Brain (1998), **121,** 1053–1063

The illiterate brain
Learning to read and write during childhood influences the functional organization of the adult brain

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Summary
Learning a specific skill during childhood may partly determine the functional organization of the adult brain. This hypothesis led us to study oral language processing in illiterate subjects who, for social reasons, had never entered school and had no knowledge of reading or writing. In a brain activation study using PET and statistical parametric mapping, we compared word and pseudoword repetition in literate and illiterate subjects. Our study confirms behavioural evidence of different phonological processing in illiterate subjects. During repetition of real words, the two groups performed similarly and activated similar areas of the brain. In contrast, illiterate subjects had more difficulty repeating pseudowords correctly and did not activate the same neural structures as literates. These results are consistent with the hypothesis that learning the written form of language (orthography) interacts with the function of oral language. Our results indicate that learning to read and write during childhood influences the functional organization of the adult human brain.

Keywords: illiteracy; learning; language processing; phonological processing; PET

Abbreviations: BA = Brodmann area; rCBF = regional cerebral blood flow; SPM = statistical parametric mapping

Introduction
Learning to read and write adds a visuographic dimension, based on the operation of matching phonemes and graphemes, to the internal representational system for spoken language. Several cognitive models dealing with the mechanisms of spoken language processing consider the written counterpart (orthography) to be a parallel processing pathway (Patterson and Shewell, 1987; Caplan, 1992). These pathways may interact during language processing operations, but such interaction is usually not discussed from an ontogenetic perspective. Previous findings (Reis and Castro-Caldas, 1997) support the hypothesis that the ontogenesis of oral language is affected by learning to read and write, which indicates that oral and written language systems interact.

Oral language is, at a behavioural level, similar in illiterate and literate subjects. However, the inability of illiterate subjects to perform certain tasks that require an awareness of the phonological structure of words indicate that they differ from literate subjects in some aspects of phonological processing (Morais, 1993). For example, illiterate adults were unable to delete or add a phone at the beginning of a non-word, while literate adults from the same sociocultural environment had little difficulty in performing the task (Morais *et al.*, 1979). These studies indicate that certain aspects of the ability to deal with phonetic units of speech are not acquired spontaneously but are a result of learning to read. The poor performance of illiterate subjects in repeating pseudowords (Reis and Castro-Caldas, 1997) may reflect different competences in certain aspects of phonological language processing.

It has been suggested that three different processing pathways (or strategies) for repeating verbal material may be used by normal literate subjects: the semantic, the lexical and the phonological. These pathways are active in language processing and may operate as subsystems (or subnetworks) that interact in parallel (Rumelhart and McClelland, 1986; Patterson and Shewell, 1987; Seidenberg and McClelland, 1989; Caplan, 1992; Martin and Saffran, 1992). A schematic and hypothetical structured network model for interactive parallel processing is illustrated in Fig. 1 (see further Pinker and Prince, 1989; Shastri and Ajjanagadde, 1993; Bienenstock

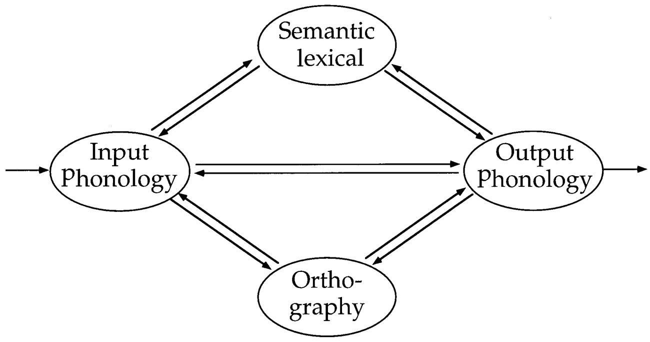

Fig. 1 A schematic representation of a structured parallel and interacting distributed processing system indicating possible processing pathways (or networks) that may be used in verbal repetition (freely adapted from Seidenberg and McClelland, 1989). Repeating words biases processing towards lexicosemantic and implicit phonological processing whereas repeating pseudowords biases processing towards explicit phonological processing. The emergence of the necessary phonological processing capacity for correct pseudoword repetition is sculptured by the learning and knowledge of reading and writing.

and Geman, 1995; Seidenberg, 1995; Shastri, 1995; Touretzky, 1995; Pinker 1997; Prince and Smolensky, 1997; Redington and Chater, 1997; Snowling *et al.*, 1997). Learning to read and write modifies the phonological system by adding a visuographic dimension, i.e. that of graphemic–phonemic matching. Presumably this will result in a network with parallel-distributed and interactive processing which is different in literate and illiterate subjects.

