
■ Exploring Dyslexics' Phonological Deficit I: Lexical vs Sub-lexical and Input vs Output Processes

Gayaneh Szenkovits^{1,*} and Franck Ramus^{1,2}

¹*Laboratoire de Sciences Cognitives et Psycholinguistique EHESS-CNRS-ENS, Paris, France*

²*Institute of Cognitive Neuroscience, University College London, UK*

We report a series of experiments designed to explore the locus of the phonological deficit in dyslexia. Phonological processing of dyslexic adults is compared to that of age- and IQ-matched controls. Dyslexics' impaired performance on tasks involving nonwords suggests that sub-lexical phonological representations are deficient. Contrasting nonword repetition vs auditory nonword discrimination suggests that dyslexics are specifically impaired in input phonological processing. These data are compatible with the hypothesis that the deficit initially affects input sub-lexical processes, and further spreads to output and lexical processes in the course of language acquisition. Further longitudinal research is required to confirm this scenario as well as to tease apart the role of the quality of phonological representations from that of verbal short-term memory processes. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: dyslexia; phonological processing; phonological deficit; verbal short-term memory

INTRODUCTION

It is widely accepted that developmental dyslexia is a neurological disorder with a genetic origin, characterized mainly by a phonological deficit at the cognitive level. According to the phonological deficit hypothesis, developmental dyslexia is a language-specific disorder stemming from an impairment in the speech processing system (Frith, 1985; Snowling, 2000; Stanovich, 1988; Vellutino, 1979). It is hypothesized that dyslexics'

*Correspondence to: Gayaneh Szenkovits, Laboratoire de Sciences Cognitives et Psycholinguistique, Ecole Normale Supérieure, 46, rue d'Ulm, 75230 Paris Cedex 05, France. Tel.: +33-1-44-32-23-62; fax: +33-1-44-32-23-60; e-mail: gayaneh.szenkovits@ens.fr; Contract/grant sponsor: Fyssen Foundation

representations of speech sounds (phonological representations) are coarsely coded, under-specified or noisy (Elbro, 1996; Hulme & Snowling, 1992; Snowling, 2000). These inaccurate representations in turn would cause reading and writing difficulties as well as the more direct phonological symptoms of dyslexia.

Symptoms of the deficit are highlighted by three main types of tasks. Firstly, dyslexics perform poorly on tasks which require phonological awareness, for instance paying attention to and manipulating individual speech sounds (Snowling, 2000). Secondly, they are ill-at-ease when required to name series of objects (rapid automatic naming) rapidly. Thirdly, their verbal short-term memory is reported to be deficient compared to controls: This is manifested by a lower memory span and poor nonword repetition, and impacts negatively on list learning, story recall, paired-associate learning, and the more complex phonological awareness tasks such as spoonerisms (Blomert & Mitterer, 2004; Tijms, 2004; Vellutino, Harding, Phillips, & Steger, 1975).

None of these tasks suffice to prove the phonological deficit hypothesis, as they all involve nonphonological components (e.g. meta-cognition, speech articulation, working memory). Nevertheless, the phonological deficit hypothesis has gained support from the fact that these three types of tasks involve phonological representations in different ways (i.e. explicit manipulation, short-term storage, retrieval), and that dyslexics often perform poorly in the three domains.

Yet, these tasks remain insufficient to fully characterize the underlying phonological deficit, as their complexity hinders the isolation of any single level of representation or processing (Ramus, 2001). Efforts to identify the underlying deficit are under way. Perhaps the most interesting hypothesis under consideration is that of a deficit in categorical perception, manifested in a less steep categorization function for speech contrasts (Adlard & Hazan, 1998; Blomert & Mitterer, 2004; Mody, Studdert-Kennedy, & Brady, 1997; Rosen & Manganari, 2001), poorer between-category discrimination as well as enhanced within-category discrimination (Serniclaes, Sprenger-Charolles, Carré, & Démonet, 2001; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004). However, these results are based on group differences. A few investigations of individual results have suggested that in fact only a fraction of dyslexics (40–50%) would have speech categorization problems (Ramus *et al.*, 2003; Rosen & Manganari, 2001; White *et al.*, in press). It is therefore not clear that this can provide the ultimate explanation for the phonological deficit.

A more basic auditory processing deficit has also been considered as a possible underlying cause for speech perception problems and the phonological deficit (Farmer & Klein, 1995; Tallal, 1980). Yet this theory does not seem to be able to account for most dyslexics' phonological deficit (Ramus, 2003). At any rate, whether the phonological deficit has a basic auditory origin or not, it needs to be characterized more precisely at the cognitive level, which is the aim of the present study.

Our approach here is to try to locate the deficit within the overall architecture of the speech processing system. A classic account of this architecture is given in Figure 1 (see Ramus, 2001 for more details).

