Outstanding questions about phonological processing in dyslexia

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Abstract

It is widely accepted that developmental dyslexia results from some sort of phonological deficit. Yet, it can be argued that phonological representations and their processing have been insufficiently tested in dyslexia research.

Firstly, claims about how tasks tap into certain kinds of representations or processes are best appreciated in the light of an explicit information-processing model. Here, a cognitive model of lexical access is described, incorporating speech perception, reading and object recognition. The model emphasises that phonological forms of lexical items are distinct from non-lexical phonological representations

Secondly, phonology, as a linguistic discipline, teaches us that there is much more to it than phonemic categorisation and awareness. The phonological level of representation also embodies phonotactic regularities, patterns of phoneme assimilation and alternation, as well as supra-segmental knowledge pertaining to syllable structure, stress, intonation and rhythm. All those aspects are in part language-dependent, and therefore must be learnt by children in order to become proficient native speakers and listeners. If all levels of phonological representations were affected in dyslexia, dyslexic children would presumably have difficulties acquiring these aspects of their language. This prediction is as yet untested. A possible research agenda is outlined, aiming to provide a more comprehensive assessment of the phonological theory of dyslexia.

Keywords: dyslexia; phonological processing; phonology; information-processing; modelling.

The last two decades of research (from Vellutino, 1979 to Snowling, 2000) have firmly established the idea that a phonological deficit plays a central causal role in developmental dyslexia. The phonological theory of dyslexia implies that this disorder results from a specific impairment of phonological representations and processes. Even competing theories acknowledge the existence of a phonological deficit, and only argue about its specificity: they try to account for the phonological deficit through more general sensory or learning impairments (Nicolson & Fawcett, 1990; Stein & Walsh, 1997; Tallal, Miller, & Fitch, 1993).

As widely accepted as the notion of a phonological deficit is within the dyslexia community, an external observer could argue that the evidence provided in its favour is indirect and incomplete, and that potentially relevant sources of information have been ignored. The goal of this paper is to expose the "external observer" point of view, which goes as follows. 1) Both the exact locus and the nature of the phonological deficit remain to be explicitly defined. 2) It may seem surprising that the vast body of knowledge available in phonology is seldom brought to bear on hypotheses about the phonological deficit. Paying more attention to what phonology has to offer may therefore help refining and testing the phonological deficit hypothesis.
Before reviewing the current evidence for a phonological deficit in dyslexia, I feel that the interpretation of this evidence requires referring to a sufficiently detailed cognitive model of reading and language. I begin by exposing such a model, which will provide a framework for the discussion to follow.

A general model of lexical access

Tasks that have been used to argue for a phonological deficit involve speech perception, speech production, reading, writing and object recognition. The model presented in Figure 1 integrates all the cognitive components that are thought to underlie these tasks. It is directly inspired from the classic logogen model (Morton, 1969) and subsequent updates, variants and refinements (Coltheart, 1978; Levelt, 1989; Morton, 1980; Seymour, 1973), as well as from ideas coming from the linguistic literature (Chomsky & Halle, 1968; Jackendoff, 1997; Prince & Smolensky, 1993). A comprehensive review of the empirical evidence that has been presented in favour of the overall architecture and the different components of the model goes far beyond the purpose of this paper. Instead, I will try to give a feeling of how the model works and of the role of the different components in tasks of interest to us. The model is specified sufficiently vaguely not to be contentious, except for one part: the distinction between lexical and pre-lexical phonology, which will require a specific justification.

General characteristics

The basic principles at work in Figure 1 are as follows: 1) boxes stand for distinct levels of representations, 2) arrows stand for "processes" that perform a mapping (or conversion, or translation) between different levels of representations, and 3) not all conceivable boxes and arrows are shown, only those that are necessary for the present discussion. In terms of neural network models, boxes could be implemented by layers of units, whereas arrows could be implemented by connections between layers.

Only the adult state is represented. The initial state of this model remains an empirical question, but it is likely that certain levels of representation are universal and present from birth, while others are created under the influence of the environment.

The model is centred around the mental lexicon, which is divided into three parts: the brain stores not only the meaning of words (semantic lexicon), but also their phonological form (including their segmental content and stress or tonal pattern) and their orthographic form. These are three necessarily distinct levels of lexical representation that interface with different aspects of the world.

Speech perception/production

All the way from the cochlea to the primary auditory cortex, speech, like all other sounds, is encoded in a non-specific manner: this is embodied by our *acoustic representation.* At a later stage of processing, speech must be encoded in a speech-specific manner: this is a *sub-lexical phonological representation*. The phonological format is not only speech-specific but language-dependent: it varies from language to language, as exemplified by the diversity of phonemic inventories; the structure and units of phonological representations are therefore learnt by each child through exposure to his/her native language. The arrow between the sub-lexical phonological representation and the phonological lexicon represents auditory word recognition (see below).