Our previous observations of behavioural differences in language processing between literate and illiterate subjects (Reis and Castro-Caldas, 1997) initiated this study of the functional anatomy of word and pseudoword repetition. Our hypothesis was that the repetition of words would bias processing towards a lexicosemantic strategy which is subserved by a functional network that is similarly developed in the two groups. In contrast, repetition of pseudowords, engaging the phonological processing pathway, requires a functional organization that is differently developed in the two groups. Using PET and statistical parametric mapping (SPM), we assessed the relative differences between the functional networks subserving the repetition of auditorily presented words and pseudowords in literate and illiterate subjects.

Method

Subjects

In this study, subjects were classified as illiterate when they, for social reasons, had never entered school and had no knowledge of reading or writing. This definition of illiteracy should be distinguished from functional illiteracy, which is not considered in this study. Functionally illiterate subjects were not included since their previous exposure to the acquisition of phonemic–graphemic associations implies experience of and the existence of a visuographic representation system based on phonology.

Twelve right-handed women from the same social and cultural background (six illiterate, aged 65 ± 5 years, and six literate, aged 63 ± 6 years) were included in the study (two sisters, one illiterate and the other literate, were included). The study was approved by the local Ethics and Radiation Safety committees at the Karolinska Hospital. Informed consent was given by all subjects.

As many confounding variables as possible were controlled and the criteria for selection of subjects were strict. Only women were selected since sex may influence the functional organization of language (Shaywitz *et al.*, 1995). All subjects (literate and illiterate) included in the study were raised and still live in the same sociocultural environment. They were all inhabitants of a small town in southern Portugal. Some years ago it was seldom possible for parents to send all their children to school. In general, the eldest girl of a family was engaged in household activities relatively early in life. She often had to take care of the younger siblings and was not sent to school when she reached school age. In contrast, the younger siblings attended school and became literate.

All subjects were fully socially functional and the absence of reading and writing skills was not a significant handicap in their everyday life. Literate and illiterate subjects were selected if they performed in the normal range (±1 SD, norms according to age and literacy group) on all subtests of a short test battery [including simple tasks, e.g. oral naming (real objects, colours, body parts), object identification, phrase comprehension, repetition of words and phrases, verbal fluency, limb and oral praxis, general knowledge and episodic memory tasks] adapted for this population (Garcia and Guerreiro, 1983). Previous diseases potentially involving the brain were carefully ruled out by clinical assessment and previous clinical information provided by the local doctor, as well as morphological investigations (diagnostic MRI scans were classified as normal, with a suggestion of possible subtle cortical atrophy in two subjects, one in each group). The literate women had 4 years of schooling and performed normally on reading comprehension and writing tests.

In the course of the selection process, all subjects underwent a letter recognition task in which single letters or very common acronyms were shown (trademarks, television channels etc.). Illiterate subjects were included if they were unable to recognize any of the letters or acronyms containing information. The ability to write their own name was not an exclusion criterion.

Pseudowords were explained as spoken words similar to comprehensible words but which do not have any meaning, which the subjects have not previously heard. All subjects were highly familiar with the tasks of word and pseudoword repetition, since they were selected from a pool of subjects that had previously participated in a behavioural study of word and pseudoword repetition (Reis and Castro-Caldas, 1997). During the pretesting the word/pseudoword repetition tasks were again explained and all subjects performed the tasks. The subjects were instructed to repeat words or pseudowords as follows: 'You are going to listen to a list of words presented one at a time that you should repeat. Some of the words are known, others you have never heard. You should repeat the words immediately and try to repeat the words exactly as you heard them' (in Portuguese: 'Vai ouvir umas listas de palavras, apresentadas separadamente, e repetir as palavras das listas. Algumas das palavras são conhecidas outras nunca ouviu. Deve repetir as palavras imediatemente e exactamente aquilo que ouvir'). All subjects had to repeat words at least 90% correctly to be included in the study. This rate of success also excluded significant auditory deficits. In repeating pseudowords the literate subjects had to repeat them at least 80% correctly to be included. Correct responses in pseudoword repetition in the illiterate group were <50%.

Stimuli and experimental design

Six lists of 20 high-frequency three-syllable words were constructed based on frequency of use in common Portuguese spoken language (Nascimento *et al.*, 1987). The mean frequency of use was the same for all lists (one-way ANOVA, $P > 0.95$). Lists of pseudowords were constructed based on the real words by changing the consonants and maintaining the vowels as well as the word length. Each list was recorded on a tape with a word presentation rate of one per 6 s. Prior to each PET experiment, the subjects were informed that they were to repeat either words or pseudowords (explained as above). The subjects were well aware of this but were not informed before starting a new repetition task whether words or pseudowords were going to be presented (Wells, 1995). The subjects were instructed to respond with a word or pseudoword, whether or not they understood the stimuli, and were instructed to avoid any other type of speech production. Before the PET study started, the word/pseudoword repetition tasks were explained and the subjects practised all aspects of the paradigm in the PET camera until they comprehended and performed satisfactorily.