The levels of particular interest to us here are phonological representations, either lexical or sub-lexical, input or output. The aim of the present study is to test dyslexics' phonological processing at each of these processing stages, and ask if

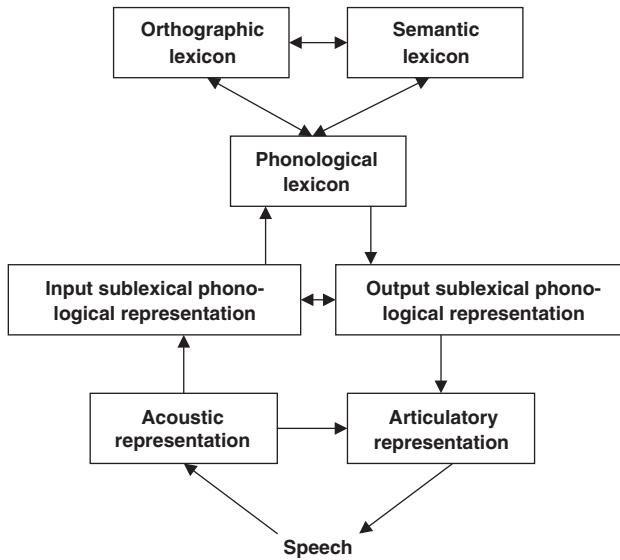


Figure 1. Model of speech perception and production adapted from Ramus (2001).

the phonological deficit could plausibly originate in just one of these stages.[†] The traditional tasks used with dyslexics point in different directions. A task like digit span involves both input and output, sub-lexical and lexical representations and is therefore not particularly decisive. Nonword repetition is more specific in that it only implicates sub-lexical levels, but both input and output. Rapid automatic naming taps more specifically the output pathway, both lexical and sub-lexical components. It is not entirely clear where phonological awareness fits within this model. It plausibly involves connections between input and output sub-lexical representations, as well as attentional and executive components external to the language system. From this brief analysis of the classic tasks, it is not entirely clear if all the aspects of the phonological deficit could be reduced to just one component of the speech system. If anything, output sub-lexical phonological representations seem implicated in all the tasks, and are therefore a plausible locus of the primary deficit. However, most authors who consider an output deficit to be primary rather situate it at the lexical level (Elbro, 1996; McCrory, Mechelli, Frith, & Price, 2005; Snowling, 2000). And as we just mentioned above, many authors would favour an 'input primary deficit' hypothesis, either at a basic auditory or at a sub-lexical phonological level (Bonte & Blomert, 2004; Mody *et al.*, 1997; Ramus, 2001; Serniclaes *et al.*, 2004; Tallal, 1980). It could also be, of course, that the locus of the primary deficit differs among dyslexic individuals. Alternatively, there might be no single primary deficit, several components of the phonological system being simultaneously affected.

[†]It should be clear by now that by 'phonological deficit' we do NOT mean a deficit of the phonological route of the reading system, but indeed a deficit of the phonological system itself (in the linguistic sense), which would in turn impact on the development of the reading system.

In order to tease apart the different hypotheses, the present study attempts to disentangle the respective contributions of lexical and sub-lexical processes on the one hand, and input and output processes on the other hand. For this purpose, we compared two types of verbal tasks: discrimination and repetition, to distinguish between input and output processes, and we used word and nonword stimuli, in order to disentangle lexical from sub-lexical processes.

MATERIALS AND METHOD

Participants

Seventeen presumed dyslexic students (4 males and 13 females; mean age: 23.5) were recruited through adverts in Parisian universities and on the basis of self-identification. Sixteen control students (6 males and 10 females; mean age: 23.8) of similar age, academic background and nonverbal IQ were also recruited. All participants were therefore university students or had higher education level. We selected this special 'high-achieving' population for the following reasons: (1) psycholinguistic tasks are demanding and less easily carried out by children, (2) to minimize possible comorbidity with other cognitive or sensory disorders, and (3) there is considerable evidence that dyslexia is a lifelong disability and that despite partial compensation of reading difficulties, dyslexic adults still present the hallmarks of the phonological deficit (see for example Bruck, 1992; Miller-Shaul, 2005). Because there is no systematic screening or diagnosis of dyslexia in France, we had to initially rely on dyslexics' self-identification, so they all went through a diagnostic battery in order to ensure that they met pre-established inclusion criteria for dyslexia.

Inclusion criteria were (1) to be a native, monolingual speaker of French, (2) to report no known neurological/psychiatric disorder or hearing impairment, (3) to have a nonverbal IQ above 90, (4a) for controls: to report no known history of reading/oral language difficulties, and to have a reading age above the ceiling (14 years old) of our standardized reading test, (4b) for dyslexics: self-identification as a dyslexic person, and a reading score 2 standard deviations below the control mean. In addition, because we specifically targeted the phonological deficit to the exclusion of any other possible cause of dyslexia (e.g. purely visual), the diagnostic battery included a set of classic phonological tasks and we verified that all dyslexics had poor performance on those.

Participants were paid 10 euros per hour of participation.

Procedure

Participants underwent three separate testing sessions. On the first one they took the diagnostic battery, then the experimental battery was split over the next two sessions (Experiments 1–4 in session 2, Experiments 5–6 in session 3). All computerized experiments were programmed and presented on a laptop computer using E-Prime (E-Prime, 2002, Psychology Software Tools, Inc.).