Speech production includes the selection of the appropriate words (typically at the semantic level), the retrieval of their phonological form (phonological lexicon), their assembly into a whole phonological utterance (sub-lexical phonological level), and the conversion of this latter level into an articulatory representation that will trigger the motor commands producing speech (this is only a summarised version of Levelt's, 1989 model).[1]

Reading/writing

From the retina to the primary visual cortex, written words are encoded, like all visual stimuli, in a non-specific format: this is the *visual representation*. At some later stage, they have to be encoded in terms of their individual letters: this is a sub-lexical *orthographic representation*. Obviously, this orthographic level is not something humans are born with, and the very units of this representation (the alphabet) need to be learnt by children. The arrow from the orthographic level to the orthographic lexicon represents visual word recognition. The orthographic lexicon is the permanent storage for words, whereas the sub-lexical orthographic level is a short-term storage for any sequence of letters. Writing takes the reverse route: from the orthographic lexicon to the sub-lexical orthographic representation, and onwards to the motor commands for the hand.

The two arrows connecting orthographic and phonological representations represent grapheme-phoneme and phoneme-grapheme conversion rules (which also need to be learnt). These routes allow us respectively to read non-words aloud and to write heard non-words. The grapheme-phoneme route also provides an alternative pathway from print to the lexicon, hence the famous dual route (Coltheart, 1978). The case can be made

for the division of both phonological and orthographic representations into input and output pathways. This distinction is ignored here.

Object recognition

Objects initially follow the same general visual pathways as written words, then are eventually represented at a more specific level (*object representation*). The representation of each object is then likely connected to the semantic representation of the corresponding word. This very schematic model of object recognition is sufficient to account for picture naming tasks.

Obviously, this is not meant to be a general model of cognition. Other aspects of cognition, not shown in the model, do intervene, whether we want it or not, in the tasks we are concerned with. Attention, awareness, working memory and executive function are such components.

Lexical vs. sub-lexical phonology

The hypothesis that there are two distinct phonological levels is in contrast with both informal accounts and connectionist models of reading (Plaut, McClelland, Seidenberg, & Patterson, 1996), according to which only lexical phonology exists. However, those models don't try to account for phonological phenomena per se, but only for the contribution of phonology to reading; they happen to account reasonably well for most aspects of reading with just a lexical phonological level. But when it comes to formulating a phonological deficit hypothesis, it may be important to have a more realistic account of phonology, and this is indeed what more sophisticated models do (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Several lines of evidence from speech perception and production militate in favour of the existence sub-lexical phonology.

Conceptually, the two levels serve necessarily distinct purposes: the phonological lexicon is a permanent storage for word forms, and word forms only, whereas the sub-lexical phonological representation is a short-term storage for whatever can be represented in a phonological format, that is, words, whole utterances, and nonsense sequences of phonemes (nonwords).
Auditory word recognition and, ultimately, speech comprehension, require to find the lexical representations that match the sub-lexical sequence of phonemes. Unsurprisingly, this architecture has been incorporated into the major models of speech perception (McClelland & Elman, 1986; Norris, McQueen, & Cutler, 2000) and production (Dell, Burger, & Svec, 1997; Levelt, Roelofs, & Meyer, 1999), and these models are now supported by a considerable amount of empirical psycholinguistic evidence, although certain points are still debated. It is notable that such models actually account for little of phonology; if they attempted to account for more of it, they would feel an even greater need for a sub-lexical level, and indeed a rather sophisticated one.

In order to account for systematic variations in the way we pronounce words, phonologists typically distinguish between the *input*, i.e., the underlying phonological form of words in the lexicon, and the *output*, i.e., the sub-lexical phonological form of the

utterance that is actually going to be produced. The output is often different from the input, and discovering the rules that convert the latter into the former (our downward arrow) is one of the main tasks of phonology as a discipline.
This point will be abundantly illustrated in the third part of this article (together with psychological evidence), but let us provide a first example now. British English speakers often pronounce phrases such as “the idea is” by inserting an “r” between the last two words. This can be accounted for neither by the way those words are represented in the lexicon (speakers do not always produce “idear” or “ris”), nor by universal articulatory constraints (this does not happen in many other languages), making a language-dependent, sub-lexical phonological level the natural explanatory locus of the effect. In addition, this productive process must have a perceptual counterpart. Since English speakers do insert an “r” in “idea is”, it follows that English listeners (the same persons, of course) must mentally remove it to understand the phrase. And indeed, when they hear "the idea-r-is", they are not puzzled by the non-words “idear” or “ris”; they recognise instantly the lexical items "the", “idea” and “is” without even being aware that they heard an “r” in the first place. Again, the sub-lexical phonological level is the inevitable locus of this perceptual interpretation: it embodies the constraints of English phonology and applies them in perception to whatever comes from the auditory level and needs to be understood, and in production to whatever comes from the lexicon and needs to be articulated.

