies, these regions are strongly connected to the processing of auditorily-perceived phonological material (e.g. Binder et al., 1994, Binder et al., 1997; Celsis et al., 1999; Demonet et al., 1992, 1994; Liu et al., 1997; Shaywitz et al., 1997). Instead, the regions in middle temporal and in inferior temporal gyri and sulci, and in lateral precentral and postcentral gyri and sulci were hypothesised to be less active. Also possible differences in patterns of activation between the processing of speech and tone discrimination tasks were explored. Activation during a speech discrimination task was thought to be spatially wider than during a tone discrimination task, as is shown in previous studies for speech-related processing within the temporoparietal and inferior frontal cortices (e.g. Binder et al., 1994; Liu et al., 1997). However, because the differences between the speech and tone stimuli of our study were reduced to a minimum, the differences also in neural-level processing were thought to be smaller than has been shown in previous studies, which have used more complex stimuli. The left hemisphere was thought to be overall more widely activated for a speech task (Celsis et al., 1999; Damasio et al., 1996; Demonet et al., 1994; Price et al., 1992) and probably also for a tone task (e.g. Liu et al., 1997).

Our main interest was, whether the brain of dyslexic subjects shows differential activation-pattern in the discrimination of speech or tone stimuli, compared to the control subjects. We hypothesized that dyslexic individuals show deviation from the normal pattern of activation in all or some of the following regions: the primary auditory cortex, secondary auditory cortex (PT and PP), STG (anterior, middle, posterior), frontal language areas (inferior frontal cortex) and the inferior parietal cortex (SMG, AG). Abnormal functioning of these temporoparietal and inferior frontal areas has been shown for dyslexic individuals in earlier studies (Brunswick et al., 1999; Flowers, Wood, & Naylor, 1991; Frost et al., 1997; Rumsey, 1996; Rumsey et al., 1992, 1994; Rumsey, Nace et al., 1997; Shaywitz et al., 1998). Specific interest was devoted to the temporal and parietal banks of the planum. For dyslexic readers, this region have shown anatomical differences compared to normal readers (Hynd et al., 1990; Larsen et al., 1990; Leonard et al., 1993; Rumsey, 1996). Also, references to functional differences have been presented (e.g. Brunswick et al., 1999; Frost et al., 1997; Rumsey, Nace, et al., 1997), but the results normally concern wider regions and there are no studies centered on functional differences, specifically in the PT.

2 METHODS

2.1 General methods

Imaging was performed on a 1.0 Tesla Siemens Magnetom Impact Expert scanner (Jyväskylä Central Hospital, Finland). Images were collected at one sagittal location in the lateral left and right hemispheres, one slice per time. Sequence used was f12d_46rb19.wfc. The slice thickness was 1 cm, and voxel volume about 1 mm x 1 mm x 1 cm. Slice placement varied by a few millimeters from subject to subject. The slices, where the PT was best visible, and from which functional images were acquired, were assessed visually from high-resolution anatomical images of the entire brain. The spatial location of the PT is typically about 45-52 mm from the midline.

The MRI -room was isolated and communication with the subject during the testing was possible through the use of microphones in the laboratory and in the monitoring-room; the subject heard the directions and the stimuli through earphones. The stimuli were presented binaurally using a computer playback system, a magnetically shielded transducer system, and air conduction through paired plastic tubes. The sound pressure level of the stimulus remained constant across all subjects and stimuli, and it attenuated the average sound pressure level of the continuous scanner noise.

2.2 Subjects

The subjects formed two groups. In the dyslexic group the subjects were six men and three women, ranging in age from 25 to 49 years. The control group consisted of five men and five women, ranging in age from 22 to 45 years. With the exception of one control subject, all participants indicated right hand dominance on the Edinburgh inventory. Participants had no history of neurological or audiological illness. The subjects in the dyslexic group were adult participants in a longitudinal study of developmental dyslexia in the University of Jyväskylä. All scored more than one standard deviation below the mean of the normal group of the same age on reading tests. Additionally, they scored below the normal group on different tests used to scan phonological/orthographic skills. The control group was chosen from among adult volunteers to match the age-level of dyslexic-group.

Subjects were informed about the nature and risks of the research and they were asked to inform the experimenters immediately, if they wanted to discontinue the test. The procedure started with a few minutes of scouting and with an anatomic imaging. This was so the subjects could become accustomed to the imaging noises before the real test situation.

2.3 Experimental design

The experiment consisted of two parts, speech condition and tone condition. Both of these were divided into four trials. The imaging procedure is illustrated in Table 1. The objective of the experimental design was to create two situations where the only difference between them was that the stimuli in one situation were pure auditory (non-speech tones) and in the other, had the speech-specific characters.

One trial consisted of multiple epochs of rest, during which subjects heard only the background scanner noise, alternating with periods of activation, during which additional auditory stimuli were present. Digitally sampled Finnish pseudo-words and sine-wave sound envelopes were used as comparison conditions. During one trial, the stimuli were presented in 10 cycles. One active listening cycle lasted for 14 seconds and was followed by a 9 second pause for provision of the answer, 14 seconds of rest with the scanner noise as a control stimulus and again, a 9 second pause. Each trial, containing 10 stimulus cycles, was repeated four times for each stimulus (40 cycles for each stimulus). In every trial the stimuli began a few seconds before the scanning to overcome the delay of haemodynamic response. For the speech condition during the first two trials the images were acquired from the left hemisphere, and during the last two, from the right hemisphere. For the tone condition, the images were first obtained from the right hemisphere and then the left. The components of one trial are illustrated in Table 2.

The speech stimuli were digitally sampled, bisyllabic, simple word-reminding sounds (pseudo-words), carrying no meaning. The basic speech stimulus was a short vowel-consonant-vowel word, 'ata' with a duration of 95 ms, and the deviant word was made by lengthening the duration of the t-sound in the middle of the word, thus producing 'atta'. This distinction between the lengths of a consonant often has a critical role with respect to the meaning of a Finnish word. There were three different durations of the prolonged version of the t-sound; the length of the deviant pseudoword lasted from 135 ms to 175 ms, and produced three different levels of difficulty when discriminating the deviant from the repeated words. The order and the amount of

the deviant stimuli were alternated between the cycles, being presented 0 to 4 times. This created ten different versions of cycles, which comprised one trial. The subject's task was to monitor the occurrence of a rarely presented word among the more frequently repeated words.

The tone stimuli were digitally constructed from the speech stimuli to sine wave sound envelopes (with frequency of 270 Hz), where only fast spectral components characteristic to speech were reduced. By other characteristics, the tone trials were exactly the same as the speech trials. Similarly to the speech stimuli, the deviant sounds also included three different versions, producing three different levels of difficulty. The tone task was presented immediately after the speech task.

TABLE 1. Description of the imaging procedure. Scouting and anatomic images were followed by eight trials of functional images, four trials for both speech and tone tasks. Images of two trials for each task were acquired from each hemisphere.

3 min	Scouting
6 min	Anatomic Images
	Functional Images
	Speech Task
8 min	1 st trial from left hemisphere
8 min	2 nd trial from left hemisphere
8 min	1 st trial from right hemisphere
8 min	2 nd trial from right hemisphere
	Tone Task
8 min	1 st trial from right hemisphere
8 min	2 nd trial from right hemisphere
8 min	1 st trial from left hemisphere
8 min	2 nd trial from left hemisphere

TABLE 2. Components of one trial lasting 8 minutes. 14-second periods of stimulus presentation ('activation') alternated with 14-second periods of scanner-noise (baseline) and 9-second pauses in a total of ten cycles.

TIME	14s	9s	14s	9s	14s	9s	14s	9s ...
STIMULUS- PHASE	Stimuli	Answer	Noise	Pause	Stimuli	Answer	Noise	Pause
IMAGING-PHASE	Imaging	Pause	Imaging	Pause	Imaging	Pause	Imaging	Pause

2.4 Procedure

After general instructions and testing the subjects' handedness, the subject was placed in an MRI device and the audibility of the stimuli and the instructions were tested. An example of the tasks was also performed. Imaging began with scouting and anatomical imaging of both hemispheres. The slice placement for functional images was chosen individually for each hemisphere of each subject using the PT and Heschl's gyrus (primary auditory cortex) as landmarks. The Sylvian fissure (SF) and the central sulcus (CS) were also used for choosing the best slice placement. The chosen slice should not be too lateral neither too central in order to have all of the gyral morphology required. After choosing the sagittal slices, the functional imaging procedure began.

In the first experiment, subjects were instructed to listen to the speech-reminding sounds (pseudo-words). Most of these were 'ata' and they were required to monitor and count the deviant 'atta', which could be presented from 0-4 times during the short sequence. In the second experiment, subjects were instructed to keep listening in the same manner, but now the deviant tones among the repeated ones. One trial lasted approximately 8 minutes and it was fully controlled by computer (the program producing the stimuli was paced with the scanner). In between the trials, communication with subjects was possible. After the experiment, all subjects were asked to describe their feelings and possible disturbing factors during the test. Questions concerning the words and tones, which they heard, were also presented.