Diagnostic Battery

Intelligence

Nonverbal intelligence was assessed by using Raven's Advanced Progressive Matrices Set I and Set II (Raven, Raven, & Court, 1998). In this test participants are required to complete 36 matrices in time-limited condition (40 min). Set I was used to familiarize participants to the test, Set II to calculate nonverbal IQ scores derived from the percentiles of United States norms (1993).

Literacy

Reading skills were assessed by the standardized French reading test 'L'alouette' (Lefavrais, 1967). This text comprises 265 words ranging from common to rarely used words. Participants are instructed to read the text as fast and as accurately as possible. Standardized reading scores are computed by combining total reading time and errors. These combined scores are used because in languages with a more regular orthography than English, reading accuracy rapidly reaches the ceiling. Hence, reading scales have to incorporate a more fine-grained speed measure in order to detect dyslexics (Sprenger-Charolles, Colé, Lacert, & Serniclaes, 2000; Ziegler, Perry, Ma-Wyatt, Ladner, & Schulte-Korne, 2003).

Orthographic skills were tested by using a list of French words representing various French spelling problems. Participants were shown pairs of words on a computer screen and were asked to decide as fast as possible which of the words was orthographically correct.

Classic phonological tasks

Digit span: From the French version of WAIS-III (Wechsler, 2000). Forward and backward spans were used to compute age-appropriate scaled scores, to obtain a measure of phonological working memory.

Spoonerisms: Participants were auditorily presented with pairs of words and were instructed to swap the first sound of each word, then pronounce the resulting nonwords while maintaining their correct order.

Rapid Automatic Naming: Participants completed three versions of Rapid Automatic Naming: picture and digit naming adapted from the Phonological Assessment Battery (Frederickson, Frith, & Reason, 1997) (2 sheets of 50 objects or digits), and colour naming (2 sheets of 50 colours). The score is the total time taken.

Experimental Battery

In order to tease apart lexical from sub-lexical representations, and input from output representations, we designed six experiments. The first four experiments are the result of a factorial design involving 2 factors: task and material. The task was either repetition (involving both input and output processes) or auditory comparison (involving only input processes). The material consisted of either words (requiring both lexical and sub-lexical representations) or nonwords (requiring only sub-lexical representations). Finally, we carried out control versions of the auditory comparison tasks, which involved simultaneous

Table 1. Task analysis of the experiments

Task	Material	Experiment	Phonological representation levels		
			Input sub-lexical	Lexical	Output sub-lexical
Repetition	W	1	X	X	X
	NW	2	X		X
Comparison	W	3	X	X	?
	NW	4	X		?
Comparison	W	5	X	X	
Art. Supp.	NW	6	X		

X indicates the involvement of a given representation level, ? indicates uncertainty about the involvement. W: words; NW: nonwords.

articulatory suppression, in order to prevent any explicit rehearsal while performing the task. Table 1 summarizes the experimental design.

Stimuli

We used digitized speech sounds recorded in a sound-proof room on a PC computer at 22 050 Hz sampling rate. Materials were recorded by two native speakers of French, a male and a female. We used Cool Edit 2000 (Syntrillium Software, Phoenix, AZ) to verify and edit the speech recording off-line. The overall amplitude of the stimuli was equalized using PRAAT software (Boersma, 2001).

Word stimuli were French monosyllabic minimal pairs whose syllable complexity was VCC, CVC, CCV, CCVC or CVCC. The phonemic contrast was voicing for half of the cases, and place of articulation for the other half, between the following plosives (d, g, t, k) and fricatives (z, Z, s, S). Pairs of nonwords were obtained, as far as possible, by changing either one vowel or one consonant from the real words while maintaining the same syllabic structure, number of phonemes and the original phonemic contrast. We then created sequences of words/nonwords ranging from 3 to 8 words in length, with a 500 ms inter-stimulus interval (ISI), which were used in all the experiments.

Procedure and design

Participants were tested individually. They were seated comfortably in front of a computer monitor and listened to the stimuli through headphones.

In Experiments 1 and 2, participants had to repeat each sequence of words/nonwords as accurately as possible, in the correct order. On each trial, the target items appeared in phonetic transcription on a computer screen visible only to the experimenter. The experimenter could thus compare the participants' productions to the target words and code the trials on-line. Any perceptible phonetic deviation from the target item was coded as an error. Sequences were presented in blocks of increasing length (3–8 words). There were four sequences per block. Participants had the opportunity to take a short break between blocks 5 and 6 and

blocks 7 and 8. When a participant failed to respond correctly on at least two sequences out of four within the same block, the experiment was terminated (a criterion similar to that used for the WAIS digit span subtest).

In Experiments 3 and 4, each trial consisted of two sequences of words/nonwords, pronounced by two different speakers (male and female), and separated by 1 second of unintelligible 'babble' noise made of a superimposition of several speech sound tracks. This was to prevent participants from relying on echoic memory and to force them to encode the stimuli at the phonological, rather than acoustic, representation level. 'Same' trials included two identical sequences, while 'different' trials included sequences that differed by exactly one minimal pair of words/nonwords. Trials were presented in blocks of increasing length (3–8 words). There were 12 trials per block, half 'same' and half 'different'. Participants had the opportunity to take a short break between blocks 6 and 7.