Interestingly, the distinction between lexical and sub-lexical phonology also seems necessary to the understanding of how children acquire the phonology and the lexicon of their native language. It is often hypothesised that children's initial representation of words is "holistic", i.e., it is not broken down into smaller units like phonemes (Charles-Luce & Luce, 1990; Jusczyk, 1986; Walley, 1993). However, there is a great deal of evidence that, long before they learn their first word, infants show categorical perception of phonemes (Eimas, Siqueland, Jusczyk, & Vigorito, 1971), can recognise words with a one-feature precision (Jusczyk & Aslin, 1995), and are familiar with some phonotactic and allophonic patterns of their native language (Hohne & Jusczyk, 1994; Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993; Jusczyk, Luce, & Charles-Luce, 1994; Jusczyk, Hohne, & Bauman, in press). This paradox can only be understood if one assumes that the latter tasks assess infants' sub-lexical phonological representations, which are distinct from their first representations of words. This also allows to understand why 14-month-old infants seem to be more sensitive to phonetic detail in speech perception than in word learning experiments (the two tasks tap different levels of representation) (Stager & Werker, 1997). In summary, the sub-lexical phonological representation is finely tuned to the native language in the first year of life; however, the incorporation of the relevant phonological details into lexical representations depends on word learning and takes a few more years.

Obviously, the distinction between lexical and sub-lexical phonology has direct consequences on the interpretations one can make of tasks administered to dyslexic individuals, as well as on possible models of the phonological deficit.

The phonological deficit hypothesis

Task analysis

Again, a complete review of the literature is beyond the scope of this paper. Here our goal is to provide a general task analysis in the light of the proposed model. Tasks that have been used to investigate the phonological deficit can be grouped into 6 broad categories: reading, short-term/working memory, meta-phonology, naming, speech perception, and phonological learning. Table 1 summarises the levels of representation and processes involved in typical tasks.

Reading aloud can be done by two different routes. In languages like English where the grapheme-phoneme mapping is not consistent, only regular words can be processed through the orthographic-phonological route. Irregular words are best recognised through the orthographic lexicon. By contrast, non-words are not represented in the lexicon. The only way to read them is therefore through the orthographic-phonological route, with possible help from similar words present in the lexicon. Regular words can take either route. Similarly, writing and spelling can follow these two routes in the reverse direction. Without entering into the sub-type debate (Castles & Coltheart, 1993), it can safely be said that dyslexics are typically worse than controls at *both* non-word reading and irregular word reading, suggesting a deficiency of 1) the orthographic/phonological route and/or sub-lexical phonology and 2) the orthographic lexicon. The latter may be a side-effect of a reduced exposure to print (Manis, Seidenberg, Doi, McBride-Chang, & Petersen, 1996).

Digit/word span, and non-word repetition exemplify verbal short-term memory tasks. Verbal short-term memory can be conceived as phonological representations being sustained for a period of time. In the case of digit/word span, representations can be sustained at both the lexical and sub-lexical levels, which may reinforce each other. In the case of non-words, they can only be sustained at the sub-lexical level. Consistently with this analysis, memory span for non-words is shorter than for words (Hulme, Maughan, & Brown, 1991).
Dyslexics are typically impaired at both word and non/word span, suggesting that at least sub-lexical phonology is deficient, and possibly the phonological lexicon as well.

Meta-phonological tasks come in a great variety: they typically involve explicit judgements and/or manipulations of phonemes and/or rimes, in the form of fluency, odd-one-out and spoonerism tasks. They are difficult to interpret because they involve many sub-tasks and levels of representation, as well as external resources like working memory and attention; but what seems to be central to all those tasks is the sub-lexical phonological representation (the only level where phonemes and rimes can be represented as such), and the capacity to consciously pay attention to and manipulate those representations and their constituents.

Naming tasks are often presented under speeded conditions ("rapid automatised naming") where object drawings are presented by series of 50 and must be named as fast as possible. Many dyslexics are reliably slower at this task, and this is usually interpreted as

showing that they have difficulties retrieving the phonological forms of words. However, this task does not disambiguate between lexical and sub-lexical phonological representations; a deficit at either level might produce the observed slowness.

Speech perception tasks (e.g. [ba]-[da] discrimination) focus most specifically on the sub-lexical phonological level. Indeed, they only require auditory processing, representation at the phonological level and production of a non-verbal response (e.g. same-different). It is not entirely clear whether such tasks pose problems to all dyslexics, or just to a sub-group (e.g., Mody, Studdert-Kennedy, & Brady, 1997).

Phonological learning involves associating novel verbal labels with objects or shapes; this task is meant to simulate the acquisition of new words. Again, the interpretation of dyslexics' problems with this task is made difficult by the multiple levels involved. Remembering the verbal labels (which are non-words, at least at the beginning) certainly plays a great role in this task; it remains an open question whether an additional role can be attributed to the creation of new phonological representations, and to their linking with object representations.