PET scanning and data analysis

Repeated measurements of regional cerebral blood flow (rCBF) were made with a 3D Ecat Exact HR PET scanner (Wienhard *et al.*, 1994) and bolus injections of [^{15}O]butanol (Berridge *et al.*, 1990). The PET images were realigned, spatially normalized and transformed into a common stereotactic anatomical space (Talairach and Tournoux, 1988), 3D isotropic Gaussian-filtered (16 mm full width half maximum), proportionally scaled to account for global confounders and analysed with SPM (Friston *et al.*, 1995*a*, *b*). The general linear model was used to model rCBF data and relevant contrasts, corresponding to null hypotheses, were used to generate statistical parametric maps SPM$\{Z\}$. The SPM$\{Z\}$ were thresholded at 3.09 (or omnibus significance $P \leqslant 0.001$). The activated or deactivated regions found were then characterized in terms of spatial extent and peak height of local maxima. The order of scans within a given condition was used as a confounding covariate. The reported P values were corrected based on the theory of 3D-differentiable stationary Gaussian random fields (Adler, 1981; Worsley *et al.*, 1992; Friston *et al.*, 1995*b*). The differences between groups, detected by visual inspection, were tested using a masking approach, yielding a more sensitive method for detecting group-specific differences since the search volume was reduced (Fletcher *et al.*, 1995*a*, *b*). The interaction contrast [group × (pseudoword – word)] was masked with relevant group-specific contrast (thresholding at $Z = 2.58$ or omnibus significance $P \leqslant 0.005$), accepting local maxima with Z score >2.58 as significant.

Table 1 *Rate of successful repetitions of words and pseudowords during scanning*

Group	Word repetition	Pseudoword repetition	Paired *t* test
Illiterate	110 ± 7	39.5 ± 13	$P < 0.00001$
Literate	118 ± 1	100 ± 19	n.s.
Mann–Whittney *U* test	$P < 0.005$	$P < 0.005$	

Maximum total score was 120 for each collection of lists; correct repetition was scored 1, and 0 otherwise. n.s. = not significant.

Procedure

During the PET scanning, subjects had their eyes closed and words/pseudowords were auditorily presented through earphones at a sound level adjusted to the subjects' own preference (presentation rate of one per 6 s). The order of scans was ABABABABABAB (A = word repetition, B = pseudoword repetition). The order of the tapes with words/pseudowords was reversed in one-half of each group. When questioned, none of the subjects reported any discomfort or anxiety during the studies. Their performance in repeating words/pseudowords was recorded.

Results

Behavioural data

Repetitions of words and pseudowords were scored 1 if correct and 0 otherwise. No subject produced any speech utterances other than correct or incorrect words or pseudowords during the word/pseudoword repetition tasks.

The repetition of words was 98% correct in the literate and 92% correct in the illiterate group. This difference, although small, reached statistical significance. The repetition of pseudowords was 84% correct in the literate and 33% correct in the illiterate group (Table 1).

An error analysis was performed on the 592 errors in pseudoword repetition during scanning (a total of 1440 pseudowords were repeated by all subjects; the literate and illiterate groups made 117 and 475 errors, respectively). The errors were classified as lexicosemantic or phonological errors (see Appendix for examples of the different types of phonological errors made and the distribution of errors in both groups). The phonological aspect of pseudoword repetition is comparable with an immediate memory test [see for example the CVC sequence test proposed by Noble (1961) and used by Newcombe (1969)]. Illiterate subjects seem to perform relatively well on rhyming tasks (Adrian, 1993) but have difficulty in performing explicit phonological segmentation relating to the beginning of words/pseudowords (Morais *et al.*, 1979). Thus, the phonological errors were subclassified according to whether the error related to the phonological structure of the beginning, middle or end of the pseudoword (see Appendix). The syllabic structure of the pseudowords was used for the error classification and the errors were classified in four types: (i) errors in the first syllable or in the first and second syllables; (ii) errors in the second syllable; (iii) errors in the third syllable or in the second and third syllables; and (iv) errors involving the whole structure. The illiterate group made 53 and the literate group made only two lexicosemantic errors (Yates' corrected $\chi^2 = 8.6$; $P = 0.003$) during pseudoword repetition. The illiterate subjects made four times more phonological errors than the literate subjects, while the distribution in subclasses of phonological errors was the same in the two groups ($\chi^2 = 0.06$; $P = 1.0$).

PET results

The computerized brain atlas of Greitz [CBA = Karolinska Computerized Brain Atlas (Greitz *et al.*, 1991)] was used for the anatomical description of the activated regions. The CBA makes it possible in a comprehensive way, through its anatomical database, to determine interactively the anatomical structures and Brodmann areas (BA) encompassed by an activated region. In this context, activations and deactivations refer to rCBF increases and decreases, respectively. For data portability, the tables of local maxima use the anatomical designations of Talairach and Tournoux (1988).