In each trial, participants had to decide whether the two sequences were identical or different (AX task) and entered their response on a response box with clear labels. When a participant failed to respond correctly on at least six trials out of twelve within the same block, the experiment was terminated.

Despite the fact that the AX task required no speech output, and therefore did not theoretically involve output phonological representations, some participants might have used covert rehearsal of the sequences to enhance their performance. In order to avoid this possibility and better isolate the contribution of input phonological representations, we performed two additional control experiments.

In Experiments 5 and 6, the same design and material were used as in Experiments 3 and 4, but, in addition, participants were instructed to continuously pronounce a nonsense sequence of syllables ('ba-ba-ba...') while performing the discrimination tasks. The experimenter stayed next to the participant to ensure that he/she performed the dual task as instructed.

RESULTS

Diagnostic Battery

One self-identified dyslexic was discarded from the analyses because her reading score exceeded the inclusion threshold. All other dyslexics had a reading level between grades 5 and 9, and more than 2 S.D.s from the controls' mean. One-Way ANOVAs showed significant group differences on all variables but age and nonverbal IQ.

For the spoonerism and orthography tasks, we had both accuracy and response time measures. One-way ANOVAs revealed that dyslexic subjects were significantly poorer on both measures (Spoonerism task: $F(1, 31) = 22.8$, $p < 0.001$ and $F(1, 31) = 11.2$, $p < 0.002$; Orthography task: $F(1, 31) = 25.4$, $p < 0.001$ and $F(1, 31) = 17.2$, $p < 0.001$). In order to capture both trends in a single variable, we divided correct responses by response time in order to compute global 'spoonerisms' and 'orthography' scores. Results of the diagnostic battery are summarized in Table 2.

In order to better appreciate each participant's overall performance on literacy and phonology variables, we computed two factors. We took as literacy factor the average of reading and orthography z-scores, and as phonology factor the

Table 2. Psychometric data and results of the diagnostic battery. Table reports *mean scores* and (standard deviations)

	Controls (<i>n</i> = 16)	Dyslexics (<i>n</i> = 16)	One Way ANOVAs
Age	23.8 (4.23)	23.6 (2.96)	$F(1, 31) < 1$ ns
Nonverbal IQ ^a	116.8 (13.27)	111.0 (11.28)	$F(1, 31) = 1.41$ ns
Digit span ^b	11.5 (2.75)	7.8 (2)	$F(1, 31) = 19.35$ $p < 0.001$
Orthographic choice ^c	0.6468 (0.12)	0.3773 (0.14)	$F(1, 31) = 30.91$ $p < 0.001$
Spoonerisms ^c	0.1551 (0.067)	0.065 (0.048)	$F(1, 31) = 19.76$ $p < 0.001$
Reading ^d	70.25 (5.70)	121 (31.82)	$F(1, 31) = 44.02$ $p < 0.001$
RAN ^e			
Object	54.75 (6.37)	75.09 (13.63)	
Digit	25.5 (4.07)	37 (5.48)	
Colour	46.71 (8.75)	58.36 (10.28)	
RAN average z-score	0 (1)	-2.99 (1.28)	$F(1, 31) = 54.32$ $p < 0.001$

^a Ravens' matrices Standard Scores.^b WAIS-III^{FR} Scaled scores.^c Percentage correct responses divided by average response time (s).^d Adjusted reading time (s) for the French 'Alouette' reading test.^e Average of the two passages for each Rapid Automatic Naming test.

average of spoonerisms, rapid naming and digit span z-scores. Figure 2 shows participants' individual scores on the two factors. It demonstrates a clear split between the two groups, and the fact that every single participant in the dyslexic group is impaired on both literacy and phonological skills, as would be expected from dyslexics with a phonological deficit. The correlation between the two factors is $R = 0.763$ ($p < 0.01$), although it is attenuated by a ceiling effect on the control's group reading performance (due to perfect accuracy and to obvious biomechanical constraints on reading speed).

Experiments 1 and 2: Word and Nonword Repetition

Since we wished to compare performance between repetition and comparison tasks, and since they are on different scales (with chance level close to zero for repetition and at 50% for comparison), we decided to report and analyse all the data in terms of span, calculated as follows.

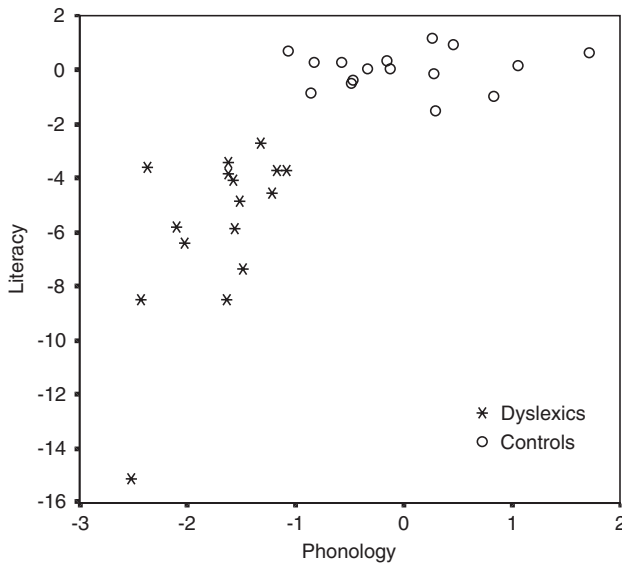


Figure 2. Subjects' distribution along phonology and literacy factors. $R = 0.763$ ($p < 0.01$).

