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Review Article

Allophonic Theory of Dyslexia: A Short Overview

Serniclaes W*

Speech Perception Lab., CNRS & Paris Descartes University, France

***Corresponding author**

Willy Serniclaes, Speech Perception Lab., CNRS & Paris Descartes University, 45, rue des Saints-Pères, 75006 Paris, France, Tel: 33-680-230-886; Fax: 33-142-863-322; Email: willy.serniclaes@gmail.com

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Abstract

Dyslexia has three discernable sources: a visual deficit in the perception of letters, a phonological deficit in the perception of speech, and an audio-visual deficit that affects the association between letters with speech sounds. The phonological deficit in dyslexia might result from a specific mode of speech perception characterized by the use of allophonic units instead of phonemes. Here I summarize the available evidence in support of the "allophonic theory" of dyslexia. Different studies showed that the dyslexia deficit in the categorical perception of phonemic features (e.g., the place-of-articulation contrast between /b/ and /d/) is due to the enhanced sensitivity to allophonic features (e.g., the difference between two variants of /d/). A recent investigation showed that allophonic perception also gives rise to an enhanced sensitivity to allophonic segments, such as those that take place inside a consonant cluster. The implications of allophonic perception for the acquisition of the written language are discussed.

ABBREVIATIONS

VOT: Voice Onset Time; F2: Second Formant; F3: Third Formant

INTRODUCTION

Developmental dyslexia is a deficit in the acquisition of written language, in the absence of other neuro-cognitive deficits. Dyslexia has a genetic basis with a fairly large prevalence (about 6% [1]). Both genetic and environmental factors determine the development of dyslexia and these factors become progressively clearer with the results of intensive research on reading and related processes in speech perception and letter vision.

Reading is basically a matter of associating letters with speech sounds. A child normally acquires written language by reading aloud, i.e. by producing the sounds that are represented by the letters, and by writing down the letters that correspond to speech sounds [2]. In the course of learning, reading becomes progressively silent, and the actual production or perceptions of speech sounds are replaced by their internal representations in phonological units. Phonological representations are activated by the visual representations of letters when reading and they activate graphical motor commands when writing.

THE THREE SOURCES OF DYSLEXIA

The acquisition of reading and writing rests on three basic components: the visual processing of letters (or other graphical symbols), the phonological representation of speech sounds and the association between letters and phonological units ([3] see Glossary). If each of these components contributes independently to the acquisition of written language, there should be three possible sources of dyslexia: a visual deficit in graphical processing, a phonological deficit in the processing of phonemes and other phonological units, and a phono-visual deficit in the set-up of the relationships between letters and phonemes. The examination of behavioral, neuro-physiological, and genetic evidence supports this view [3].

The three different core deficit scan be expressed in different ways, in terms of perceptual, attentional or short-term memory limitations [4], giving rise to a vast array of individual differences in the manifestations of dyslexia. Several different types of visual deficits seem to coexist, some being due to low-level processing [5], some others to different kinds of attentional problems [6,7], and still others in the visual representation of words[8]. Similarly, the phonological deficit surfaces in terms of perception [9], attention [10] and memory [11] limitations. These are different manifestations of the same core deficit which takes a different form depending on the individual developmental trajectory.

ALLOPHONIC THEORY

The very nature of the phonological deficit in dyslexia, beyond its different manifestations, remains debatable. However, there is growing evidence that such deficit arises from the representation of speech sounds in "allophonic" units ([12] see Glossary). According to the "allophonic theory", the phonological deficit in dyslexia arises from a specific mode of speech perception that is characterized by the use of allophonic units, rather than phonological ones [13]. Allophonic units give a highly detailed description of speech sounds that is unnecessarily complex for accessing meaning. Even transparent writing systems - those with one-to-one relationships between phonemes and graphemes - are much too abstract for people who perceive speech with allophonic units, giving rise to major problems for the acquisition of the written language.

7. Glossary
Visual processing of letters: the ability to perceive, remember, and pay attention to relevant differences between letters.
Formant: a concentration of acoustic energy in some frequency band. Speech sounds are mainly characterized by three formants (F1, F2, F3), located in different frequency regions.
Phonological representation: mapping of speech sounds in phonological units (features and segments).
Phonological Features: elementary distinctions between speech sounds that pay independent contributions for distinguishing words and are specific to given language [15]. Examples (in English): the place-of-articulation feature differentiates sounds that are articulated at different places along the vocal tract (e.g. the b/d/g-like distinction between consonants with front/medial/back places of articulation); the voicing feature differentiates sounds that are articulated either with or without vibrations of the vocal folds (e.g. the b/p-like voiced-voiceless distinction between consonants).
Phonemes: phonological segments based on the conjunction of phonological features 15]. Examples: /b/ is both voiced and front-articulated; /t/ is both voiceless and medial-articulated, etc.
Allophones: contextual variants of a phoneme that do not pay independent contributions for distinguishing words in a given language [25]. Examples: the differences in /g/ place-of-articulation between English words such as 'good', 'great' etc; differences in /p/ voicing between English words such as 'pot', 'spot' etc.
Allophonic Features: universal acoustic-auditory features that are combined for perceiving features in a given language [42]. Example: the difference in the direction of a single formant transition, either rising or falling.