The results of the PET data analysis are given in Fig. 2 and Table 2. In the words versus pseudowords comparison, there were similar bilateral activations (thresholding at $Z = 3.09$ or omnibus significance $P \leqslant 0.001$) in the superior and inferior parietal regions (Table 2A and B; BA 7, 39 and 19) in both groups, with a greater left-sided posterior parietal dominance in the literate compared with the illiterate group. In the literate group posterior midline activations were limited to the right posterior cingulate cortex (BA 23), and in the illiterate group the precuneate region (BA 7 and 31) extending into the posterior cingulate region (BA 23) was activated. In the literate group there were also activations in the left superior and middle frontal region (BA 8 and 9), in the right posterior parieto-occipito-temporal region (BA 39, 37 and 19) and left occipito-temporal region (BA 19 and 37), which were not seen in the illiterate group. These group differences (by visual inspection) were mostly due to thresholding effects, and when thresholding at a lower level the activation pattern in literates and illiterates tended to converge towards similar activation patterns, as confirmed by the interaction analysis (Table 2E). Thus, the only activation in words versus pseudowords that was greater in the literate than in the illiterate group was the more prominent left-sided posterior parietal activation. In particular, when masking with the activation pattern defined by the words–pseudowords contrast in literates, there was increased activation of a left inferior parietal region (BA 40) in literates compared with illiterates in words versus pseudowords. There were no differences when masking with the words–pseudowords contrast in illiterates.

In the reverse comparison (pseudowords versus words), the literate group displayed significant activation (Table 2C) in the bilateral anterior insular (BA 14 and 15) and right frontal opercular cortices (BA 44, 45, 47 and 49), left perigenual anterior cingulate cortex (BA 24 and 32), left basal ganglia (putamen, globus pallidus and head of caudate nucleus), anterior thalamus/hypothalamus and midline cerebellum. In the illiterate group (Table 2D), significant activation was only seen in the middle frontal/frontopolar region (BA 10). In general, the interaction analysis confirmed these differences between the literate group and the illiterate group (Table 2F). In particular, when masking with the activation pattern defined by the pseudowords–words contrast in literates, the literate group activated more strongly the right frontal opercular–anterior insular region, left anterior cingulate, left lentiform nucleus and anterior thalamus/hypothalamus in pseudowords–words contrast compared with the illiterate group. There were no differences when masking with the pseudowords–words contrast in illiterates.

Discussion

This study confirmed previous behavioural observations that illiterate subjects perform more poorly than literate subjects in pseudoword repetition (Reis and Castro-Caldas, 1997). The error analysis of the pseudowords produced showed that the qualitative difference between groups related to the intrusion of lexicosemantic analogies. The phonological errors made during pseudoword repetition revealed similar behaviour for the two groups, but the number of incorrect productions was four times larger in the illiterate group. It should be emphasized that all subjects produced only words or pseudowords (no other type of speech was produced) during the PET scanning. Also, when a subject failed to repeat a pseudoword correctly, another pseudoword was still repeated (except for the lexicosemantic analogies).

The difference between the groups in word repetition performance was small but significant and is not easily explained by differences in lexical knowledge, since the subjects had very similar sociocultural backgrounds. Errors in word repetition by the illiterate subjects may reflect the lack of fully developed, multiple parallel and interacting systems for processing phonological information. The results presented are consistent with the hypothesis that the absence of proper training of the visual bound phonological system