Sequences increased in length with each block. When a participant failed to respond correctly on at least two sequences out of four within the same block, the experiment was terminated. The length of the sequences in the preceding block gave his/her span. Average spans are shown in Table 3.

One-Way ANOVAs revealed significant group differences in both word and nonword repetition ($F(1, 31) = 16.164$ $p < 0.001$; $F(1, 31) = 24.61$ $p < 0.001$, respectively), which replicates a classic result. A Repeated-Measures ANOVA with Lexicality (word vs nonword) as within-subject variable and Group (dyslexics vs controls) as between-subject variable revealed significant effects of both Lexicality ($F(1, 30) = 65.57$ $p < 0.001$), and Group ($F(1, 30) = 30.11$ $p < 0.001$) but the Group $\times$ Lexicality interaction failed to reach significance ($F(1, 31) = 1.47$ $p = 0.23$). This indicates that lexicality affected both groups to the same extent, equally decreasing their performance on nonwords compared to word repetition.

Experiments 3 and 4: Word and Nonword Comparison

Results of the auditory comparison task were also coded as word and nonword span. Participants' span was determined as a function of performance on a given block length. When a participant failed to respond correctly on at least six sequences out of twelve within the same block, the experiment was terminated. The length of the sequences in the preceding block gave his/her span. Average scores are shown in Table 3.

One-Way ANOVAs revealed significant group differences in both word and nonword comparison ($F(1, 31) = 22.06$ $p < 0.001$; $F(1, 31) = 13.1$ $p < 0.001$, respectively). A Repeated-Measures ANOVA with Lexicality and Group factors showed significant effects of Lexicality ($F(1, 30) = 23.85$ $p < 0.001$), and Group

Table 3. Results of the experimental tasks. Table reports *mean spans* and (standard deviations)

Experiment	Controls (<i>n</i> = 16)	Dyslexics (<i>n</i> = 16)	One Way ANOVAs
(1) Word repetition	5.4375 (0.96)	4.25 (0.68)	$F(1, 31) = 16.16 \ p < 0.001$
(2) Nonword repetition	4 (0.51)	3.1875 (0.4)	$F(1, 31) = 24.6 \ p < 0.001$
(3) Word comparison	6.875 (1.14)	4.875 (1.25)	$F(1, 31) = 22.1 \ p < 0.001$
(4) Nonword comparison	5.4375 (1.45)	3.8125 (1.05)	$F(1, 31) = 13.1 \ p < 0.001$
(5) Word comparison with articulatory supp.	5.5625 (1.75)	3.75 (0.85)	$F(1, 31) = 13.8 \ p < 0.001$
(6) Nonword comparison with articulatory supp.	4.6875 (1.89)	2.9375 (0.77)	$F(1, 31) = 11.8 \ p < 0.01$

($F(1, 30) = 26.01 \ p < 0.001$) but the Group $\times$ Lexicality interaction did not reach significance ($F < 1$) indicating again that nonwords were harder to memorize than words in both groups.

Experiments 5 and 6: Word and Nonword Comparison with Articulatory Suppression

Results of the comparison tasks with articulatory suppression were coded as for Experiments 3 and 4. One-Way ANOVAs revealed significant group differences in both word and nonword comparison ($F(1, 31) = 13.84 \ p < 0.001$; $F(1, 31) = 11.78 \ p < 0.01$, respectively). A Repeated-Measure ANOVA with Lexicality and Group factors showed significant effects of Lexicality ($F(1, 30) = 8.31 \ p < 0.01$) and Group ($F(1, 30) = 19.47 \ p < 0.001$) but the Group $\times$ Lexicality interaction did not reach significance ($F < 1$) indicating again that nonwords were equally harder to memorize than words in both groups.

Comparisons Between Tasks

We first performed a Repeated-Measures ANOVA on Experiments 1–4, with Lexicality and Task (repetition vs comparison without articulatory suppression) as within-subject variables and Group as between-subject variables. Analyses revealed significant effects of Lexicality ($F(1, 30) = 57.71 \ p < 0.001$), Task ($F(1, 30) = 37.55 \ p < 0.001$) and Group ($F(1, 30) = 38.59 \ p < 0.001$) and a significant interaction between Task $\times$ Group ($F(1, 30) = 5.82 \ p < 0.05$). No other two-way or