From this short task analysis it is quite clear that all tasks involve multiple processes and levels of representation, and therefore that no single task can unambiguously inform us on the locus of the deficit. However, the whole collection of different tasks provides converging evidence that certain representation levels are impaired in dyslexia. Indeed, it seems necessary to postulate that at least the sub-lexical phonological representation and the orthographic-phonological route are deficient in order to explain such a wide array of impairments. It can also seem plausible that the orthographic lexicon, the phonological-orthographic route and the phonological lexicon are deficient, although the tasks reviewed here are perhaps not sufficient to ascertain this.

Perhaps the greatest paradox of the phonological deficit hypothesis is that it should predict that dyslexics have trouble speaking and understanding speech, since these involve both lexical and sub-lexical phonological representations; at first sight this does not seem to be case. This observation requires several remarks.
Dyslexics, like everyone else, have infinitely far more training in perceiving and producing speech than in all other tasks such as reading, spelling, remembering digits, doing spoonerisms or discriminating syllables. One might therefore expect that their impairment would be less apparent in speech than in other tasks.
Nevertheless, it is true that dyslexics have certain problems with speech production and perception. In production, this manifests under speeded conditions, i.e., in rapid automatised naming tasks. Elbro, Nielsen, & Petersen (1994) also showed that dyslexics' pronunciation of words is less distinct than that of controls. In perception, both the lexicon and contextual information may allow to compensate for slightly inaccurate sub-lexical phonological representations. This is what happens in normal subjects when listening to speech under slightly noisy conditions. One might then predict that embedding speech in increasing amounts of noise would impair dyslexics to a greater extent than controls, if their representations are slightly degraded to begin with. This is

indeed what has been found (Brady, Shankweiler, & Mann, 1983; Cornelissen, Hansen, Bradley, & Stein, 1996).
Therefore, consistently with the phonological deficit hypothesis, dyslexics have indeed subtle difficulties in speech perception and production, but they are mild enough not to be noticeable in real-life situations. Certainly, it may happen that the phonological deficit is severe enough to provoke noticeable language difficulties. But then it is likely that the child will be characterised as having a specific-language impairment, rather than just dyslexia.

The locus of the phonological deficit

Having identified a number of levels of representations that are likely to be impaired in dyslexics, one may want to know if there is a single core deficit, from which all the others might follow in the course of development.

Traditionally, theorists have assumed that the core deficit was at the lexical phonological level. But this view relied on a model of reading and language that didn't include sub-lexical phonology, so the question of the locus was not relevant (e.g., Snowling, 2000; but see Elbro, 1996). In the light of the above task analysis, sub-lexical phonology would seem the best candidate for a core deficit. Indeed, it is the only level that is involved in *all* the tasks inspected, except perhaps for silent irregular word reading.

Let us now assume that dyslexic children have a congenital deficit at the level of their sub-lexical phonological representations, and only at this level, and let us explore the likely consequences in the course of development.
Firstly, word learning involves (among others) storing words' phonological forms in the phonological lexicon. The only way the phonological lexicon can receive such information is through the sub-lexical phonological level: if the latter is deficient, then the former is likely to become so. In particular, if certain phonological features are misrepresented or under-specified at the sub-lexical level, there is little hope that this will improve in the lexicon.
Secondly, learning to read involves learning the two-way route between the sub-lexical orthographic and phonological levels (grapheme-phoneme correspondence rules). Again, if the phonological level is deficient, routes built upon it are likely to be so too.
Finally, the orthographic lexicon also needs to be acquired and linked with the phonological lexicon. This acquisition probably relies considerably on the orthographic-phonological route: indeed, before a word's orthography is learnt and stored in the lexicon, this route is about the only way its visual form can be linked with its sound and meaning.[2] In other words, the less functional the orthographic-phonological route, the less the orthographic lexicon can be bootstrapped through reading, and the more it needs to be acquired like a purely logographic system. In addition, the orthographic lexicon needs to be built through exposure to print, which is likely to be reduced in children who experience initial difficulties with reading. One can thus expect that the orthographic lexicon of dyslexic children will be acquired more slowly and will be less complete at any given time than that of their same-age peers.
In summary, if we only assume that at birth the core deficit is located at the sub-lexical phonological level, we are able to predict that the school-age dyslexic reader will have

deficits at three additional levels: the phonological lexicon, the two orthographic-phonological routes, the orthographic lexicon, and eventually in reading and spelling of course.
This sub-lexical deficit hypothesis therefore provides a parsimonious way to explain the impairment both in reading and in the wide range of standard phonological tasks.