The experiment lasted 73 minutes and about 30 minutes was used in giving instructions, testing handedness and the questions afterwards. The 73 minutes consisted of about 3 minutes of scouting, 6 minutes of anatomical imaging and the 8 x the 8-minute lasting trials.

2.5 Differentiating the signal from noise

The data were pre-processed in several steps. First, all images from each trial were co-registered using AFNI software (Cox, 1996). Second, individual images, which could not be aligned with other images, were visually detected using a spatio-temporal display and replaced with the mean image of the series. Finally, linear trend was removed from all time series'.

Two different statistical methods were used to analyze the functional images. The first was based on methods developed in the context of Bayesian image analysis (Besag, 1995). In Bayesian analysis, a priori information can be taken into account using prior distributions, which reflect beliefs about the nature of activation and noise. Since it is plausible to expect that activation

and noise variance varies smoothly in brain tissue, two spatial smoothing priors were used to quantify this initial belief. The priors were chosen to be Gaussian pairwise difference distributions. Because of the design, temporal correlation structure of the noise was weak and thus only spatial correlation structure of the noise was included into a linear statistical model. Conditional autoregressive gaussian random fields (CAR) were used for this purpose (Besag, 1991).

The goal of the analysis was to draw inferences concerning activation that is, the regression coefficients of explanatory stimulus variable. The resulting posterior distribution of activation was simulated using computationally intensive Markov chain Monte Carlo methods to construct a pixel map of activations. All the pixels for which the posterior probability of being positively activated was at least 0.99 were classified as responding to the stimulus.

This analysis yielded a map of responses to speech sounds relative to a resting state and a map of responses to tones relative to a resting state.

Also, direct difference images were created where the simple pixel maps for speech sounds vs. tones were based on a t-test and a threshold p-value of 0.01. Positive values (white pixels) represent greater activation by speech sounds and negative values (black pixels), greater activation by tones. These images were obtained to gain a general impression of the differences between the activations generated by speech and tone tasks (for an example, see Fig. 3).

2.6 Defining the regions of interest

One anatomical and 40 functional images (20 for each stimulus) were obtained for each subject and each hemisphere. All landmarks and regions of interest were identified on sagittal anatomical images individually for each subject and each hemisphere, without reference to the functional data. The main gyri and sulci visible in the anatomical slice were marked.

The Atlas of The Human Brain (Mai, Assheuer, Paxinos, 1997) and Human Brain Anatomy in Computerized Images (Damasio, 1995) were used for defining the regions. The anatomical images of each sagittal slice of both hemispheres were divided into 6 parts by the main gyri: inferior frontal gyrus, precentral gyrus (PreCG), postcentral gyrus (PostCG), supramarginal gyrus, superior temporal gyrus and middle temporal gyrus (MTG). The parietal gyri were divided additionally into lateral and inferior parts and the temporal gyri were divided into anterior, middle and posterior parts. The subdivision into smaller parts was necessary in order to separate the activations in the functionally important smaller areas within one gyrus.

In addition to gyri, the sulci were also marked for later measurement of the activation within them. The sulci within the analysis were the Sylvian fissure, including the ascending ramus (arSF), and the horizontal ramus (hrSF) of the SF, superior temporal sulcus (STS), inferior temporal sulcus, inferior frontal sulcus, precentral sulcus (preCS), central sulcus and postcentral sulcus (postCS).

The three smaller regions within the STG - the primary auditory field in Heschl's gyrus or the transverse temporal gyrus (TTG), and the temporal and parietal banks of planum - were also defined as distinct regions. The area of the PT was defined by the primary auditory field from the anterior end and by bifurcation of the SF into an ascending ramus and a descending ramus from the posterior end (as e.g. in Binder et al., 1996). The posterior end of the PT was used as a mark for the anterior end of the PP.

There were some difficulties in defining the areas and activation within them. First, the landmarks for defining the regions were unable to be seen in some images. Second, in different hemispheres, the position of landmarks differed and sometimes produced highly different sized areas. Finally, the definition of certain sulci was sometimes difficult, for example to decide whether the sulcus ended totally or continued after a break. The three small areas in the superior surface of the temporal lobe were also sometimes difficult to define properly because the areas did not separate clearly. In a few cases, when some region was impossible to define, the degree of activation was not given.

2.7 Quantification of the activation in the regions of interest

The functional images from the speech and tone experiments were superimposed on high-resolution anatomic images of the same brain slices, and were analyzed with reference to defined anatomical regions. Regions which were only randomly or not at all seen in anatomical slices (inferior temporal gyrus, AG) and the regions with only random or no activation were excluded from further analysis. From the functional images, each of the regions (six main gyri, three of them divided in two parts and two divided in three parts, seven main sulci correspondingly divided and three smaller regions; PT, PP, TTG) was analyzed in terms of the percentage of the activated pixels within them. The activation within regions was assessed on a scale from zero to four. If the area had no activated pixels, or less than one quarter ($1/4$), it would be awarded a zero degree. If the proportion of activated pixels were more than $1/4$ but under $1/2$ of the whole region, the degree

would be 1. On the same lines, half of the area activated would give 2, 3/4 activated would give 3, and the whole area activated would give a degree of 4. If the activation in the area was suspected to reflect some irrelevant functioning or processing (for example the subject sleeping), the degree was not given. The irrelevant activation was supposed to occur when there was an abnormal type of activation pattern within the hemisphere (see Fig. 2). Also, the observations on subject's behavior gained during the imaging-procedure were used to detect irrelevant activation.

The first research problem concerning the distribution of activation in general, was executed for all regions defined properly (see Fig. 1.) The second and the third research problems – the difference between stimuli and the difference in activation pattern between dyslexic and normal readers – were executed only for the regions of interest resulting from the first analysis, i.e. the regions obtaining more than 25 % of the pixels activated.

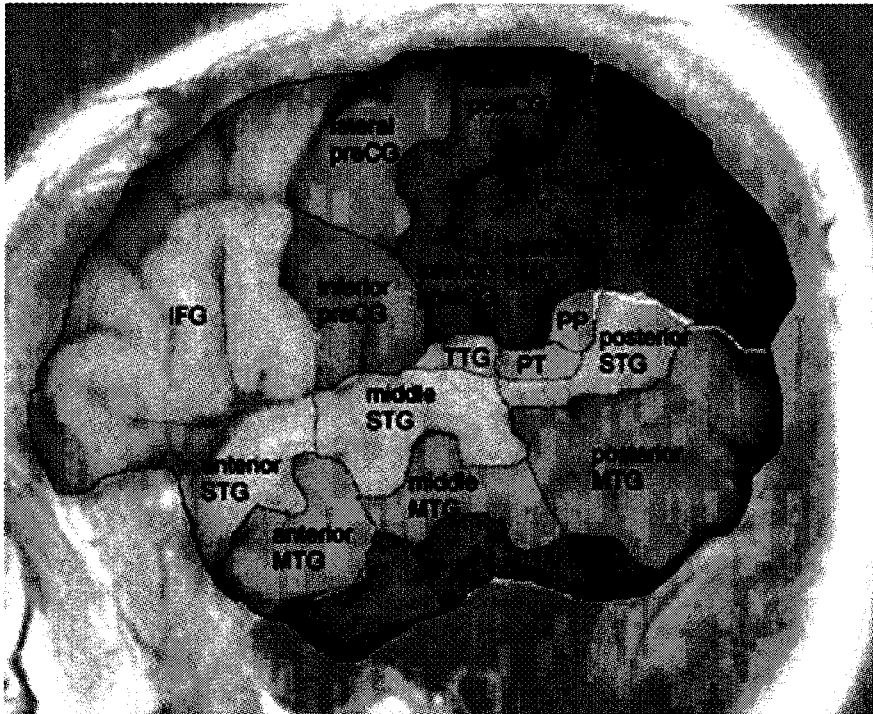


FIGURE 1. Regions within the analysis. All regions were assessed individually for each subject and each hemisphere. Inferior frontal gyrus (IFG), lateral precentral gyrus (preCG), inferior preCG, lateral postcentral gyrus (postCG), inferior postCG, lateral supramarginal gyrus (SMG), inferior SMG, anterior superior temporal gyrus (STG), middle STG, posterior STG, anterior middle temporal gyrus (MTG), middle MTG, posterior MTG, transverse gyrus (TTG, or Heschl's gyrus), planum temporale (PT) and planum parietale (PP).