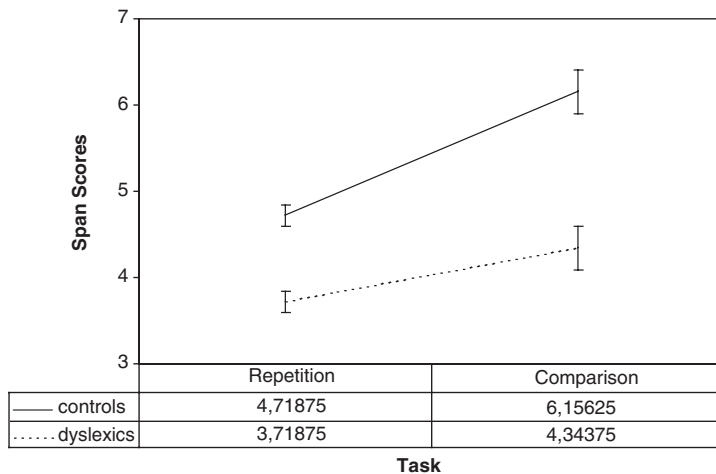


Figure 3. Group $\times$ Task interaction for Experiments 1–4.

three-way interactions reached significance. ANOVAs restricted to each group show that both groups were significantly better in the comparison task than in the repetition task (controls: $F(1, 15) = 35.6$, $p < 0.001$; dyslexics: $F(1, 15) = 7.1$, $p < 0.05$). This may be attributed to differences in task difficulty: in the comparison task, chance responses are correct 50% of the time, while in the repetition task a chance response is extremely unlikely to be correct. Yet, the significant Task $\times$ Group interaction demonstrates that, irrespective of task difficulty, dyslexics' impairment was even more pronounced in the comparison than in the repetition task. Interaction plot of data collapsed across words and nonwords are shown in Figure 3.

One might argue that the comparison task implicates more than just input phonological processing. Indeed, one possible strategy to perform the task is to covertly rehearse the first sequence while hearing the second one, thereby engaging both input and output sub-lexical phonological representations. Then, it cannot be taken for certain that the group difference specifically reflects dyslexics' impairment in input representations. For instance, it could be that controls are able to engage in covert rehearsal of the stimuli more than dyslexic participants, which might enhance their performance. The group difference would then reflect differences in output (or input–output transfer), rather than strictly input phonology. In this case, one would predict that articulatory suppression, by keeping their output phonological representations busy, would hinder this rehearsal strategy and therefore diminish the difference between the two groups.

In order to assess the role of the rehearsal component in the comparison tasks, we ran a Repeated-Measures ANOVA on Experiments 3–6 with Articulation (with vs without articulatory suppression) and Lexicality (word vs nonword) as within-subject variables and Group as between-subject variable. The analysis revealed significant effects of Lexicality ($F(1, 30) = 33.08$ $p < 0.001$), Articulation ($F(1, 30) = 22.9$ $p < 0.001$) and Group ($F(1, 30) = 32.48$ $p < 0.001$) but none of the interactions (neither two way nor three way) reached significance (all $F_s < 1$).

The overall drop in performance consecutive to articulatory suppression therefore suggests that covert rehearsal may indeed have played a role in participants' performance in the comparison task. However, the absence of a Group $\times$ Articulation interaction (and any trend thereof) indicates that this factor affected both groups equally. Therefore, it can be concluded that the results of Experiments 3–4 are not due to group differences in output phonology, but truly reflect group differences in input phonology.

Given our special interest in sub-lexical representations, we ran the repeated-measures ANOVA again restricted to the nonword tasks. When comparing Repetition and Comparison *without* articulatory suppression, the Task $\times$ Group interaction remained nearly significant ($F(1, 30) = 3.32$, $p = 0.078$). Between Repetition and Comparison *with* articulatory suppression, the Task $\times$ Group interaction also was marginally significant ($F(1, 30) = 3.74$, $p = 0.063$). Finally, between Comparison with and without articulatory suppression, the interaction was as before not significant ($F < 1$). Therefore, despite some loss of statistical power, the analysis restricted to nonwords shows exactly the same trends as before, but only marginally significant: dyslexics tend to be more impaired in nonword comparison than in nonword repetition (relative to controls), and this holds with or without articulatory suppression.

DISCUSSION

In this series of experiments, we have found that dyslexics are significantly impaired relative to controls in all the conditions we have investigated: repetition and comparison of sequences, of both words and nonwords. Like controls, they have greater difficulties with nonwords than with words. Furthermore, relative to controls, they are significantly more impaired in the comparison than in the repetition task, suggesting that their input representations might be more affected than their output representations. Their significantly poorer performance than controls in the nonword comparison task with articulatory suppression confirms the specific involvement of sub-lexical input representations in dyslexia.

Clearly the present data, together with the existing literature, are compatible with several different patterns of impairment of the adult dyslexic phonological system. As we explained in the Introduction, poor performance in one task can always be explained by deficits at different levels, since a given task seldom isolates a single component. This is the case in particular for tasks using words (involving both lexical and sub-lexical levels), as well as repetition tasks (involving both input and output levels). In this respect, our nonword comparison task seems purer, as it taps solely input sub-lexical representations (at least in its version with articulatory suppression). The demonstration that dyslexics are impaired on this task adds a new constraint to the possible pattern of impairment: It is necessary to postulate a deficit in input sub-lexical representations in order to explain our data. This does not preclude deficits in other components, of course. Indeed, rapid automatic naming involves for instance output lexical and sub-lexical representations, but not input ones, which requires postulating an additional deficit at either level.