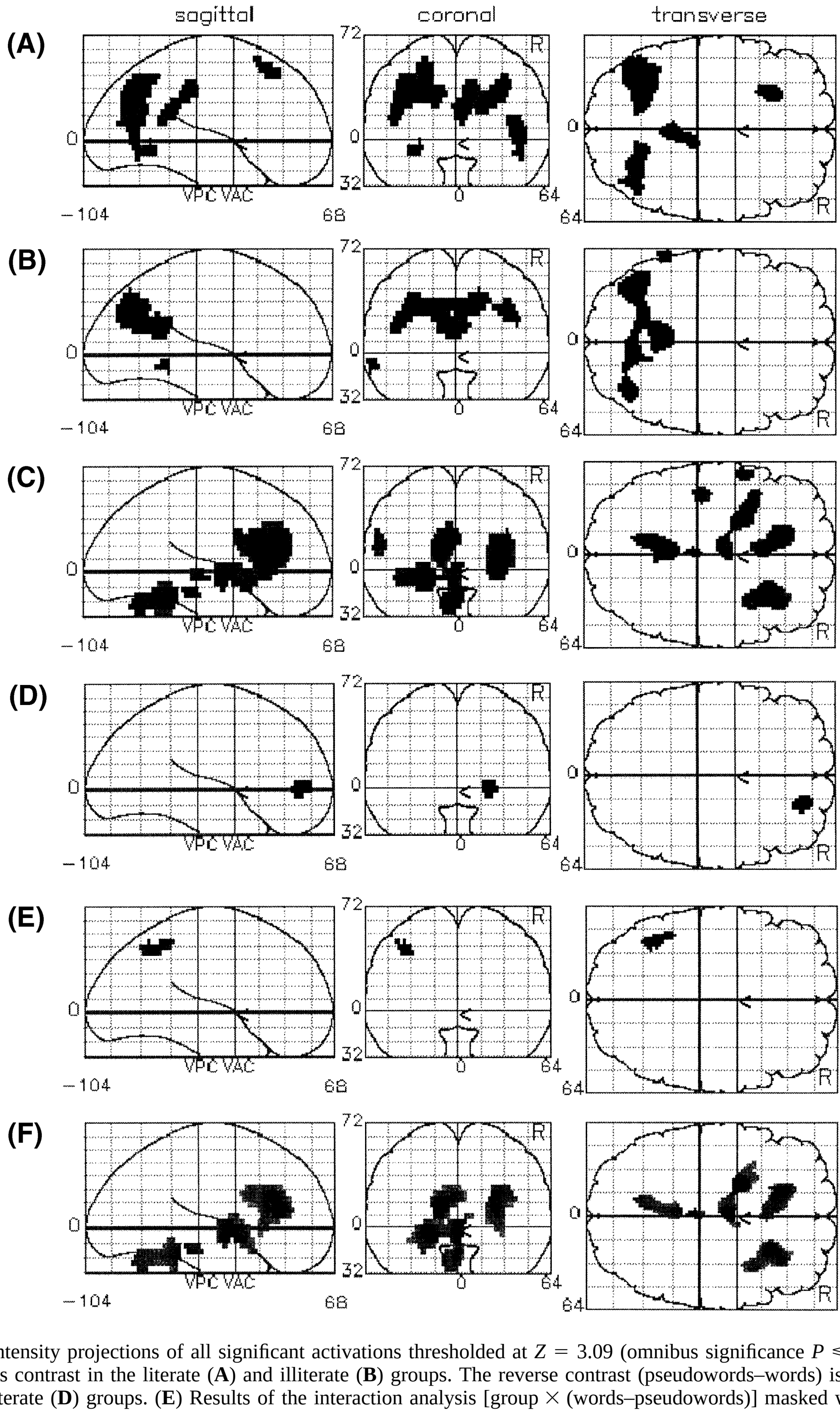

Fig. 2 Maximum intensity projections of all significant activations thresholded at $Z = 3.09$ (omnibus significance $P \leqslant 0.001$) in the words–pseudowords contrast in the literate (**A**) and illiterate (**B**) groups. The reverse contrast (pseudowords–words) is shown for the literate (**C**) and illiterate (**D**) groups. (**E**) Results of the interaction analysis [group × (words–pseudowords)] masked with the word–pseudoword contrast in the literate group, and the interaction contrast [group × (pseudowords–words)] (**F**) masked with the pseudoword–word contrast in the literate group. For illustration, the threshold in the conjunction was set at $Z = 2.33$ (omnibus significance $P \leqslant 0.01$).

Table 2 *Activations (increases in rCBF) in the words versus pseudowords and pseudowords versus words comparisons in the literate and illiterate groups (A–D) and group-specific differences (interaction contrasts) in activation patterns (E and F)*