ALLOPHONIC VS. PHONOLOGICAL UNITS

Reading and writing processes call upon phonological representations of speech sounds, whatever the writing system [14]. The most basic phonological units are distinctive features, i.e. distinctions between sounds that support differences in meaning [15]. A restricted set of some ten features such as "voicing" (e.g. d/t-like distinctions), "place-of-articulation" (e.g. b/d/g-like distinctions) … allow to generate ten thousands of different words by combinations in phonemes and concatenations of phonemes.

DEVELOPMENT OF PHONOLOGICAL REPRESENTATIONS

Phonological representations are the end-product of a long-standing developmental process. At the start, before some six months of age, the child is endowed with universal features that do not depend on language [16]. For instance, infants below one-year of age perceive the difference in the direction of a frequency transition, either rising or falling, much better than equivalent acoustic differences between transitions of the same category [17]. Such difference is "allophonic": it contributes to the discrimination of articulatory movements, but it is not specific to language perception and is not specifically related to the phonology of a given language.

Allophonic features are integrated into language-specific distinctive features that fit into the phonological categories of the native language before the age of one year old [18]. Much later, not before the ages of five to six years old, phonological features are in turn grouped into phonemic segments, as evidenced by the increased precision in their perception [19-20] and the progressive apparition of phonemic awareness in pre-reading children [21].

ALLOPHONES VS. PHONEMES

The integration of universal features into language-specific ones and the grouping of the latter into phonemic segments face difficult challenges. Universal features cannot readily be used to generate the language-specific ones, and they must be "coupled" in specific ways to cope with the articulatory distinctions present in the language. Coupling means that the perception of one feature affects the perception of another one ("percept-percept" couplings: [22]). Similar difficulties arise for the concatenation of distinctive features into phoneme segments. Features correspond to different qualitative changes (i.e. place-of-articulation: change in the direction of frequency transitions) that are not synchronized in the acoustic signal, and phoneme perception can only be obtained by a temporal alignment of the features during neural processing.

Further difficulties in the build-up of distinctive features and their concatenation in phonemic segments arise from the occurrence of non-phonological features and segments in the speech signal. The coarticulation [23] between adjacent features gives rise to "allophones", contextual variants of phonemes that do not contribute independently to separate the words in the language [24,25]. By extension," allophonic features" correspond to distinctions between allophones. For instance, French voiceless stops can be produced as aspirated stops in some contexts, giving rise to a threefold voiced/voiceless/aspirated distinction, that is allophonic because voiceless/aspirated contrasts cannot be used alone to operate distinctions between French words [26]. However, such distinction is phonemic in some other languages (e.g. the threefold voiced/voiceless/aspirated distinction in Thaï).

The fact that features corresponding to a given phoneme are not synchronized in the acoustic speech signal can also create several allophonic segments in the same context, For instance in the French word /paRol/ ('speech') the frequency transitions that differentiate are not synchronized and the perceptual limits between /R/, /o/ and /l/ do not coincide with any of these transitions (Figure 1). Such discrepancies engender different vocalic segments, a prototypical /o/ surrounded by /Ro/ and /ol/ transitional segments. These two latter segments are acoustically different from the prototypical /o/ and correspond to vowels that might constitute separate phonemes in some other languages.

In summary, the development of phonological representations faces two obstacles. First, fairly complex combinations (percept-percept couplings) between universal acoustic features must take place in order to generate language-specific phonological features. Second, the acoustic features are not synchronized in the speech signal and they need to be aligned during neural processing to create phonemic segments.

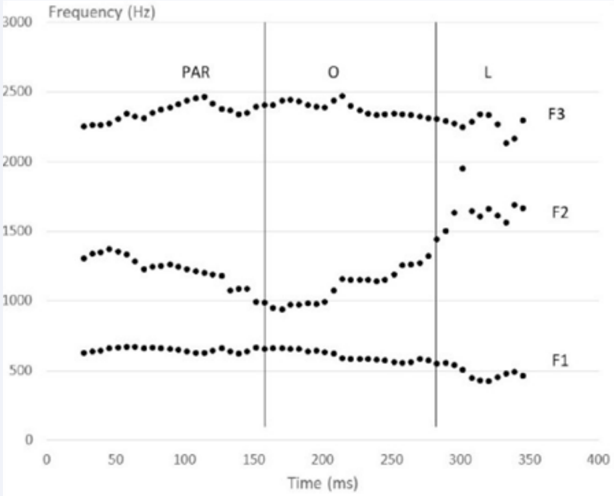

Figure 1 Formant frequencies (Praat© [27]) in the word /paRol/ produced by a French speaker. The vertical lines correspond to the perceptual limits between the /Rol/ segment and the initial (PAR) and final (L) parts of the word. F1, F2, F3 correspond to formants one, two and three, respectively.