There is no doubt that cognitive deficits of adult dyslexics are multi-faceted. Yet, dyslexia is a developmental disorder, so the state of the adult system may not

reflect that of the newborn one. For the sake of parsimony, one might want to consider the possibility that the congenital, primary cognitive deficit were restricted to a minimal core component. Let us now consider the different possibilities.

Could a strictly lexical deficit plausibly be the core deficit? Given that, according to the present results, the adult system shows a deficit at the input sub-lexical level, one would need to explain how a lexical deficit might disrupt the input representations that feed it. This is by no means impossible, given the presence of top-down feedback connections in many cognitive systems (although the existence of top-down feedback in lexical access remains hotly disputed, e.g. Norris, McQueen, & Cutler, 2000). Yet this may seem relatively indirect and remains to be demonstrated.

Alternatively, output sub-lexical representations might be the locus of the core deficit. Again, one would need to explain how the deficit might propagate from output to input representations. One possible counter-argument comes from cases of congenital dysarthria which were famously involved in the reshaping of the motor theory of speech (Liberman & Mattingly, 1985): such children, despite being entirely speechless, do not appear to have any problems with language comprehension, speech perception and even literacy (Cossu, 2003; Fourcin, 1975a,b; Lenneberg, 1962). This suggests that even the total absence of output phonological representations does not hinder the development of input ones.

On the other hand, if input sub-lexical representations were initially affected, it is obvious that this would have an impact on the development of both lexical and output representations, since input representations are the filter through which phonology is acquired. This hypothesis therefore does not present the same problems as the others. Although neither our data nor our reasoning prove that this is indeed the locus of the primary deficit, at least this seems the most parsimonious hypothesis in the light of the available data.

Experiments on adults, and even on school-age children, will never be sufficient to unambiguously establish the nature of the primary congenital deficit. Only experimentation on would-be dyslexic new-borns could. In this respect, it is quite interesting that a longitudinal study starting at birth has suggested that there is a speech categorization problem on one phonological contrast in 6-month-old infants at familial risk of dyslexia (Leppänen *et al.*, 2002; Richardson, Leppänen, Leiwo, & Lyytinen, 2003). This is obviously a far cry from a thorough investigation of these babies' phonological system, but this may be interpreted as one manifestation of a deficit in their input sub-lexical representations, well before either lexical or output representations show any sign of functionality.

Besides the arduous empirical verification of our 'specific sub-lexical input phonological deficit' hypothesis at the very first stage of language acquisition, many questions remain to be investigated, for which the present study was not tailored. Can this deficit in input phonology be reduced to a deficit in categorical perception of speech sounds, or does it affect phonological structure more globally? Is the deficit a problem with the format of these representations, with their processing, or alternatively with the short-term memory buffer which operates on them? These questions will need to be investigated in further experiments.

CONCLUSION

In summary, the present results suggest that adult dyslexics' phonological representations are impaired at many different levels. Yet, among these different levels, input sub-lexical representations are the one component whose deficit can be most unambiguously pinned down. Furthermore, postulating a congenital deficit specific to these input sub-lexical phonological representations is sufficient to explain the broader pattern of impairment observed after language acquisition. Nevertheless, more research is needed to assess whether this hypothesis is indeed correct, or whether other components of the phonological system are also congenitally impaired.

ACKNOWLEDGEMENTS

We thank the Fyssen Foundation for its financial support, Liliane Sprenger-Charolles for her help at the start of the project, Emmanuel Dupoux and the LSCP team for critical feedback.

REFERENCES

- Adlard, A., & Hazan, V. (1998). Speech perception in children with specific reading difficulties (dyslexia). *Quarterly Journal of Experimental Psychology*, 51A(1), 153–177.
- Blomert, L., & Mitterer, H. (2004). The fragile nature of the speech-perception deficit in dyslexia: Natural vs synthetic speech. *Brain and Language*, 89(1), 21–26.
- Boersma, P. (2001). PRAAT, a systems for doing phonetics by computer. *Glott International*, 5(9/10), 341–345 (<http://www.praat.org/>).
- Bonte, M. L., & Blomert, L. (2004). Developmental dyslexia: ERP correlates of anomalous phonological processing during spoken word recognition. *Cognitive Brain Research*, 21(3), 360–376.
- Bruck, M. (1992). Persistence of dyslexics' phonological awareness deficits. *Developmental Psychology*, 28, 874–886.
- Cossu, G. (2003). The role of output speech in literacy acquisition: Evidence from congenital anarthria. *Reading and Writing: An Interdisciplinary Journal*, 16, 99–122.
- Elbro, C. (1996). Early linguistic abilities and reading development: A review and a hypothesis. *Reading and Writing: An Interdisciplinary Journal*, 8, 453–485.
- Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin and Review*, 2(4), 460–493.
- Fourcin, A. J. (1975a). Language development in the absence of expressive speech. In E. H. Lenneberg & E. Lenneberg (Eds.), *Foundations of language development*, Vol. 2 (pp. 263–268). New York: Academic Press.
- Fourcin, A. J. (1975b). Speech perception in the absence of speech productive ability. In N. O'Connor (Ed.), *Language, cognitive deficits and retardation* (pp. 33–43). London: Butterworths.
- Frederickson, N., Frith, U., & Reason, R. (1997). *Phonological assessment battery*. Windsor: NFER-NELSON.
- Frith, U. (1985). Beneath the surface of developmental dyslexia. In K. E. Patterson, J. C. Marshall, & M. Coltheart (Eds.), *Surface dyslexia* (pp. 301–330). London: Lawrence Erlbaum.