Region/structure	BA	*Z* score	*P* value	*x, y, z*
A. Literate, words vs pseudowords				
Prefrontal activations: vol = 91 voxels, n.s.				
Left superior frontal gyrus	BA 8 sin	4.05	$P < 0.07$	–22, 24, 48
Posterior cingulate activations: vol = 173, $P < 0.1$				
Right posterior cingulate	BA 23 dx	4.25	$P < 0.03$	6, –40, 24
Right posterior cingulate	BA 31 dx	4.01	$P < 0.08$	6, –34, 32
Posterior parieto-occipital activations: right vol = 240, $P = 0.05$, left vol = 569, $P = 0.005$				
Right superior parietal lobule	BA 7 dx	4.16	$P < 0.05$	30, –70, 36
Left superior parietal lobule	BA 7/19 sin	4.59	$P = 0.009$	–18, –66, 36
Left superior/inferior parietal lobule	BA 7/19 sin	4.58	$P = 0.009$	–18, –66, 36
Occipito-temporal activations: right vol = 129, $P < 0.15$, left vol = 50, n.s.				
Right inferior temporal/inferior occipital gyrus	BA 37/19 dx	4.18	$P = 0.04$	42, –68, –4
Left fusiform gyrus	BA 37/19 sin	3.83	$P < 0.14$	–30, –58, –8
B. Illiterate, words vs pseudowords				
Parieto-temporo-occipital activations: vol = 960, $P < 0.001$				
Precuneus	BA 7	3.81	$P < 0.15$	2, –76, 32
Right precuneus/superior occipital gyrus	BA 7/19 dx	3.70	$P < 0.2$	14, –74, 36
Left precuneus/posterior cingulate	BA 31 sin	4.13	$P = 0.05$	–10, –58, 16
Right superior parietal lobule/superior occipital gyrus	BA 7/19 dx	3.70	$P < 0.2$	34, –74, 28
Left superior parietal lobule/superior occipital gyrus	BA 7/19 sin	4.38	$P = 0.02$	–34, –74, 28
Left inferior parietal lobule/middle temporal gyrus	BA 39 sin	4.17	$P < 0.04$	–40, –66, 20
C. Literate, pseudowords vs words				
Frontal opercular and insular activations: vol = 622, $P = 0.004$				
Right frontal operculum/anterior insula	BA 49*/14* dx	5.10	$P < 0.001$	28, 20, 8
Left anterior insula	BA 14*/15* sin	4.10	$P = 0.06$	–30 8 –4
Anterior cingulate activations: vol = 622, $P < 0.02$				
Anterior cingulate	BA 24/32	4.45	$P < 0.01$	–2, 16, 24
Left anterior cingulate	BA 24 sin	4.93	$P < 0.002$	–14, 28, 16
Subcortical activations: vol = 328, $P < 0.03$				
Left putamen		4.23	$P < 0.03$	–22, 2, –4
Left caudate nucleus (head)		5.40	$P < 0.001$	–16, 18, 12
Anterior thalamus/hypothalamus		4.47	$P = 0.01$	0, –8, –4
Midbrain/pons		4.36	$P = 0.02$	0, –32, –12
Cerebellar activations: vol = 305, $P = 0.03$				
Medial cerebellum (vermis)		4.92	$P = 0.002$	–2, –48, –16
D. Illiterate, pseudowords vs words				
Prefrontal activations: vol = 63, n.s.				
Right superior/middle frontal gyrus	BA 10 dx	4.18	$P = 0.04$	20, 44, 0
E. Greater activation in literates compared with illiterates in words vs pseudowords				
Posterior parietal activations: vol = 24				
Left inferior parietal gyrus	BA 40 sin	3.00	$P = 0.001$	–36, –52, 48
F. Greater activation in literates compared with illiterates in pseudowords vs words				
Frontal opercular and insular activations: vol = 42				
Right frontal operculum/anterior insula	BA 49*/45*/14* dx	2.78	$P = 0.003$	22, 22, 28
Anterior cingulate activations: vol = 75				
Left anterior cingulate	BA 24 sin	3.59	$P < 0.001$	–16, 26, 12
Subcortical activations:				
Left putamen/pallidum, vol = 48		3.20	$P = 0.001$	–20, 0, –4
Anterior thalamus/hypothalamus, vol = 39		3.04	$P = 0.001$	0, –6, 0
Pons, vol = 4		2.69	$P = 0.004$	–2 –34 –16
Medial cerebellum (vermis): vol = 6		2.66	$P = 0.004$	–4, –40, –20

Anatomical structures and Brodmann areas (BA) refer to the atlas of Talairach and Tournoux (1988) except when marked with an asterisk, when they refer to the Karolinska Computerized Brain Atlas of Greitz *et al.* (1991). *P* values relating to parts A–D are corrected for multiple non-independent comparisons. *P* values relating to parts E and F are uncorrected. n.s. = not significant.

(orthography) in illiterate subjects limits their ability to correctly repeat words and especially pseudowords.

Consistent with the behavioural data, the PET activation patterns in words versus pseudowords are similar in the two groups. The first step in the process of repetition of verbal material is primary auditory analysis. This takes place in the superior temporal gyri and occurs when the subject listens to either words or pseudowords. This analysis is subsequently followed by a process of complex pattern recognition (Démonet *et al.*, 1992; Wise *et al.*, 1991; Howard *et al.*, 1992). If a subject has previous experience of the verbal material, as in real words, the word is recognized and oral production may then be biased towards lexicosemantic processing. This is likely to include storage in working memory of information which is based on global processing of the word sound or semantic content of the word. If instead pseudowords are presented, the lexicosemantic search will be unsuccessful. Therefore, oral production cannot be based entirely on stored lexicosemantic information, but must rely on efficient phonological processing. Lexicosemantic matching of words heard has been associated with activations in the left middle and inferior temporal gyri, the left inferior parietal region and the left dorsolateral prefrontal region (Démonet *et al.*, 1992; Wise *et al.*, 1991; Howard *et al.*, 1992). The absence of activation differences in the left perisylvian and region of Broca suggests that these areas were activated similarly during both word and pseudoword repetition.

It has been hypothesized that there are different phonological processing pathways, one related to oral and the another related to written language (for a general reference see Caramazza, 1997). The system related to written language allows awareness of certain aspects of the phonological components and is fully developed in literate subjects. Thus literate subjects can monitor and correct their production of pseudowords. However, when they fail to correct their production their behaviour resembles that of illiterate subjects. Similar errors arise since the production may be based on activation of the auditory-bound phonological systems, i.e. using the implicit phonological system. In the pseudoword versus word PET comparison, literate subjects activated several regions including the left anterior cingulate, right frontal operculum/anterior insula, left lentiform nucleus and anterior thalamus. This pattern of activations was not seen in the illiterate group. In contrast, the illiterate subjects activated the right middle frontal/frontopolar region (BA 10), an activation not seen in the literate subjects.