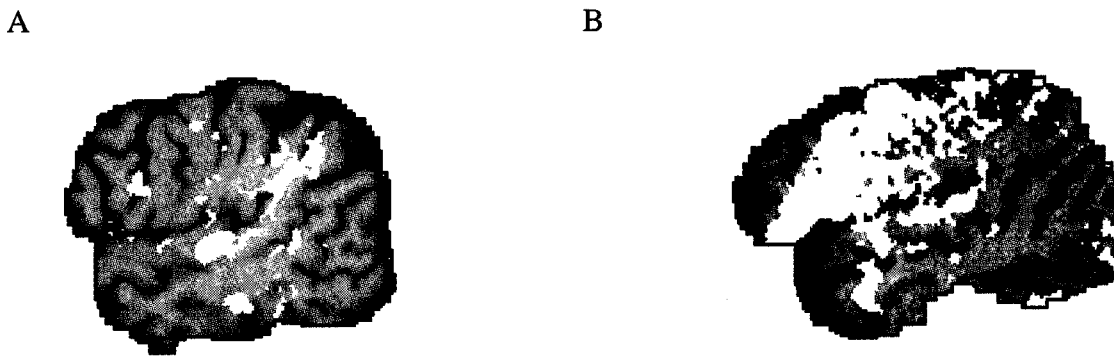


FIGURE 2. Examples of activation images constructed using Bayesian analysis. Simulation of the posterior distribution of activation was based on Markov chain Monte Carlo methods. All the pixels for which the posterior probability of being positively activated was at least 0.99 were classified as responding to the stimulus and are seen as white on the anatomic image as background. (A) Activation of one subject in a series of 40 scans taken during the speech discrimination task. (B) Activation image with irrelevant activation patterns, probably reflecting movement artifacts, seen extensively in the inferior frontal region.

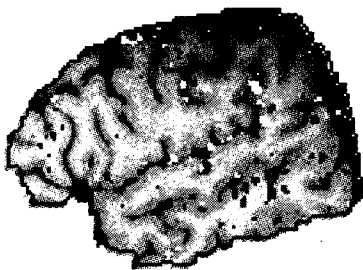


FIGURE 3. An example of a direct difference image obtained by subtracting activation between the speech sound task and the tone task. Within the white pixels the activation for speech stimuli is greater than activation for tone stimuli and within the black pixels the tone stimuli are stronger.

2.8 Hypothesis Testing

Statistical analysis for testing the hypothesis was executed by SPSS. Group-means and standard deviations were calculated for all variables (regions of interest) from the scores representing proportional portions of activation within each region. The first research hypothesis concerning the general distribution of activation was examined directly from the group means. Multivariate analysis of variance was used to examine the differences between stimuli and between groups. This was done for all the regions gaining activation percent over 25%. Also Group x Stimulus (speech/tone) and Group x Hemisphere interaction effects were calculated.

3 RESULTS

3.1 Differences in the task performance

The total number of subjects imaged was 21. However, the data from two subjects (one control and one dyslexic) were lost during the transferring procedure so the final number was 19. Movement artifacts were mostly modest and no image-series was unusable in the 19 subjects. In two subjects, the procedure was in some parts incomplete and only the completed parts were analyzed.

All the subjects learned the tasks easily. Two kinds of error could occur in the discrimination of the deviant stimuli from among the repeated stimuli within both the speech and the tone tasks. The deviant stimulus could elude observation or the subject could report too many deviant stimuli among the 14-stimulus trial. It can be said that either an over-estimation or under-estimation of the number of deviant sounds would reflect a difficulty for the listener to perceive the length of the middle component in the word or sound.

The averaged performance was very similar between the groups. In the speech task, which was considered to be easier by almost all subjects, the control-group attained an average score of 86 % correct and the dyslexic-group, 87 % correct. The tone task was considered to be more difficult and the averaged correct score for controls was 78 % and for subjects with dyslexia, 77 %. Accordingly, dyslexic subjects discriminated the different pseudo-words and tones as well as controls. The distribution of errors is presented in Table 3.

TABLE 3. Task performance. Distribution between different types of inaccurate detections and the distribution between inaccurate detections for different stimuli within trials.

	Control Group		Dyslexic Group	
	Count	%	Count	%
Number of trials	120	100	120	100
Number of inaccurate detections	21,6	18	21,6	18
Types of inaccurate detections				
Over-estimations (of all)	2,9	2	3,3	3
Under-estimations (of all)	18,7	16	18,3	15
Distribution of inaccurate detections				
In speech stimuli (of all)	8,5	7	7,7	6
In tone stimuli (of all)	13,1	11	13,9	12

Subjects also provided an answer to a verbal questionnaire concerning how they felt about, and reacted to the situation. Almost everyone (18 of 19 subjects) reported some kind of physical inconvenience during the test situation (aches in back, neck, limbs etc.) and also psychological disturbances were often reported (tension, fear, fatigue, difficulties to concentrate on the task etc). More disturbances, both physical and psychological were reported during the sound task, probably because it was the last part of a reasonably long test situation. For the most part, the audibility from the earphones was reported as good, but 14 of 19 subjects reported that the noise from the scanner was either a moderate or a major disturbance, mainly at the point where the scanning commenced. Despite the disturbance factors, when asked about how difficult the subjects found the test, almost everyone found the task to be easy with only a few difficulties.

3.2 General activation

General activation for stimuli is reported only for control subjects. The differences in activation concerning dyslexic subjects are examined in next section. Multiple regions within the inferior frontal, temporal and inferior parietal cortices responded to stimuli in general. All the regions, where activated pixels constituted over 25 % of the area, were included in further analysis and can be seen in Table 5. For analysis of differences, the regions were finally categorized into two sets according to the percentage of activated pixels – over 40 % and over 25 % activated. When examining the proportional portions of activation in each region, the highest percentage of activation for the control group concentrated in the main language regions of the STG: the primary auditory cortex and PT of both hemispheres. In addition to the above-mentioned regions, in the posterior and anterior parts of the SF and in the middle and posterior parts of the STG in the left hemisphere, the activated pixels were also over 40 % of the region. Correspondingly, in the right hemisphere, in addition to the TTG and PT, the ascending ramus of the SF, middle SF and middle STG also gained activation percent over 40.

Only one region showed significant difference in direct comparison between the activation generated by the speech and tone tasks. In the lateral preCG in the left hemisphere, there were more activated pixels during the speech task than during the tone task ($F = 4.7$, $df 1/19$, $p < 0.05$).

3.3 Differences between groups

All the regions where the activated pixels constituted over 25 % of the region, were included in the analysis of difference between the groups. A comprehensive table of results is presented in Table 5, which presents all the regions of interest and the activations within them for both groups, both stimuli, and both hemispheres. For the main group –differences see Fig. 6. The differences are also illustrated in Appendix A, where regions are arranged in order of magnitude according to control subjects. In these figures, arrows mark the regions where the difference between groups gains statistical significance. Some preliminary notions concerning the distribution of the activation can be made on the basis of these figures.

The concepts of “exceeded-“, “over-“ and “increased-“ activation are used here to refer to wider activation, i.e. more activated pixels within the target region compared to the other group. Correspondingly, the concepts “diminished-“, “under-“ and “decreased-“ activation refer to less activation respectively.

For speech stimuli in the left hemisphere, subjects in the dyslexic group show the highest percentage of activated pixels in the same regions as controls, but they over-activate these areas. Additionally, there is a tendency for participants with dyslexia to over-activate some middle and anterior regions, which were lower activated for controls.

For tone stimuli in the left hemisphere, the over-activation within the most highly activated areas (e.g. PT) is not seen, but the tendency to use some different areas from controls appears to be present.

For the right hemisphere, the situation is almost opposite with regard to the activation in the areas of highest percentage of activated pixels (PT for speech and hrSF for tone stimuli); participants with dyslexia show references to less-activated pixels than controls within these regions. Overall, the activation within the right hemisphere seems to be generally lower for the dyslexic group than for control group.

The statistical analysis gives more detailed information about the differences between groups. The distribution of activation within dyslexic subjects was mainly similar to that of the controls, but clearly differed in certain regions. Our main interest was in the differences between normal-reading subjects and dyslexic subjects within the regions where activated pixels were over 40 %. In case significant interactions with stimulus or hemisphere emerged the differences is specified accordingly. The clearest difference was found in the region around the

posterior SF of the left hemisphere, where the amount of activated pixels of the dyslexic subjects was lower than that of controls. This difference was clearly significant in both the speech and tone conditions.

Second difference within the left hemisphere was the excessive activation of dyslexic subjects compared to controls in the middle parts of the STG, the results showed references to over-activation also in the PT for dyslexic subjects. These differences were present only in the speech condition. For the PT, the Group x Hemisphere interaction was significant during the speech task. A closer analysis showed that the activation was higher for control group in right hemisphere and for dyslexic group in left hemisphere (see Fig 4b).

If we also take the regions into account, where activated pixels were over 25 % of the region, over-activation for dyslexic subjects is also seen during the tone task within the anterior STG and IFG. For both the anterior STG and the IFG, the Group x Hemisphere interaction was significant during the tone task. While the amount of activated pixels in the left hemisphere was clearly higher for dyslexic group than for control group, the activation in right hemisphere was almost equal between groups. Also, the lateral preCS showed increased activation for dyslexics compared to controls during the tone task.