The obvious alternative is to hypothesise that the core deficit is located at the lexical level. A strong version of this hypothesis would be that in development the deficit remains purely lexical, and does not affect sub-lexical phonology. Then it is difficult to see why the orthographic-phonological routes would become deficient, which would make difficult an explanation of poor non-word reading. A further difficulty with this hypothesis would be to explain the poor performance of dyslexics in purely sub-lexical tasks such as non-word repetition. This strictly lexical hypothesis therefore appears less promising. A weaker version would be to say that, as the child acquires a lexicon, the lexical deficit has a certain impact on sub-lexical phonology. In this case, the development of dyslexia would be quite similar as in the sub-lexical hypothesis, after the initial stage. One way to distinguish between the two hypotheses would be to test young infants' sub-lexical phonology (see below): the lexical hypothesis should predict that it becomes affected only once the lexicon starts being acquired, that is at least after 12 months of age.

Another possible hypothesis would be of course that both lexical and sub-lexical levels are deficient from the start. Then, again, the scenario would unfold as in the sub-lexical hypothesis and the two possibilities would be hard to distinguish. In the absence of independent evidence for a congenital lexical deficit, the sub-lexical hypothesis therefore seems more parsimonious.

From this exploration of the different logical possibilities, it therefore appears that a strictly lexical hypothesis is hardly tenable. The other three possible hypotheses, although different in theory, would probably predict the same final pattern of deficiencies; in all three an early deficit at the sub-lexical level plays a crucial role. Of course, the question of the locus should eventually be settled empirically. Let us now turn to what such empirical investigations might be.

Phonology and the nature of the phonological deficit

So far I have argued that there are two distinct levels for phonological representations, a lexical and a sub-lexical one; and I hypothesise that the sub-lexical level must be deficient early in life in order to explain the full range of difficulties that dyslexics experience. Yet, the main challenge for dyslexia research still remains: to determine the precise nature of the deficiency.

Of course, specifying the nature of the deficit can only be based on an accurate model of phonological representations. Possibly the most widespread conception is that they consist of strings of phonemes, and that those of dyslexics are perhaps sparser or have an insufficient resolution, e.g. that their smallest unit of representation may be larger than the phoneme, thereby explaining their deficient phonemic awareness. A more

sophisticated view proposes that the featural definition of phonemes is under-specified, and that only phonotactic constraints allow dyslexics to reconstitute correct lexical representations (Elbro, 1996). Another theory proposes that the phonological representations themselves are fine, but that they compete excessively against each other during retrieval processes (McCrory, 2001). Alternatively, from a purely computational point of view, connectionist researchers have modelled the phonological representation by a set of interconnected units (representing phonemes or phonetic features), and the deficit by the probabilistic removal of units or connections, by the addition of noise, or by having connections decay over time (Harm & Seidenberg, 1999; Plaut et al., 1996). These different conceptions converge in that they ignore the vast body of linguistic research that exposes the full complexity of phonological representations.
Indeed, these are not just strings of phonemes, but whole hierarchical structures, at one level of which the phoneme is merely a shorthand for a bundle of features. As a consequence, the vast array of tasks described in the preceding section has only touched the surface of the phonological representations of dyslexics. At one extreme, there are the most complex and indirect tasks that can be imagined, meta-phonological tasks, involving many levels of representations, high attentional and memory loads, top-down processes, explicit awareness and manipulation of representations. At the other extreme, there are purely perceptual tasks tapping into the most basic aspect of phonology, that is phoneme discrimination and categorisation. In-between, the core of phonology is virtually unexplored.

Phonology is the study of the sounds and sound patterns used by languages to convey meaning. The diversity of phoneme inventories is well-known, but languages impose many other constraints on the utterances we may produce. One consequence of such constraints is that a given word will not always be pronounced in the same manner depending on the context: this is *phonological variation*, an example of which was given above with "the idea-r-is". Before going into the exploration of phonology, let me summarise my main point: 1) Speech sounds and sound patterns vary greatly across languages; therefore they must be learnt by children through exposure to a particular language. 2) Phonology is not simply a description of the sounds and sound patterns that can be observed in the phonological lexicon: it also describes active processes that operate on-line on representations in the course of speech perception and production. Therefore, phonology does not come freely as the child acquires the lexicon. It is a generative grammar that must be learnt in addition to the lexicon[3] (Chomsky & Halle, 1968; Jakobson, 1971; Kenstowicz, 1994). 3) If dyslexic children have deficient sub-lexical phonological representations to begin with, shouldn't they have difficulties acquiring the phonology of their native language? This prediction remains largely untested.

The point can be illustrated with another English example, place assimilation. Typically, consonants whose place of articulation is coronal (like [t], [d], [n]) often adopt the place of articulation of the following segment if it is not coronal, e.g., labial ([p], [b], [m]…) or velar ([k], [g], [ŋ]…). So the sequence "sweet girl" will often be pronounced "sweek girl", the underlying [t] borrowing the velar place of articulation of the following [g] and thus becoming [k][4]. This process is optional but widespread in British English, and it is

fully productive: it will apply to any coronal consonant followed by a non-coronal one, including in newly acquired words or non-words.
Since English speakers perform such assimilation of place, it follows that, as listeners, their phonological representations must undo the effects of assimilation. That is, when they hear "sweek girl", they must recognise the lexical item "sweet" rather than being puzzled by the non-word "sweek". And indeed, they actually hear (or think they hear) "sweet girl" (Gaskell & Marslen-Wilson, 1996). Therefore, the phenomena imposed by the phonological level of representation work both ways: in production and in perception.