In the parallel, interactive, three-route model proposed to describe the process of word/pseudoword repetition, the phonological system plays a critical role in the repetition of pseudowords, while all three systems may be used for repetition of words, i.e. the semantic, lexical and phonological systems (Rumelhart and McClelland, 1986; Patterson and Shewell, 1987; Seidenberg and McClelland, 1989; Caplan, 1992; Martin and Saffran, 1992; Arbib, 1995; Reis and Castro-Caldas, 1997). If there is automatic engagement of all available cognitive processing pathways interacting in parallel, differences between tasks would tend to be less prominent (Cohen *et al.*, 1990; Wise *et al.*, 1991; Démonet *et al.*, 1993). It has been shown in literate subjects that incidental processing of pseudowords takes place despite non-attendance to linguistic content (Frith *et al.*, 1995). Most cognitive models of language processing consider the engagement of lexicosemantic processing to be greater in word than in pseudoword repetition. In other words, the possibility of parallel interactive distributed processing is greater in word than in pseudoword repetition. The PET results revealed an activation of the inferior parietal region in both groups during word repetition, suggesting that both groups use lexicosemantic processing. Since words but not pseudowords have semantic content, our data support the contention that the inferior parietal lobule is involved in accessing long-term semantic memory (Wise *et al.*, 1991; Démonet *et al.*, 1992).

The analysis of errors made during pseudoword repetition indicated that illiterate subjects tended to transform pseudowords into real words more than the literate subjects. This indicates that the oral production of the illiterates is based on a neural system with a different capacity for phonological processing in conjunction with a bias towards lexicosemantic processing, i.e. their parallel distributed and interactive processing is different from that of literate subjects (see also Castro-Caldas *et al.*, 1996; Reis and Castro-Caldas, 1997). The PET results revealed an absence of activations in the illiterate group (Table 2D and Fig. 2D), seen in the literate group (Table 2C and Fig. 2C), in the pseudoword versus word comparison. This suggests that illiterate subjects are unable to activate an adequately configured neural network that is involved in procedural processes (Ullman *et al.*, 1997) serving the *de novo* sequential organization of new phonological output based on phonological analysis of pseudowords. On the other hand, the activation of these structures in literate subjects (Table 2C and Fig. 2C) may be interpreted as resulting from a change in the level of phonological processing (from the implicit to the explicit form), which is related to learning alphabetic orthography. These differences between the two groups are consistent with the hypothesis that the absence of knowledge of orthography limits the ability of illiterate subjects to repeat pseudowords correctly, which is related to a failure to activate an adequately configured neural network.

Furthermore, the PET data revealed an activation in the right middle frontal-frontopolar region (BA 10) in the illiterate group in the pseudoword versus word comparison. The absence of a specific functional network which allows literate subjects to perform accurately when repeating pseudowords seems to recruit a general-purpose support system. Activation of the right middle frontal-frontopolar region has been associated with aspects of the episodic memory system, such as explicit monitoring and postretrieval processing (Tulving, 1995; Rugg *et al.*, 1996), general-purpose systems that illiterate subjects may recruit to support pseudoword repetition. A negative correlation between the activity of the frontopolar region and reading skill has also been observed in developmentally dyslexia subjects (Ingvar *et al.*, 1996).

When repeating pseudowords, literate subjects engage components of phonological processing (attention/awareness) which illiterate subjects fail to engage. The production of new motor sequences not previously learned, as in pseudoword repetition, may depend on these aspects of phonological processing. Pseudowords cannot be repeated exclusively using a lexicosemantic processing system or the type of (implicit) phonological system recruited by illiterate subjects, but also requires an organization of the phonological system like that found in literate subjects. In other words, it seems that certain aspects of phonological attention/awareness are necessary for the *de novo* sequential arrangement of verbal output. Learning to read and write, i.e. learning the visual representation of language and the rules for matching phonemes and graphemes, develops new language processing possibilities. Such acquired processing possibilities may explain the pattern of activations observed in literate subjects that was not observed in illiterate subjects. The illiterate, but not the literate group, failed to activate the anterior cingulate cortex and basal ganglia when attempting to repeat pseudowords. Only the literate group had a trained system for phonological attention/awareness driving the organization and production of motor sequences not previously learned. This is consistent with findings of previous PET studies which indicate that the left basal ganglion has an important role in language function (Aglioti and Fabbro, 1993; Poline *et al.*, 1996) and that the anterior cingulate cortex is a component of the anterior attention system (Pardo *et al.*, 1990; Raichle *et al.*, 1994). Furthermore, the anterior insular and frontal opercular activations during pseudoword repetition were only observed in the literate group. Similar activations in the anterior insular and frontal opercular regions have been observed in a PET study of declarative retrieval in which a less practised state was compared with a well-practised and hence more automatic state (Petersson *et al.*, 1997). Reciprocal connections of the anterior half of the insula include inferotemporal, temporopolar, medial temporal and mediodorsal thalamic nuclei (Mesulam and Mufson, 1985). The anterior and mid-cingulate cortices connect reciprocally most prominently to the middle part of the insular cortex. There are also widespread interconnections between the various sectors of the insular paralimbic region (Mesulam and Mufson, 1985). The posterior insula receives projections from the posterior auditory association area of the superior temporal gyrus and sends projections to the opercular paramotor cortex (Mesulam and Mufson, 1985). It has been hypothesized that the posterior insula may be a neural relay for more automatic language processes (Raichle, 1994; Mesulam and Mufson, 1985). This hypothesis is consistent with PET results indicating that activations of the posterior insula are associated with repetition of words under conditions minimizing semantic processing and with the development of automaticity in learning a language task (Petersen *et al.*, 1989; Raichle *et al.*, 1994).