In the right hemisphere, no significant differences between the groups were seen in regions where activated pixels were over 40% of the region. Of the regions with over 25 % activated pixels, the lateral postCS was under-activated by the dyslexic group during the tone task and the middle STS showed references to over-activation by the dyslexic group during the speech task. In the middle STS, the interaction of Group x Stimulus was significant. The control group activated both stimuli equally highly, but the dyslexic group activated the speech stimuli more than the tone stimuli. Within other regions, no interaction effect between Groups and Stimuli was found. P-values for statistically significant group differences, and Group x Stimulus and Group x Hemisphere interactions are presented in Table 6 and illustrated also in Fig. 4.

In the overall analysis between the hemispheres, the control subjects seemed to produce a higher percentage of activated pixels in the right hemisphere for both tasks, while participants with dyslexia produced higher activation in the left hemisphere. The interaction between Group and Hemisphere was significant ($F = 5,6$, $df 1/17$, $p < 0.05$) (see Table 7 and Fig. 4e). In this examination, the overall averaged activation was calculated for each hemisphere and each stimulus without differentiating the regions, and the groups were compared.

TABLE 5. The group-means of activation within each region of interest with over 25% activated regions for both groups, both hemispheres and both stimuli. Statistically significant group differences are illustrated with bold text. Scores representing higher activation in comparison between groups are under-scored.

Region of Interest	Control group				Dyslexic group			
	Left hemisphere		Right hemisphere		Left hemisphere		Right hemisphere	
	Speech	Tone	Speech	Tone	Speech	Tone	Speech	Tone
Sylvian Fissure (anterior)	.90	.90	.80	1.10	.78	1.71	1.00	.14
Sylvian Fissure (middle)	1.30	1.70	1.5	1.6	1.33	.88	1.5	.88
Sylvian Fissure (posterior)	1.40 *	1.70 **	1.2	1.50	.33	.25	1.00	1.00
Superior Temporal Gyrus (anterior)	.50	.30 *	.80	.40	.88	1.29	1.43	.57
Superior Temporal Gyrus (middle)	1.20 *	1.50	1.40	1.40	2.22	2.00	1.38	1.38
Superior Temporal Gyrus (posterior)	1.30	1.30	1.40	1.30	1.33	1.75	.63	.89
Primary Auditory Cortex	1.50	2.00	2.40	1.60	2.22	1.75	2.13	1.25
Planum Temporale	1.60	2.40	2.70	2.20	2.56	2.50	1.50	1.78
Planum Parietale	1.40	.80	.90	.80	1.44	1.22	.88	.78
Superior Temporal Sulcus (middle)	.60	.80	.50 *	.70	.89	1.00	1.50	.44
Superior Temporal Sulcus (posterior)	.70	1.10	.50	1.10	.67	1.25	.38	.56
Horizontal ramus of Sylvian Fissure ¹	.25	.50	1.50	2.75	1.08	0.50	(0.00)	1.40
Ascending ramus of Sylvian Fissure	.50	.90	1.17	2.00	.56	1.25	.67	1.00
Inferior Frontal Gyrus	.50	.50 *	.56	.78	.89	1.50	1.00	.71
Precentral Sulcus (lateral)	.50	.40 *	.67	.60	1.44	1.57	.75	1.13
Precentral Sulcus (inferior)	.63	.13	.67	.70	1.20	.67	.63	.38
Precentral Gyrus (lateral)	1.10	.40	1.25	.67	.78	1.14	1.13	1.25
Precentral Gyrus (inferior)	.50	.50	.63	.67	1.22	.63	.38	.50
Central Sulcus (lateral)	1.4	1.3	1.56	1.00	.89	1.57	.88	1.11
Postcentral Gyrus (lateral)	.70	1.00	1.33	1.0	1.22	.86	.63	.78
Postcentral Gyrus (inferior)	.40	.90	.89	.90	1.11	.63	.88	.44
Postcentral Sulcus (lateral)	.60	.80	.90	1.40 *	.89	.43	.63	.22
Supramarginal Gyrus (lateral)	.60	.70	.70	1.00	.33	.75	.25	.56

¹ statistical significance is not reliable, because of many uncertain cases regarding the region within control subjects.

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

TABLE 6. Significant main and interaction (between Groups, Tasks and Hemispheres) effects of ANOVA involving ROIs which showed differential activation between groups. Within the referred areas, the activation for dyslexic group is either wider (marked with + after p-value) or smaller (marked with -).

Region of interest	Posterior	Hemi	Main Effects		Interaction Effects	
			F	df	F	df
Sylvian Fissure		Left	6,36	1/18	.022* -	Speech
		Right	10,99	1/17	.004** -	Tone
Superior Temporal Gyrus	Anterior	Left	7,97	1/16	.013* +	Tone
		Right				
Superior Temporal Gyrus	Middle	Left	5,55	1/18	.031* +	Speech
		Right				
Planum Temporale		Left	4,423	1/18	.051 +	Speech
		Right				
Superior Temporal Sulcus	Middle	Left				
		Right	4,31	1/17	.054 +	Speech
Inferior Frontal Gyrus		Left	4,90	1/17	.042* +	Tone
		Right				
Precentral Sulcus	Lateral	Left	6,99	1/16	.018* +	Tone
		Right				
Postcentral Sulcus	Lateral	Left				
		Right	4,66	1/18	.045* -	Tone

1 during the tone task, the activation in the right hemisphere was almost equally high between groups, but in the left hemisphere, the activation for the dyslexic group was wider.

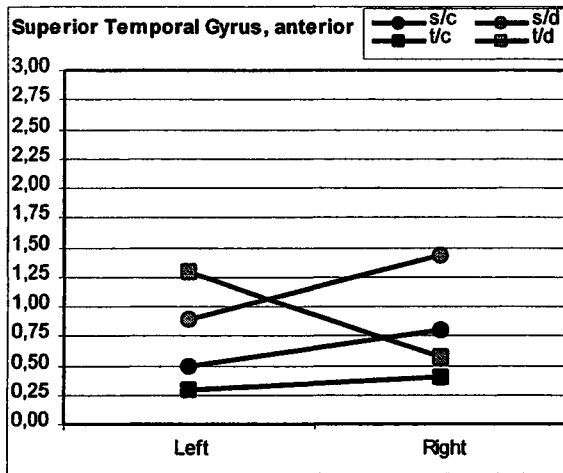
2 during the speech task, in the right hemisphere the activation was wider for the control group and in the left hemisphere the activation was wider for the dyslexic group.

3 in the right hemisphere, the control group had almost equal amounts of activated pixels for different stimuli, but the dyslexic group had wider activation for speech stimuli than for tone stimuli.

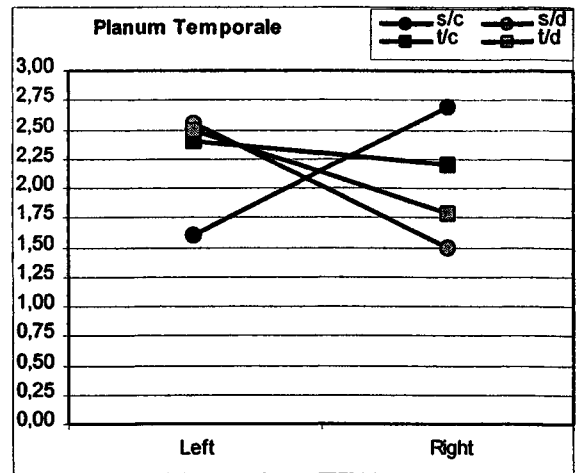
4 during the tone task, the activation in the right hemisphere was almost equally high between groups, but in the left hemisphere, the activation for the dyslexic group was wider.