Now, English children, in order to become proficient speakers and listeners of this language, must learn how place assimilation works in English (indeed if they were in a French environment, they would need to learn that there is no place assimilation, but that there is voicing assimilation). That is, their sub-lexical phonological representation must evolve, from whatever universal initial state it has at birth, to the specific English adult state which embodies and enforces phonological constraints governing phenomena such as place assimilation. Do English dyslexic children learn place assimilation as well, as fast as control children do? This question could be addressed in several different ways. First, simply by analysing the speech of dyslexics to see if there is evidence of assimilation or not. Second, the perceptual side of this phenomenon can be assessed using the paradigm of Gaskell & Marslen-Wilson (1996) (where a lexical decision has to be made after listening to priming sentences where the target words did or did not follow assimilation rules). One could also investigate whether infants at risk of dyslexia take place assimilation into account when learning words (at an age when controls do), using the word segmentation paradigm of Jusczyk & Aslin (1995).

Place assimilation is of course only one example among a great variety of phonological processes. Explaining such phenomena, their interactions, and their conditions and domains of application has led phonologists to analyse the phonological representation in terms of a highly organised hierarchical structure. Each postulated unit or level is justified by the existence of phonological phenomena that could not be explained without appealing to them.
As we mentioned before, phonemes are themselves analysed in terms of distinctive features, describing their place of articulation (such as coronal, velar and labial mentioned above), their manner of articulation (plosive, fricative, liquid etc…), whether the vocal cords vibrate or not (voicing), etc… Features are the adequate level of description of assimilation processes.
Phonemes can be distinguished by the features mentioned above, but in some languages like Finnish they can also be distinguished by their duration. For instance, "tuli" means fire whereas "tuuli" means wind and "tulli" means customs. This is incorporated quite naturally by Finnish children in their lexical phonological representations, but not by children in languages where the contrast does not exist (like English or French). Do Finnish dyslexics have difficulties learning duration contrasts? At least in this domain, there have been a few studies suggesting that indeed they do; already at birth, children at risk of dyslexia may well have difficulties perceiving the difference between "ata" and "atta", and this difficulty seems to persist until adulthood, at least for certain individuals (Richardson, Leppänen, Leiwo, & Lyytinen, in press).

Higher up, phonemes are assembled into syllables. Constraints on syllable structure capture many constraints on the possible sequences of phonemes. In most languages, each syllable includes one vowel, but in certain languages like Berber a syllable needs not include one (like [tsqssft]); in English, both simple ("the") and relatively complex syllables ("strengths") are allowed, while in Japanese only simple ones are ("hon" is one of the most complex). Again, the syllabic grammar of a given language is not simply a fact about the lexicon: it is a productive process in speech production and perception. For instance, Japanese speakers cannot produce syllables ruled out by their phonology, as exemplified by their adaptation of foreign words ("sufinkusu" for sphinx: syllabification is operated by insertion of vowels) (Itô & Mester, 1995). Similarly, they have difficulties discriminating between non-words like "ebzo" and "ebuzo", showing that syllabification by vowel insertion operates in perception as well (Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999). Naturally, Japanese speakers become so through exposure to Japanese during infancy, while English children learn to license more complex syllables. What about dyslexic children? Are they as apt to learn a syllabic grammar? A possible hypothesis would be that English dyslexics, like Japanese speakers, have difficulties representing the most complex syllables, leading them to simplify consonant clusters (probably by deleting segments). This could be tested by analysing the structure of syllables produced by dyslexic and control children (Levelt, Schiller, & Levelt, 1999) and by performing perceptual experiments like those of Dupoux et al. (1999).

Syllables can carry stress or tones. Stress typically refers to the increase of physical parameters such as duration, intensity and pitch on a given syllable. In English, most words are stressed on the first syllable (e.g., "**syll**able"). In languages like Italian, stress can be used to distinguish words that have the same sequence of the phonemes, such as **an**cora (anchor) and an**co**ra (again). The same is true in English, although much rarer (**for**bear vs. for**bear**)[5]. In those languages, listeners must store stress in their lexical representations, perceive it in order to understand which word is meant, and produce it correctly to make themselves understood. In French, however, stress is irrelevant to word recognition (because all words are stressed on their last syllable); French children therefore don't have to learn this aspect of phonology. As a result, French speakers consistently misplace stress when speaking in other languages. They are also at a loss when asked to discriminate between minimal pairs like **an**cora and an**co**ra (Dupoux, Pallier, Sebastian, & Mehler, 1997). What about dyslexics? Can they easily learn the particulars of stress in their native language? Again, this question could be tackled with relatively straightforward production and perception experiments.