The results of this study are consistent with the hypothesis that absence of knowledge of orthography limits the ability of illiterate subjects to repeat pseudowords correctly, and that this inability is related to failure to activate an adequately configured neural network. These findings are in general agreement with the hypothesis that experience through learning partly determines the development and organization of the human brain and, in particular, that language experience influences the functional organization of language-relevant systems (Neville, 1995; see also McClelland and Plunkett, 1995; Plunkett, 1997; Snowling *et al.*, 1997).

In conclusion, we present experimental evidence indicating an alteration in the functional organization of the human brain which can be correlated with the absence of early learning experiences (i.e. to acquire written language in the early years of formal education). Our study indicates that the functional neuroanatomy for language processing is altered in socially induced, non-functional illiteracy. The interpretation of the differences between groups in terms of specific language processes or increases/decreases of rCBF in a given state is complicated by the lack of a language-neutral reference state in the experimental design. However, the absence of such a reference state does not affect our main conclusion, that learning to read and write during childhood influences the functional organization of the adult human brain.

Acknowledgements

This study is part of the EU Biomed 1 programme (BMHI CT94-261) and was financed in part by grants from the Swedish Medical Research Council (8276, 9847), the Karolinska Institute, the Knut and Alice Wallenberg Foundation, the Swedish Bank Tercentenary Foundation and project STRIDE (no 352/92-JNICT). The authors wish to thank Marita Lindberg, Walter Pulka, Monica Serrander and Peter Söderholm for their assistance, the volunteers for their participation, Dr F Reis for assisting in the recruitment of the subjects, the Portuguese Embassy in Stockholm for their help, and Professors R. S. J. Frackowiak, R. J. S. Wise and C. Weiller for valuable comments on the manuscript. We also thank anonymous referee B for valuable comments on cognitive models of language.

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Received August 21, 1997. Revised October 30, 1997.
Accepted December 22, 1997

Appendix

Distribution of different types of errors during pseudoword repetition in literate and illiterate subjects

Type of error	Literate subjects	Illiterate subjects
(i) Lexicosemantic errors	2 (2%)	53 (11%)
(ii) Phonological errors		
(a) In the first or first and second syllables	42 (36%)	146 (31%)
(b) In the second syllable	31 (26%)	114 (24%)
(c) In the third or second and third syllables	27 (23%)	102 (21%)
(d) Involving the whole structure	15 (13%)	60 (13%)
Total sum of errors	117	475

(i) Examples of lexicosemantic analogies made by illiterate subjects during pseudoword repetition

Pseudoword	Lexicosemantic analogy
TRAVATA (trαυatα)	GRAVATA (grαυatα) 'tie'
TASAPO (tαzatu)	CASACO (kαzatu) 'coat'
CAPETA (kαpetα)	CABEÇA (kαbesα) 'head'
VUALHA (vuaλα)	TOALHA (tuaλα) 'towel'
BINHEILO (biρejlu)	DINHEIRO (diρejru) 'money'

(ii) Examples of phonologic analogies made by illiterate subjects during pseudoword repetition

Pseudoword	Phonological analogy
(a) Phonological errors in the first syllable or first and second syllables	
GAPNEIDO (gαpnejdu)	BACLEIDO (bαklejdu)
CILHEDE (siλedδ)	FILHEDE (fiλedδ)
(b) Phonological errors in the second syllable	
EPLARA (eplarα)	EFLARA (eflarα)
LIPALIO (lipaliw)	LIFALIO (lifaliw)
(c) Phonological errors in the third syllable or second and third syllables	
PAREPA (pαrεpα)	PARIFA (pαrifα)
COZEIPO (kuzejpu)	COZEIVO (kuzejou)
(d) Phonological errors involving the whole structure	
FEPUNES (fδpunδò)	CETUMES (sδtumδò)
TASAPO (tαzapu)	GAVAITO (gαvajtu)