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

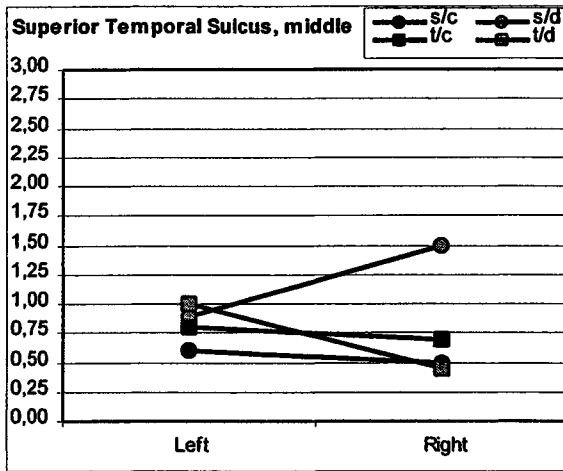
A



B



C



D

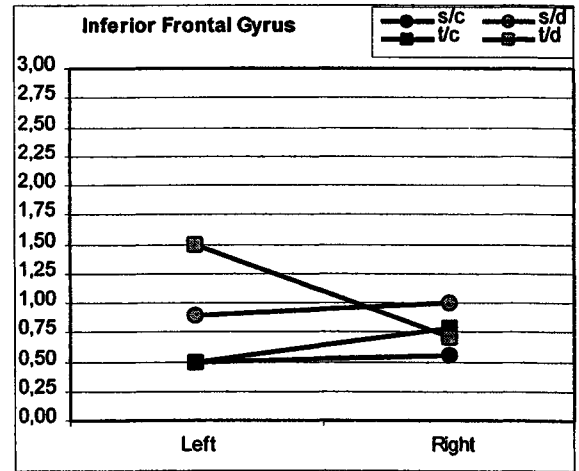


FIGURE 4. Statistically significant Group x Hemisphere and Group x Stimulus interactions are illustrated. Dark lines represent the control group and light lines the dyslexic group. Circles represent the speech task and squares represent the tone task (s/c = speech task for the control group; t/c = tone task for the control group; s/d = speech task for the dyslexic group; t/d = tone task for the dyslexic group). (A) Anterior superior temporal gyrus, (B) Planum temporale, (C) Middle superior temporal sulcus, (D) Inferior frontal gyrus, (E) Overall activation (all regions). Continues on the next page.

E

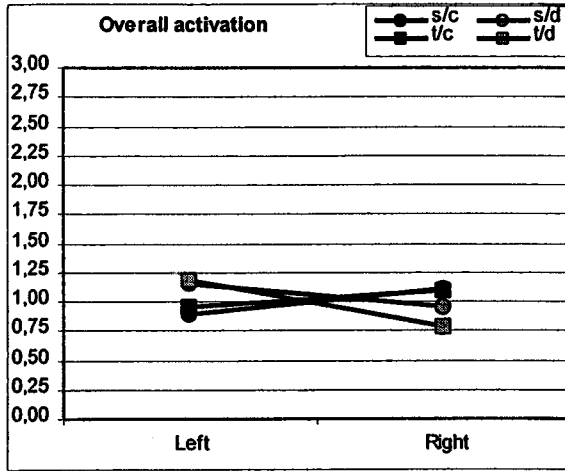


FIGURE 4. Continues from the previous page.

TABLE 7. The averaged values for the overall activation in each hemisphere and for each stimulus in the groups.

Condition	All	Control group	Dyslexic group
Speech, left	1,012	0,889	1,148
Tone, left	1,068	0,963	1,185
Speech, right	1,034	1,114	0,945
Tone, right	0,948	1,092	0,787

DYSLEXIC GROUP > CONTROL GROUP

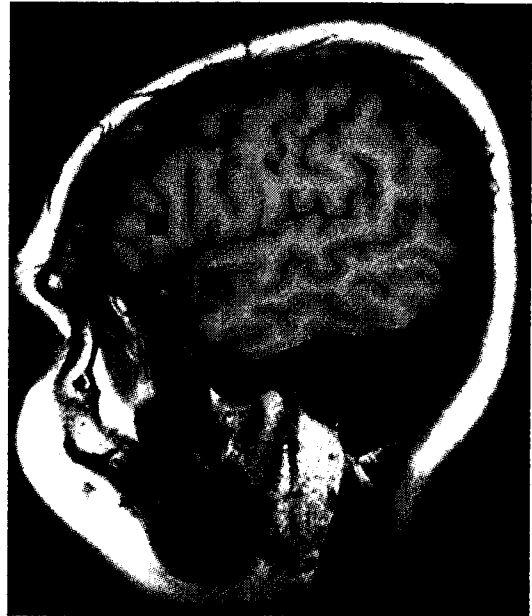
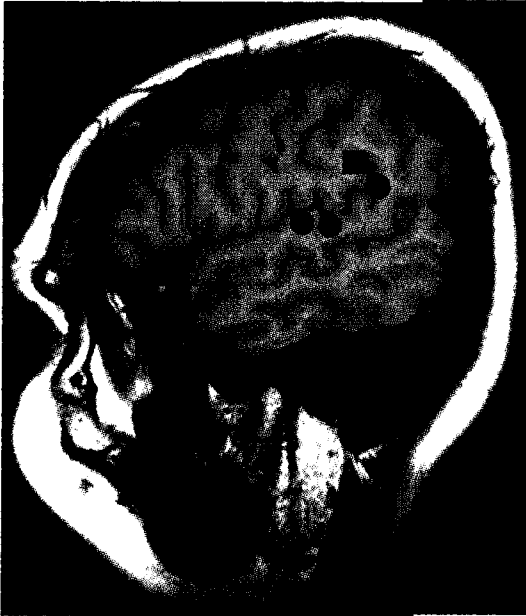
- Speech stimuli
- Non-speech stimuli

CONTROL GROUP > DYSLEXIC GROUP

- Speech stimuli
- Non-speech stimuli

Left Hemisphere, activated pixels over 40%

Left Hemisphere, activated pixels over 25%



Right hemisphere, activated pixels over 40%

Right hemisphere, activated pixels over 25%

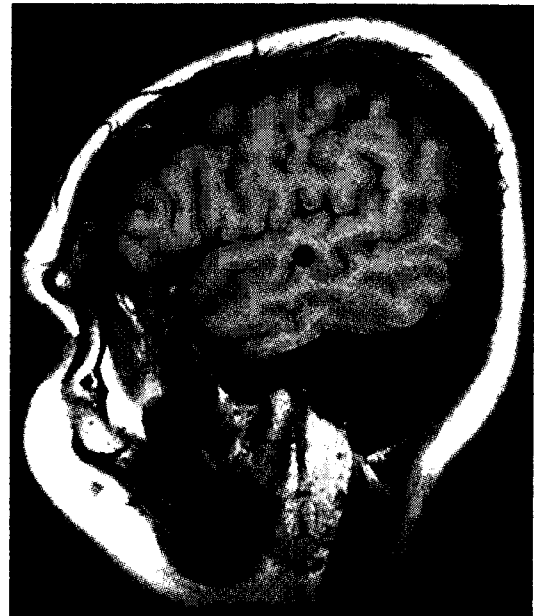
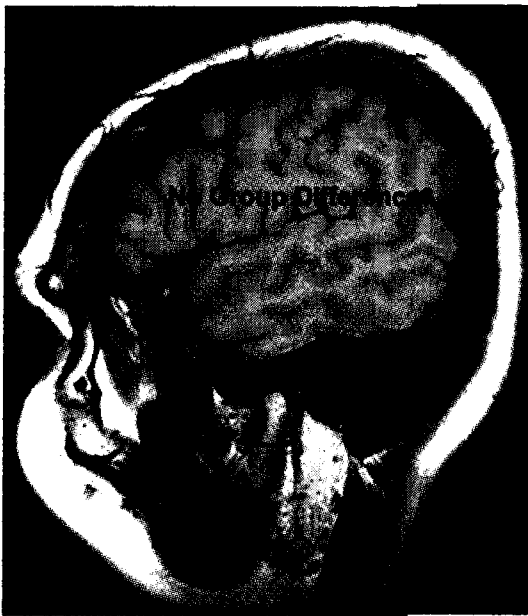


FIGURE 5. The main results for differences between the groups in regions where activated pixels are more than 40% and in regions where activated pixels are over 25%.

4 DISCUSSION

We measured and compared the activation of the language-related cortex of dyslexic and normally reading adults during highly similar speech and tone discrimination tasks. The results showed temporal, parietal and inferior frontal activation for auditory-linguistic processing for both groups. Only small differences were found in the activation between different stimulus tasks. For the control group, the lateral part of the left preCG was wider activated during the speech task than during the tone task. The main result of differences between the groups showed that subjects in the dyslexic group process the stimuli differently from controls. Subjects with dyslexia used their left hemisphere more, both for speech and for tone tasks, while among the controls, the overall activation during the tasks was higher in the right hemisphere. Closer examination revealed two considerable differences between the groups. Firstly, in the posterior temporal areas of the left hemisphere, in the posterior part of the SF, there were less activated pixels in the dyslexic group compared to the control group. Under-activation of these areas was present for both stimuli. Secondly, in the anterior and middle temporal areas and in inferior frontal cortex of the left hemisphere there were more activated pixels for dyslexic-group than for control-group. The wider activation in the middle temporal areas was specific to speech task and the wider activation in anterior temporal and inferior frontal areas was specific to tone task.

The results concerning the general activation for speech and tone stimuli, is consistent with earlier research (e.g. Binder et al., 1996; Celsis et al., 1999; Demonet et al., 1992,1994; Liu et al., 1997; Pugh et al., 1996; Rumsey, Horwitz, et al., 1997; Zatorre et al., 1992) and supports our hypothesis of general activation arising within temporal cortex (PT, TTG, STG, SF) and in IFG.