ALLOPHONIC PERCEPTION

Different studies suggest that people with dyslexia perceive speech sounds with allophonic units. Most studies have been devoted to the perception of allophonic features but a recent study deals with allophonic segments.

Dufor et al., using PET imaging were able to show that dyslexics subjects showed sensitivity to within phonemic category cues and brain activation enhancement in the left BA6 (premotor cortex in the frontal lobe) might suggest persistence of motor coding for allophonic representations of speech [33].

Sensitivity to Allophonic Features

Different stimulus continua were used to probe differences between people with dyslexia and typical readers in the perception of allophonic and phonemic boundaries. Voicing boundaries were investigated with VOT ("Voice Onset Time"; the time interval between the release of the oral closure and the onset of laryngeal pulsing [28]) continua. Discrimination and identification data collected with French children with dyslexia show that they are sensitive to a VOT boundaries that isallophonic in this language, whereas typical-reading controls are only sensitive to the phonemic VOT boundary [12,29]. However, children with dyslexia also perceive the phonemic VOT boundary but with a lesser precision than typical-reading children.

Place-of-articulation boundaries were investigated with F2-F3 stop-vowel transitions (frequency transitions between a stop consonant a vowel) continua, generated by systematic variation of the onset frequencies of the second and third formants. In a longitudinal study with Dutch children at familial risk for dyslexia, behavioral (discrimination and identification) data collected when the children were in the first grade showed that they were sensitive to an allophonic place-of-articulation boundary, whereas typical-reading controls were only sensitive to a phonemic boundary [30]. Such behavioral differences between groups were no more present when the children were in the second grade, but they were still present in neuro-physiological responses [31]. Similar findings were evidenced for Dutch adults with dyslexia [32]. And a study with French adults with dyslexia evidenced an enhanced sensitivity to allophonic place-of-articulation contrasts in the left pre-motor cortex [33].

To sum up, the results collected in French and Dutch show that people with dyslexia: (1) are sensitive to allophonic features contrary to typical-reading controls; (2) still present such allophonic sensitivity in neural recordings after reading instruction, although it is sometimes absent in behavioral responses; (3) are also sensitive to phonemic boundaries but to a lesser extent than typical-readers.

Sensitivity to allophonic segments

Another prediction of allophonic perception is that it should also give rise to an enhanced sensitivity to allophonic segments, such as those that take place within a consonant cluster. In order to evidence an enhanced sensitivity to such allophonic variants, the duration of the acoustic segment between /R/ and /l/in the French word /paRol/ was reduced by segmenting out progressively larger portions starting from the middle [34]. As we have seen, segment between /R/ and /l/ contains a prototypical /o/ surrounded by /R/ and /l/ variants (Figure 1). If people with dyslexia indeed perceive the allophonic variants of /o/ as separate units, their paRol/ paRl boundary should be located at shorter durations along the continuum. This is indeed what was found. There was a fairly small (15 ms) but highly consistent difference in the location of the boundary, which afforded about 90% correct reclassification of the children in the dyslexic vs. control groups.

Finally, it remains possible that the enhanced sensitivity to the presence of a vocalic segment inside a consonant cluster might reflect a better temporal acuity, irrespective of allophonic status of the segment. The results of different studies indicate that people with dyslexia encode incoming information at higher cortical rates, providing a general framework to explain various phenomena, including the perception of allophonic features ("Temporal Sampling Framework" [35]) and sub-phonemic segments [36]. However, work in progress suggest that the enhanced sensitivity to short vocalic segments, as evidenced by differences in boundary location between children with dyslexia and controls on the paRol/paRl continuum, depends on their phonological status. No differences in boundary location between groups were found when the various segments that compose the natural segment in /paRol/ are replaced by a homogeneous /o/ segment (i.e. a segment with constant formant frequencies).

IMPLICATIONS OF ALLOPHONIC PERCEPTION FOR READING

In a study with English-speaking school-age children, neuro-physiological responses to an allophonic durational contrast (atta/ata), that is phonemic in Finnish, were better correlated to reading skills than those with English place-of-articulation contrasts. Importantly, better performance with the foreign contrast was related to poorer reading skills [37].

Intervention studies that proceeded by training children to discriminate a d/t phonemic VOT contrast with a better precision evidenced effects on phonemic awareness skills (in children with dysphasia [38]) and on both phonemic awareness and reading skills (in children with dyslexia [39]).

However, the specific implications of allophonic perception for reading are still not entirely clear. The competition between allophonic and phonemic representations in children with dyslexia probably affects the synchronization of grapheme and phoneme decoding in the temporal cortex, which has critical importance for learning to read [40]. Allophonic decoding is faster than phonemic decoding in children with dyslexia, as evidenced by the latencies of the electrophysiological responses [31]. The fact that allophonic activation is faster than phonemic activation in children with dyslexia might prompt the synchronization between graphemes and allophones in the temporal cortex, at the detriment of the one between graphemes and phonemes.

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