- Hulme, C., & Snowling, M. J. (1992). Deficits in output phonology: An explanation of reading failure? *Cognitive Neuropsychology*, 9, 47–72.
- Lefavrais, P. (1967). *Test de l'Alouette* (2ème ed.). Paris: Editions du Centre de Psychologie Appliquée.
- Lenneberg, E. H. (1962). Understanding language without ability to speak: A case report. *Journal of Abnormal and Social Psychology*, 65(6), 419–425.
- Leppänen, P. H., Richardson, U., Pihko, E., Eklund, K. M., Guttorm, T. K., Aro, M., & Lyytinen, H. (2002). Brain responses to changes in speech sound durations differ between infants with and without familial risk for dyslexia. *Developmental Neuropsychology*, 22(1), 407–422.
- Liberman, A. M., & Mattingly, I. G. (1985). The motor theory of speech perception revised. *Cognition*, 21, 1–36.
- McCrory, E. J., Mechelli, A., Frith, U., & Price, C. J. (2005). More than words: A common neural basis for reading and naming deficits in developmental dyslexia? *Brain*, 128(Pt 2), 261–267.
- Miller-Shaul, S. (2005). The characteristics of young and adult dyslexics readers on reading and reading related cognitive tasks as compared to normal readers. *Dyslexia*, 11(2), 132–151.
- Mody, M., Studdert-Kennedy, M., & Brady, S. (1997). Speech perception deficits in poor readers: Auditory processing or phonological coding? *Journal of Experimental Child Psychology*, 64(2), 199–231.
- Norris, D., McQueen, J. M., & Cutler, A. (2000). Merging information in speech recognition: Feedback is never necessary. *Behavioral and Brain Sciences*, 23(3), 299–325.
- Ramus, F. (2001). Outstanding questions about phonological processing in dyslexia. *Dyslexia*, 7, 197–216.
- Ramus, F. (2003). Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction? *Current Opinion in Neurobiology*, 13(2), 212–218.
- Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain*, 126(4), 841–865.
- Raven, J., Raven, J. C., & Court, J. H. (1998). *Advanced progressive matrices*. Oxford: Oxford Psychologists Press.
- Richardson, U., Leppänen, P. H. T., Leiwo, M., & Lyytinen, H. (2003). Speech perception of infants with high familial risk for dyslexia differ at the age of six months. *Developmental Neuropsychology*, 23(3), 385–397.
- Rosen, S., & Manganari, E. (2001). Is there a relationship between speech and nonspeech auditory processing in children with dyslexia? *Journal of Speech Language and Hearing Research*, 44(4), 720–736.
- Serniclaes, W., Sprenger-Charolles, L., Carré, R., & Démonet, J. -F. (2001). Perceptual discrimination of speech sounds in developmental dyslexia. *Journal of Speech, Language and Hearing Research*, 44, 384–399.
- Serniclaes, W., Van Heghe, S., Mousty, P., Carré, R., & Sprenger-Charolles, L. (2004). Allophonic mode of speech perception in dyslexia. *Journal of Experimental Child Psychology*, 87, 336–361.
- Snowling, M. J. (2000). *Dyslexia* (2nd ed.). Oxford: Blackwell.
- Sprenger-Charolles, L., Colé, P., Lacert, P., & Serniclaes, W. (2000). On subtypes of developmental dyslexia: Evidence from processing time and accuracy scores. *Canadian Journal of Experimental Psychology*, 54, 88–104.
- Stanovich, K. E. (1988). Explaining the differences between the dyslexic and the garden-variety poor reader: The phonological-core variable-difference model. *Journal of Learning Disabilities*, 21(10), 590–604.

- Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, 9(2), 182–198.
- Tijms, J. (2004). Verbal memory and phonological deficit in dyslexia. *Journal of Research in Reading*, 27(3), 300–310.
- Vellutino, F. R. (1979). *Dyslexia: Research and theory*. Cambridge, MA: MIT Press.
- Vellutino, F. R., Harding, C. J., Phillips, F., & Steger, J. A. (1975). Differential transfer in poor and normal readers. *Journal of Genetic Psychology*, 126(1st Half), 3–18.
- Wechsler, D. (2000). *WAIS-III: Echelle de l'intelligence de Wechsler pour adultes—Troisième Edition*. Paris: Les Editions du Centre de Psychologie Appliquée.
- White, S., Milne, E., Rosen, S., Hansen, P. C., Swettenham, J., Frith, U., & Ramus, F. (in press). The role of sensorimotor processing in dyslexia: A multiple case study of dyslexic children. *Developmental Science*.
- Ziegler, J. C., Perry, C., Ma-Wyatt, A., Ladner, D., & Schulte-Körne, G. (2003). Developmental dyslexia in different languages: Language-specific or universal? *Journal of Experimental Child Psychology*, 86, 169–193.