However, our results failed to support the hypothesis concerning the differences between processing of speech sounds and non-speech sounds. Contrary to Liu et al. (1997) results, we found only small significant differences in activation generated by speech and tone stimuli. This would suggest that, at this level of processing, speech sound is not processed differently from other (non-speech) auditory material.

The overall activation discovered for the control-group was opposite to our hypothesis of left hemisphere dominated activation; the result showed that among control subjects the right hemisphere was more widely activated compared to the left hemisphere in both speech and tone

tasks. This was not what we expected on the basis of earlier research. Previous research suggest pure auditory processing to be dominant in the right hemisphere (Celsis et al., 1999; Demonet et al., 1992, 1994) but linguistic processing to be dominant in the left hemisphere (Celsis et al., 1999; Damasio et al., 1996; Demonet et al., 1994; Price et al., 1992). Some authors report left hemisphere dominance also during non-speech auditory processing (e.g. Liu et al., 1997). Interestingly, the dyslexic-group showed this expected left hemisphere specialization of processing.

One explanation for the right hemisphere activation of the controls in seemingly language-related task could be the nature of the stimuli. During the 14-second period each stimulus (ata/atta/sound) started every second and created a certain rhythm for the stimulus trial. Both the speech and tone stimulus trials also fluctuated in pitch depending on the duration of the critical parts of the stimuli and created a certain “melody” for the trial. This probably enabled the perception of the differences between standard and deviant stimuli to be based on something other than on the phonological content. The stimuli may have been processed as a rhythmic material - as music, instead of as words or as separate sounds. Different aspects of musical perception have been shown to be predominantly right hemisphere processes (Samson & Zatorre, 1994; Zatorre et al., 1994).

However, dyslexic readers seemed to process the stimuli as linguistic material, if this can be concluded on the basis of the usage of the left hemisphere more. They probably need to practice a more analytical point of view to work out the task, to engage in a phonological analysis of the stimuli. Controls processed the contents of the trials apparently more as a whole, as a rhythmic entity.

There is an attention component in the tasks and the right hemisphere is also devoted to attentional domain. This component should be equal for both groups, but the differential engaging in different forms of attention can be unequal between groups. The frontal cortex, which seemed to be over-activated in left hemisphere for dyslexic-group, can also be considered important in respect to attention, but it may have a differential role than the right hemisphere, reflecting more controlled and directed attention. The right hemisphere activation could reflect more general arousal and concentration.

The main interest in this study was the difference between the groups. In addition to the differential engagement of the hemispheres, there were also differences within the left hemisphere. The main activation for both groups was seen in primary and secondary auditory

cortices, but the participants in the dyslexic-group tended to show increased activation in the middle and anterior language areas and decreased activation in the posterior areas, in SF, during tasks, compared to control subjects.

The paucity of activation in posterior areas for individuals with dyslexia is shown in many earlier studies (e.g. Frost et al., 1997; Rumsey, 1996; Rumsey et al., 1992, 1994; Rumsey, Nace, et al., 1997; Shaywitz et al., 1998). These results together with our study strongly support the presumption of dysfunctional posterior phonological system in left hemisphere to be characteristic to dyslexia.

The findings concerning activation differences in middle and anterior language areas of left hemisphere are more contradictory. References to increased activation, or absence of negative activation have been reported earlier (Frost et al., 1997), but also decreased activation within this area during phonological tasks is reported for dyslexic subjects (Brunswick et al., 1999; Rumsey, Nace, et al., 1997). Results showing abnormalities within inferior frontal cortex have also been reported referring to both increased activation (Shaywitz et al., 1998) and decreased activation (Frost et al., 1997) compared to normal-reading controls. In the Shaywitz et al. (1998) study both posterior under-activation and anterior over-activation was observed, but they did not find any abnormalities in temporal regions.

These contradictory findings probably reflect the different tasks and/or methods used – at least partly. The difference in studies of Rumsey, Nace, et al. (1997) and Brunswick et al. (1999) compared to both our and Frost et al.'s (1997) studies was that the stimuli in the former were presented visually and in the latter, aurally. Accordingly, compared to control subjects, the studies using visual presented phonological tasks report under-activation of STG and studies using aurally presented phonological tasks report over-activation of STG for dyslexic subjects, or actually absence of negative activation as seen further. Further analysis of these differences between visually and aurally presented material is not in the scope of this study, but as suggestive notion for further study there could be asked, whether the result can be interpreted as stronger bounding of neural resources in the lower level of processing of each sensory modality (here, to basic auditory processing regions). Another distinctive factor to Rumsay, Nace, et al. study (1997) and to Brunswick et al. study (1999) was that our and Frost et al.'s (1997) stimuli needed to be kept in memory before responding, while the tasks in former studies could be done in the presence of the stimuli. Rumsey, Nace, et al.'s study (1997) required also pronunciation. The presence of memory

component seems to affect on the activation-differences between dyslexic subjects and normally reading subjects in the area of STG while the paucity of activation in parietal regions is more general. If there is a memory component with the task, it seems to generate over-activation in the STG in addition to diminished activation in posterior regions.

Frost et al. (1997) suggested that the diminished activation of posterior areas was compensated by exceeded activation in STG. Our result support this view of compensation, but we suggest, that the compensation happens in the processing, and probably at an early stage of development. The dyslexic brain processes the auditory-linguistic stimuli differently because of, probably congenital, deficit of processing at some critical point of the auditory system in the brain. The aberrations in the brain functioning of dyslexic subjects are already seen at infancy (Lyytinen & Leppänen, in press). The differences in language-related cortex may lead dyslexics - during their language development - to employ differential, apparently less refined processing strategies of auditory and linguistic material. One candidate for the neural level location of this congenital deficit is the posterior language region, where there was seen diminished functioning during phonological tasks in our study and in numerous earlier studies, and abnormal functioning also at rest (Rumsey et al., 1994).

The regions, where the neural processing seems to be shifting, or whose processes are weighted more, are the middle temporal and anterior language regions. The areas in the temporal cortex (STG, PT) and recently also inferior frontal cortex are strongly connected to speech perception and phonological processing (Binder et al., 1997; Celsis et al., 1999; Demonet et al., 1992, 1994; Pugh et al., 1996; Rumsey, Horwitz, et al., 1997; Shaywitz et al., 1997; Zatorre et al., 1992).

We already know the association of dyslexic syndrome to impaired phonological processing and abnormal functioning of the phonological areas in temporoparietal and inferior frontal cortices. As is suggested in earlier research, phonological processing is not a single, homogeneous function, and it is not localized to single region in language-related cortex. What is needed, is to go on searching for more exact functions of these areas and more exact deficits in dyslexic syndrome. Our result can be interpreted as an expression of need for extra resources in middle temporal and anterior phonological processing regions while engaging in basic temporal discrimination task. Dyslexic subjects seemed to weight the middle temporal functions specifically for speech-related discrimination task, and anterior temporal and inferior frontal functions

specifically for tone discrimination task. Also, dyslexic-group weighted less the posterior parts of SF. These differential results imply us to use more specific level of explanation for processing within regions devoted to phonological functions.

Heilman (1996) states that the discrimination of different phonemes from changing phonetic flow requires the sub-articulator functions of frontal language cortex. Luria has stressed the importance of left anterior language areas in fluent processing of language, moving from one articulator gesture to another. This processing is not specific to speech production, but is needed also during speech perception. As Demonet et al. (1992) concluded, activation of left inferior frontal cortex during speech perception is consistent with the motor theory of speech, presented by Liberman and Mattingly (1985). This suggests that the role of left hemispheres inferior frontal cortex is associated to motor functions in language. We can speculate that it affects to speech processing, and probably also to non-speech processing, of temporal information, which, according to Tallal (1993), is one central element in language perception. The over-activation within these inferior frontal and temporal regions reflects probably not only need for more basic phonological processing, but also more fundamental need in basic processing of duration-related auditory material for dyslexic subjects. Whether the temporal nature of the stimuli is the central problem for processing is a question waiting for further evidence.

During speech task, dyslexic subjects weighted the functions of middle temporal regions more. These regions reflect some other component in phonological processing, probably phonemic identification or discrimination, which are shown to activate these middle regions for normal subjects. Our speech task probably required the brain of individuals with dyslexia to process the stimuli more separately and phonologically, by breaking them down into pieces, in order to find out which category (ata or atta) the stimuli belongs to.

The activation in the region of our main interest was rather contradictory. While dyslexic subjects seemed to have more activation in the left PT during speech task, the control subjects seemed to have more activated pixels in right PT. One interpretation of the lower activation for speech stimuli in left hemisphere for controls could be that activation in PT is connected more to basic auditory processing for normally reading subjects. This was shown also in Binder et al. (1996) study demonstrating slightly higher activation in left PT for tone task than for speech task for normal readers. But why the right PT was specialized to speech processing in control subjects? This result needs further studies to be confirmed, but in our study, it can probably

be explained by the same reason as why controls activated the right hemisphere overall more. Their brain 'interpreted' the stimuli differently from dyslexics.