Tones present similar characteristics, except that they are reflected only in the pitch contour of a syllable. For instance, in Cantonese, tone distinguishes "si" with high pitch (poem) from "si" with rising pitch (cause) from "si" with falling pitch (silk) (Clements, 1999). Obviously, both French and English listeners are "deaf" to these subtleties. What about Cantonese dyslexics?

Stressed and unstressed syllables are grouped into rhythmic units called metrical feet. In languages like English, feet comprise a stressed followed by an unstressed syllable (trochaic pattern), whereas in many other languages it is the contrary (iambic pattern). Metrical theory describes how in each language the sub-lexical phonological

representation may enforce a metrical structure on utterances, shifting stresses depending on syllable structure or stress clashes (thus, "thir**teen men**" is often pronounced "**thir**teen **men**"). How children learn the particular metrical grammar of their language is a difficult problem that has been a matter of considerable debate and theorising (Dresher & Kaye, 1990; Tesar & Smolensky, 1998). It is clear however that the acquisition of this part of phonology starts very early, as demonstrated by experiments where American infants between 7 and 9 months old show sensitivity to the trochaic pattern of English words (Jusczyk, Cutler, & Redanz, 1993; Morgan, 1996). Moreover, this sensitivity is thought to be a key element to initiate word learning; indeed babies seem to use it to recognise words in fluent speech (Jusczyk, Houston, & Newsome, 1999). Do dyslexic children show such precocious acquisition of metrical phonology? If not, could this delay or impair other stages of language acquisition? Is there any evidence of a deficient metrical phonology in dyslexic adults?

There are more levels above the foot. From the syllable to the whole utterance, prosodic phonology describes 7 hierarchically structured levels[6] (Nespor & Vogel, 1986). These levels are necessary to define the domain of application of many phonological phenomena similar to the ones we have discussed before. For instance, in the utterance "boys are sweet, girls are even sweeter", there can be no place assimilation, because "sweet" and "girls" belong to different phonological phrases. Large prosodic units are also the domain of intonation and rhythm. The end of phonological phrases (and larger units) is marked by a lengthening of the final syllables' duration and a decrease in pitch. Phonological phrases typically have one prominent word, either at the beginning (as in Turkish) or at the end (as in English): in the utterance above, made of two phonological phrases, the prominent words are "sweet" and "sweeter". Learning those prosodic regularities is important for the child, not only because it is part of her language's phonology, but also because prosodic units signal syntactic constituents and properties. Prosody can indicate focus and whether a sentence is affirmative or interrogative (in English). It can also facilitate syntactic parsing of so-called garden-path sentences like "the horse raced past the barn fell": this sentence is most incomprehensible in writing, not when uttered with the proper prosody. Since prosodic boundaries are also word boundaries, they are good cues for infants trying to segment words from the speech stream. Several experiments have shown that young infants pay attention to such boundaries (Christophe, Dupoux, Bertoncini, & Mehler, 1994) and prefer well-formed prosodic units to ill-formed ones (Hirsh-Pasek et al., 1987; Jusczyk et al., 1992). In summary, prosodic phonology constitutes another important part of what makes a proficient speaker and listener. It is acquired early and certainly plays an important role in language acquisition. It would therefore be desirable to investigate how this is tackled by dyslexics.

Discussion

This very schematic overview of phonology should have made clear to the reader that there is much more to phonology than phonemic awareness and categorisation. In retrospect, the "phonological representation" box in Figure 1 looks scandalously simplistic, and will need to be elaborated in further versions of the model.

What might the proposed investigations reveal? First, let us note that the question is a priori very open. Because phonology comprises a whole hierarchy of many different levels, it is perfectly conceivable that only some of those levels are deficient in dyslexia, while others are spared.