Dyslexic readers showed diminished activation in posterior language region, which is also connected to phonological processing. The processing in posterior regions (SMG, AG) has been connected to phonological memory functions (Demonet et al., 1994; Paulesu et al., 1993). Clear and comprehensive defects in using this region among dyslexic readers can reflect a diminished emphasis in phonological memory functions, perhaps because of more need's in basic phonological analysis.

The posterior part of SF probably reflect also processing the material at more multi-modal level and more as a whole, at a higher stage in the hierarchy of processing. The temporoparietal junction is a polysensoric region, which contributes the quasi-spatial component to language (Kolb & Wishow, 1996;). The understanding of the wholes and the relations within different components can be seen as the functions of this area, also affecting language and probably even pure auditory processing. Our results could be interpreted as diminished emphasis of these processes in comparison to basic phonological analyzing processes during speech and tone discrimination tasks for dyslexic subjects compared to the processing-pattern of control subjects.

Probably control subjects processed the stimuli more as a whole, and as the right - left distinction showed, maybe not at all as a linguistic stimuli but rather somehow as music. It can be speculated that the phonological processing in middle and anterior temporal areas is so automated for normally-reading subjects that the tasks concerning simple speech stimuli does not need so much processing power any more. Rather, in the posterior areas the activation refers to a more direct processing at a more complex or multimodal level. Future research is needed for certify this speculation and to reveal more detailed functions of the different regions within anterior and posterior language areas related to dyslexia.

As is shown here, the abnormalities in the brain activation of individuals with dyslexia failed to show specialization to mere language-related stimuli. Our result supports the idea that at the neural level dyslexia is not specific to speech-related processing (suggested e.g. by Tallal et al., 1993; Tallal, Mertzenich, Miller & Jenkins, 1998). The clearest abnormality - the diminished activation in posterior SF - was equal when compared between processing of pure auditory sounds and speech-specific sounds. However, over-activation for the dyslexic-group appeared in slightly different areas: in the PT and in middle STG during the speech task, and in the anterior parts of the

STG and in inferior frontal cortex during the tone task. Altogether, the distinction between the speech and non-speech sound discrimination did not cause a clear-cut difference at the neural level compared between dyslexic and normal readers. Both discrimination tasks produced aberrations from normal activation of the perisylvian cortex of the left hemisphere of dyslexic subjects.

Overall, there seemed to be a tendency for dyslexic subjects to under-activate the left posterior regions and over-activate more anterior regions and also the whole left hemisphere. We suggest that the reported results reflect differential weighting of different processes included in the phonological analysis between dyslexic readers and normally reading controls. The processing of the linguistic material could be viewed in two different ways. The laborious way, which is used when learning to speak and read and also in adulthood when reading a difficult language, goes through a phonological analysis of separate sub-word components for comprehending the whole word. This process could be seen as a bottom-up assembling of the word. The processing of language can also proceed straight to the whole word image and the complicated analysis of separate syllables is not needed. In base of our results, we can speculate that dyslexic brain is enforced to weight more the former, laborious way.

Demonet et al. (1994) state that language tasks reflect a parallel involvement of many functional systems corresponding to different cognitive dimensions of the task. According, brain activation should be viewed as the result of interplay and competition between these functional systems. In our study, the dyslexics and controls used slightly different way of processing of the same task resulting in the same outcome. Probably, in more difficult task, the dyslexics' way of processing is slower and more prone to errors. The processing at the top-level of hierarchy is probably faster and more sophisticated and is enabled by the complex functioning of more multimodal regions of the brain. Thus, while the congenital deficit of functioning (or even structure) of brain of some children leads to some sort of compensation in language-related network (discussed above), it predisposes them to impaired processing of language material (dyslexia).

In trying to reveal the probable neural level differences within the normally reading and dyslexic working brain in relation to speech - non-speech auditory processing, our research was among the first ones and thus naturally of explorative nature. Accordingly, it should be seen as suggestive and require further research. In using fMRI there are some methodological limitations. It is difficult to avoid other sources of activation (psychological and physiological artifacts) and separate the wanted cognitive process. However, the possibility of such intrusions was equal

between the experimental conditions in our study. Only factor, which differed between situations besides the target variable, was that the speech task was executed first and the non-speech task last. Some subjects reported to become tired towards the end of the situation and the differences in concentration and disturbing factors were increased. This must be taken in to consideration as they can affect the differential results of the two situations. In our results, however, the result refers to the fact that the situations did not differ at the neural level for either group.

Another limitation in using MRI-device is often the small group sizes within study. This produces a factor of uncertainty to reliably comparing groups.

The spatial placement of the slices affects the visibility of the activated tissue in gyral morphology. As Binder et al. (1994) argue, the ability of one slice to fully represent homogeneous, contiguous regions of activation is limited. In our study we were mainly interested in the perisylvian region surrounding PT, and we chose our slice placement with respect to that interest. Although some potential activated brain areas might have been left out of sight and thus the activation seen probably does not reflect the whole response to the stimuli, the results revealed differences in the processing of speech and tone stimuli between poor and normally reading subjects. These results naturally concern only the area covered by the used slice, but give also tentative suggestions for more comprehensive processing differences.

It is very likely that we have to look for multiple core deficits and multiple sub-syndromes in dyslexia in order to explain the heterogeneous nature of the deficits shown in both cognitive and neural-level processing (as suggested also by Manis et al., 1996 and Ridzen et al., 1997). As is seen in this and in previous studies, the functional aberrations from normal neural-level processing are not simple and clear. In order to get closer to the real nature of the dyslexic syndrome, we have to examine more and more specific functions at the neural and cognitive levels. Whether this examination will reveal some clusters of sub-syndromes in dyslexia, is an interesting question for further study.

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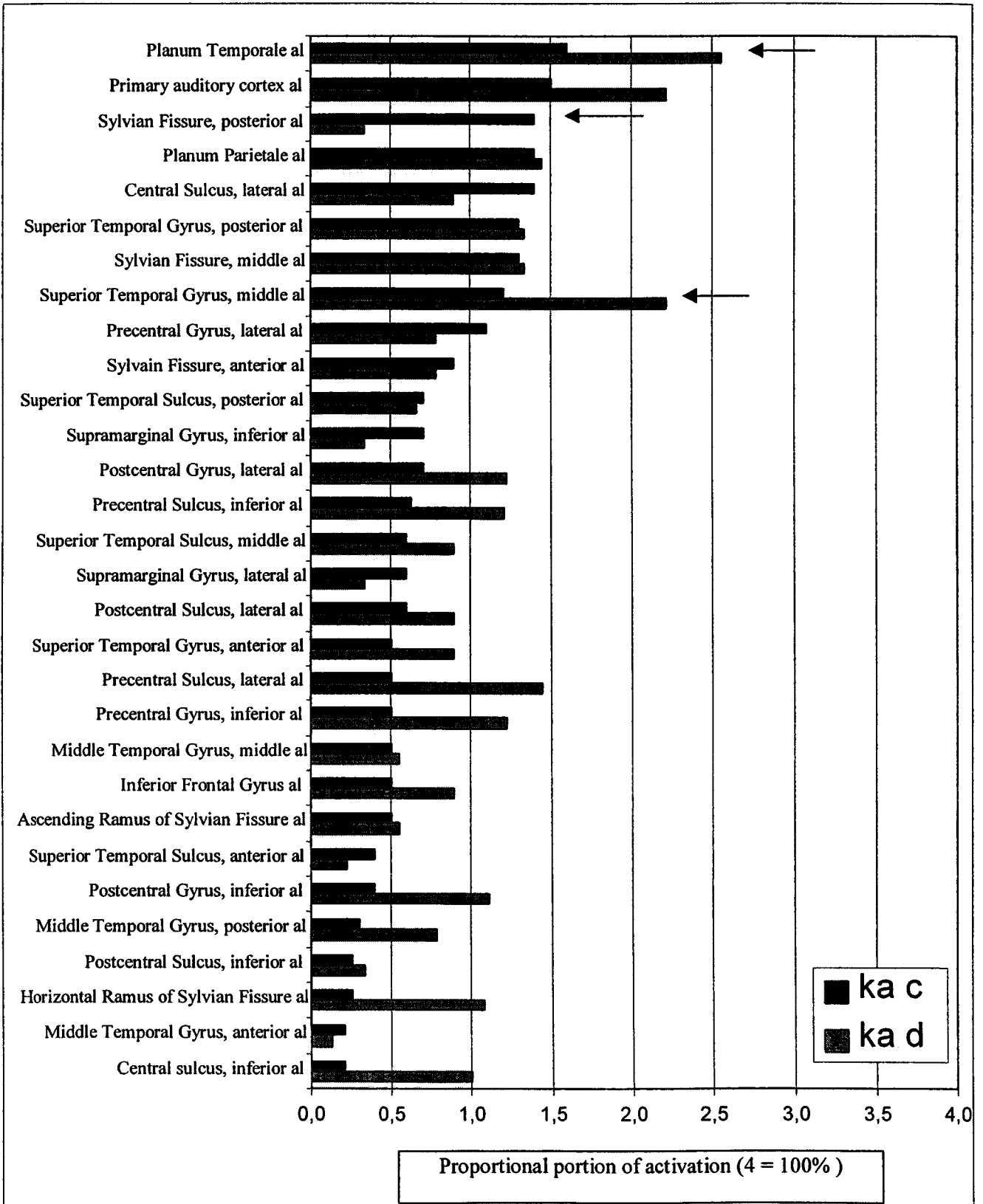
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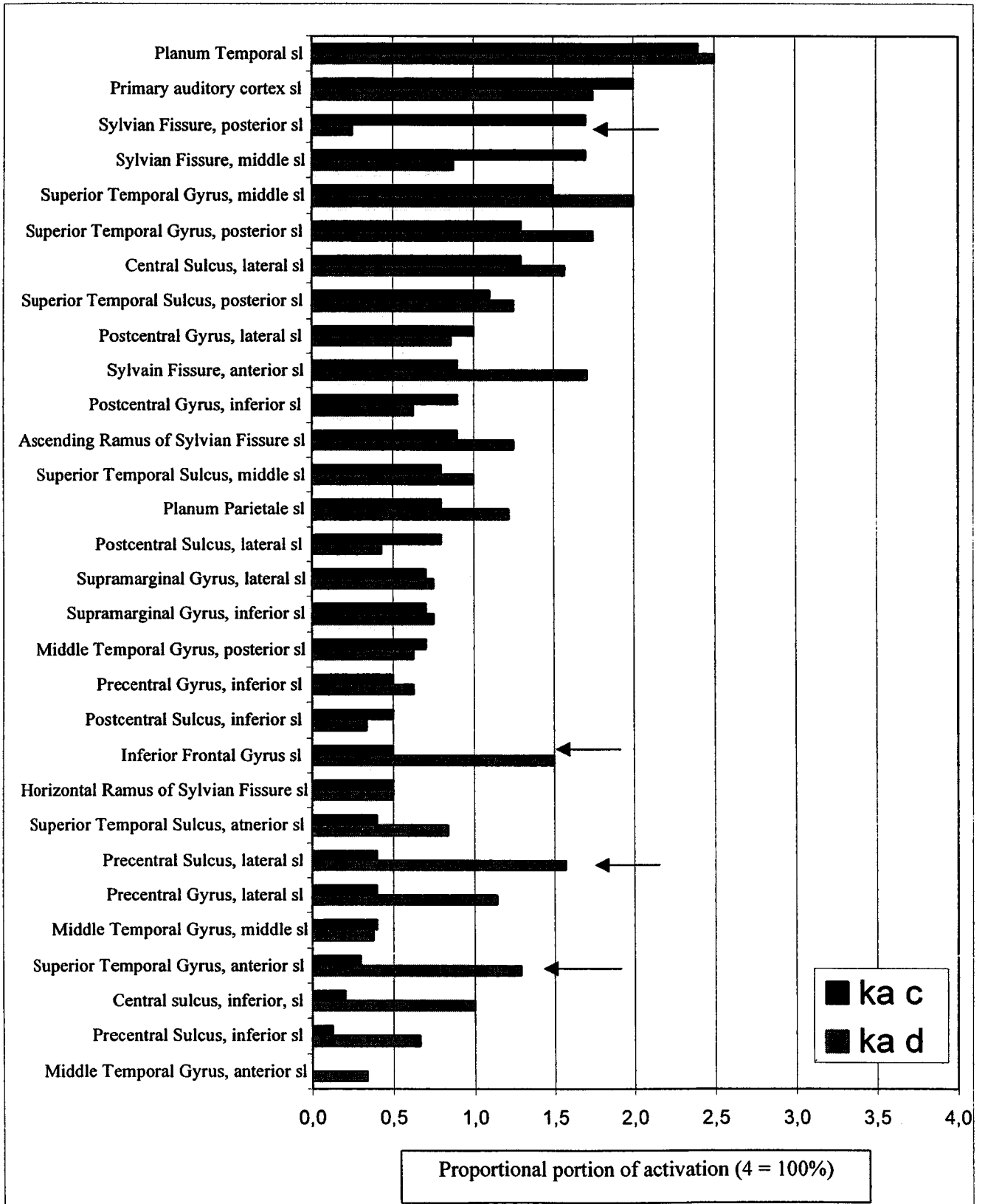
6 APPENDIXES

APPENDIX A. Distribution of activation between groups in order of magnitude according to controls. Arrows point at the regions where there is significant difference between the groups.

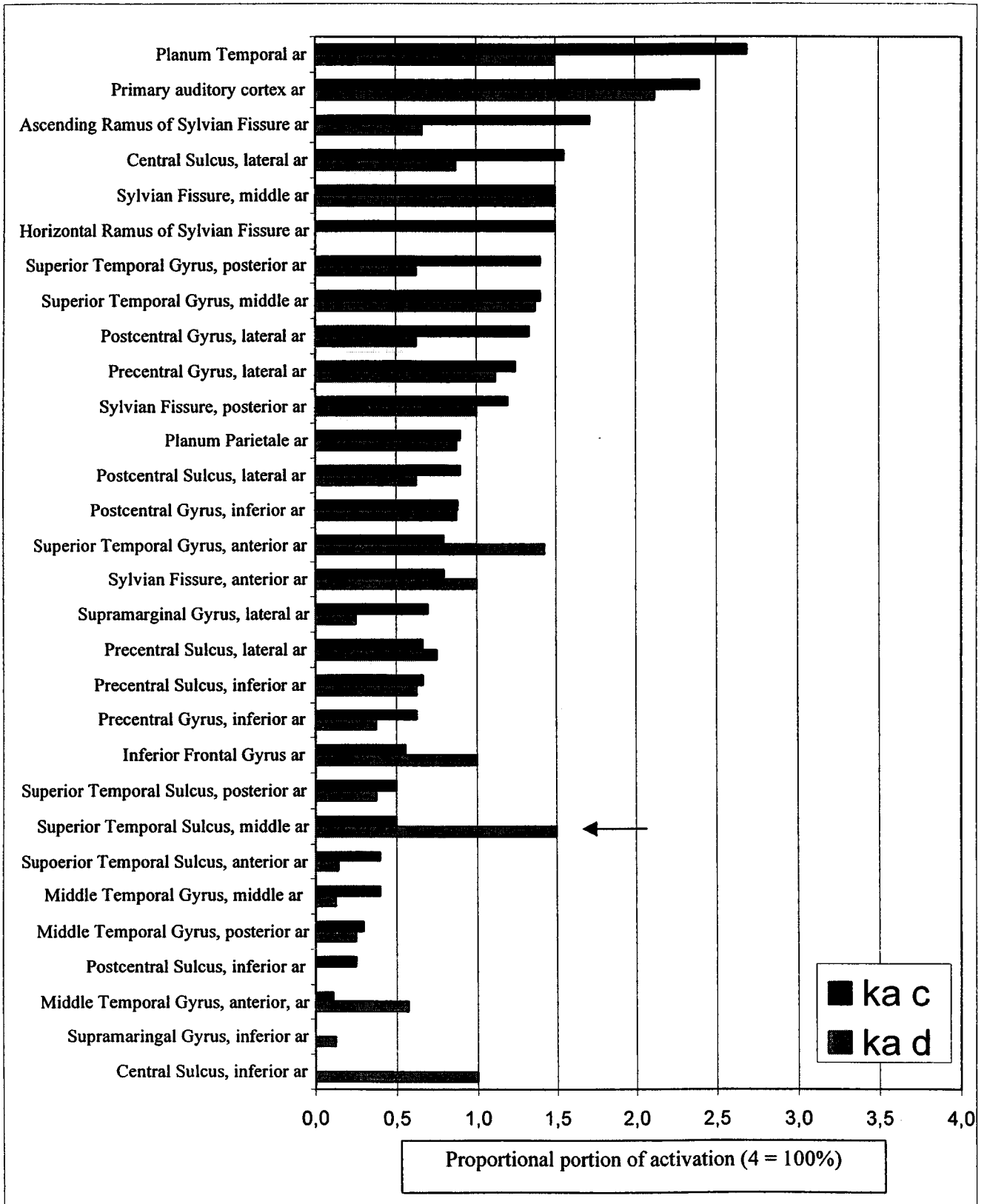
1. Speech discrimination task, left hemisphere



2. Tone discrimination task, left hemisphere



3. Speech discrimination task, right hemisphere



4. Tone discrimination task, right hemisphere