One question that such investigations might inform is the one concerning the locus of the phonological deficit: indeed, part of phonological knowledge belongs to the lexicon, while another part belongs to the sub-lexical level. To illustrate this point let us take the example of stress. In speech production, stress can be assigned to words at the lexical and/or at the sub-lexical level, and this varies both across languages and within each language. French is a language where stress is not contrastive (i.e., it never disambiguates between two words), because all words have their last syllable stressed. Therefore, stress is not encoded in the lexicon of French speakers, but is assigned sub-lexically to the last syllable (Dupoux et al., 1997). If French dyslexics did not correctly place stress on the last syllable, this would then be evidence for a sub-lexical (rather than lexical) prosodic deficit. In Italian, many words also have stress assigned by a sub-lexical rule (when the penultimate syllable is heavy, it bears stress, like in "co**lom**ba"). But other words haven't (when the penultimate syllable is not heavy), i.e., stress can be on any syllable, and it may serve to disambiguate between two words, like "**an**cora" and "an**co**ra": for those words, stress must be encoded in the lexicon. Therefore, a specific difficulty with predictable-stress words (like colomba) would be evidence for a sub-lexical prosodic deficit, whereas difficulty with unpredictable-stress words (like ancora) would be evidence for a lexical prosodic deficit (this is the case of the patient described by Cappa, Nespor, Ielasi, & Miozzo, 1997). English stress assignment works with a similar combination of lexical encoding and sub-lexical rules; an additional twist of English is that stress can shift in certain contexts to avoid stress clashes (like in **thir**teen **men**). Problems with stress clash avoidance in English dyslexics would then be evidence for a sub-lexical deficit. The example of stress is of course particularly remarkable because of the complex interaction of lexical and sub-lexical processes; but the point here is just that each phonological phenomenon investigated in dyslexics can be analysed in terms of the level(s) where it operates.

Questions about the nature of the deficit can also be addressed. For instance, if one takes seriously the view that the temporal resolution of dyslexics' phonological representations is below the normal range, one might predict that they would be impaired only on the fine-grain, i.e. phonemic aspects of phonology (like feature assimilation), whereas they would be spared on more low-resolution aspects such as prosody.
Quite similarly, the version of the distinctness hypothesis proposed by Elbro (1996) predicts that the deficit would be apparent at the featural/phonemic levels, but not at the phonotactic level or above. However, it should be noted that the concept of distinctness could also be extended to other phonological properties, such as the placement of stress, tone, etc…
Another possible hypothesis is that dyslexics' phonology is essentially intact, and that the only problem is one of awareness of those representations. The prediction would then be that dyslexics are normal on all the proposed tasks (but this hypothesis has difficulty explaining poor performance in less explicit tasks such as rapid automatic naming).

Investigations of dyslexics' phonology may also shed some light on theories that assume that an auditory deficit is the cause of the phonological deficit. For instance, it is claimed that excessive backward masking might underlie difficulties in perceiving short formant transitions followed by vowels (like in [ba] or [da]) (Wright et al., 1997). Other aspects of phonology would then not necessarily be affected by this kind of auditory impairment (among others, [ab] or [ad] would pose no problems to dyslexics, see Rosen & Manganari, in press). Another auditory deficit that is often mentioned is the ability to recall the order of two rapid successive sounds (Tallal et al., 1993). If this is the case, the obvious prediction (untested to my knowledge) would be that this applies to short phonemes as well: dyslexics would have problems discriminating between non-words such as [abda] and [adba], and words such as "beets" and "beast" when the consonants are short enough. One would then predict a range of difficulties with phonotactics, but not necessarily with other domains. Finally, it is also suggested that dyslexics have difficulties detecting amplitude and frequency modulations (Witton et al., 1998; Witton, Talcott, Stoodley, Green, & Stein, 2001). This particularly type of deficit would rather suggest difficulties at the prosodic level, i.e. stress/tone perception at the word level, and rhythm/intonation perception at the phrasal level. In summary, it would be most interesting if such auditory deficits, when found, could be related to the predicted phonological levels. In the opposite event, one would have to reconsider the causal role that is attributed to mild auditory dysfunction.

To conclude, I have argued here that there are good reasons to think that dyslexics have a congenital dysfunction of their sub-lexical phonology. However, there is much more to do to fully characterise the locus and the nature of the problem. A rapid overview of the body of knowledge produced by phonologists suggests many areas of potential interest for dyslexia research.

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Notes

[1] The reader might wonder where this model stands with respect to the motor theory of speech (Liberman & Mattingly, 1985). The model is compatible with it to the extent that it assumes a direct bridge between auditory and articulatory representations, in the form of the sub-lexical phonological representation. I don't feel the need to claim that phonological representations are articulatory in nature, a rather terminological point in my opinion.

[2] The only other ways are either getting the sound for free, i.e. if the word is pronounced by a teacher, or getting the meaning for free, i.e. if a picture or a definition is provided with the word. These ways are obviously more limited in that they do not allow children to learn new words by themselves simply through reading.

[3] Of course, phonology is not taught by parents and is not learnt explicitly by the child. The acquisition of phonology remains a difficult problem, but the current research suggests that much of it proceeds implicitly within the first year of life. See Jusczyk (1997) for a full review of perceptual experiments showing infants' early sensitivity to the phonology of their native language.

[4] To be precise, only the closure of the [k] will surface, not the burst, because of another constraint that prevents two consecutive bursts at the same place.

[5] In English, this is most of the time accompanied by a change in vowel quality (**re**cord [rɛkɜd] vs. re**cord** [rikoːd]), in which case stress is not the only disambiguating factor.

[6] The syllable, the foot, the phonological word, the clitic group, the phonological phrase, the intonational phrase and the phonological utterance.