Deficits in beat perception and dyslexia: evidence from French

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Recent research has suggested a novel link between deficits in the perception of cues relevant to speech rhythm (i.e., deficits in amplitude envelope rise time processing, or beat perception) and the phonological deficits seen in most dyslexic children. In this research, we investigated whether these beat perception deficits were specific to a stress-timed language, such as English, or whether they would generalize to languages with different rhythmic properties, such as French. Eighteen dyslexics, 18 reading level controls, and 20 chronological age controls were tested on a battery of phonological tasks, reading tasks and psychoacoustic tests. The results suggest that deficits in the perception of cues important for speech rhythm may be universal in developmental dyslexia. *NeuroReport* 15:1255–1259 © 2004 Lippincott Williams & Wilkins.

Key words: Auditory processing; Developmental dyslexia; Phonological awareness; Psychophysics; Temporal envelope

INTRODUCTION

Developmental dyslexia is a specific reading and writing disorder that manifests despite normal IQ, adequate educational opportunity, and in the absence of any obvious sensory or neurological damage. The current consensus is that most dyslexics have a deficit in phonological processing reflected by poor performance in phonological awareness, phonological decoding, rapid automatized naming, and verbal short-term memory [1]. To the extent that learning to read a language depends on acquiring an understanding of both its spoken properties (onsets, rimes, phonemes) and its written form (graphemes), a deficit in phonological processing is assumed to be causal to reading difficulty [2,3].

A crucial but still debated question is whether the phonological deficit is due to a more basic deficit in auditory perception. The rapid temporal processing theory is one of the most influential theories [4] based on this idea of a direct link between acoustic processing and reading skill. According to this theory, deficits in the discrimination of spectro-temporal speech cues lead to a breakdown in phonemic discrimination, and consequent disorders in reading. The claim is that dyslexics are significantly impaired in their ability to discriminate, sequence, or remember brief auditory stimuli that follow one another within a few tens of milliseconds [4]. Given that the discrimination of the majority of phonemes, consonants in particular, depends on the ability to pick up frequency changes and voicing onsets that take place over a brief time scale, a deficit in the processing of rapid, transient cues might explain dyslexics' poor phonemic awareness and consequently difficulties in literacy acquisition.

Recently, however, the generality of the rapid temporal processing deficit has been called into question because a number of studies did not find dyslexic deficits in tasks that required the perception of very brief events [5,6]. Thus, it is probably fair to say that the fast temporal processing hypothesis can currently not fully account for the comprehensive phonological deficits found in most dyslexics [1]. One obvious shortcoming of the theory has been its narrow focus on rapid temporal processes [7].

Of course, low level auditory processing is not restricted to rapid spectro-temporal speech cues: perception of speech rhythm reflected in the slow modulations of the temporal envelope also plays an important role in speech perception. Psychophysical data suggest that the temporal envelope, i.e. the slowest frequency modulations present in the speech waveform, is important for the identification of linguistic contrasts and conveys sufficient information for its intelligibility. One example is the diminution of speech intelligibility when amplitude modulation frequencies <50 Hz are removed [8].

The temporal envelope can be modulated in terms of frequency (frequency modulations, FM) and/or depth (amplitude modulations, AM). Dyslexics seem to exhibit deficits in the envelope processing under 20 Hz both for FM and AM [9,10]. Slow FM (2 Hz), but not fast FM (240 Hz), is a strong predictor of reading skills in normally developing children [11]. It is plausible that such temporal deficits disrupt the normal development of an efficient phonological system, which in turn leads to serious problems for the beginning reader. However, at least one study failed to find deficits at 2 Hz AM [12]. Therefore, it has been suggested that the reduced auditory modulation sensitivity associated with dyslexia apparently does not extend to all slow modulations ([12], p. 871).

Low frequency and amplitude modulations are not the only cues relevant for temporal envelope processing. An equally important cue is the rise time of the amplitude envelope [13]. The rise time may denote the point in time at which a vowel or a syllable is perceived [13], and this point in time has been designated the Perceptual (P-) center. Efficient P-center perception may be crucial for representing two important linguistic sub-syllabic segments, that is the onset (the phoneme(s) preceding the vowel) and the rime (the vowel and any following phonemes) [14]. To the extent that onset-rime awareness is causally related to reading progress in normal children [3] and deficient in dyslexic children [2], it has been argued [15] that a perceptual deficit in P-center processing used to extract suprasegmental attributes of the speech stream may cause a deficit in phonological awareness and thus literacy problems.

In a previous study [15], P-center processing was investigated through a beat perception task in English-speaking dyslexics. Significant differences were found between dyslexic and normally reading children in sensitivity to AM-driven beats. In addition, individual differences in sensitivity to beats accounted for 25% of the variance in reading and spelling acquisition even after controlling for individual differences in age, non-verbal IQ, and vocabulary. From this, it was suggested that a more general P-center deficit that affects both speech and non speech processing might constitute the primary deficit in developmental dyslexia [15].

It is however possible that the need for effective P-center processing is relatively specific to the English language. Indeed, English is a stress-timed language, in which syllables can either be strong or weak; strong syllables contain full vowels, while weak syllables contain reduced vowels. Analyses of the prosodic structure of the English lexicon revealed that a very high proportion of content words in English conversational speech contain a full vowel in their first syllables [16]. Consequently, the earliest segmentation strategy, the so-called metrical segmentation strategy, might consist of language learners trying to identify potential onsets of words by detecting the occurrence of full vowels [17]. Given that P-centers and the occurrence of vowels are closely connected, the necessity of effective P-center processing could simply be a consequence of the rhythmic structure of the English language.

The goal of the present study was therefore to investigate the universality of the beat perception deficit hypothesis by studying whether French developmental dyslexics exhibit similar problems. Indeed, romance languages such as French have no distinctive lexical accent apart from systematic word final stress. In French, each syllable is important for speech segmentation [18]. Therefore, French provides an ideal test of whether a deficit in P-center processing generalizes to languages with different rhythmic properties.

We thus replicated the English study [15] using the same beat perception task with French dyslexic children and their controls. In addition, we used phonological tasks that index potential difficulties in phonological processing: phonological awareness, as estimated using rhyme and onset oddity tasks, phonological decoding, as measured by a nonword reading task, rapid access and retrieval of phonological representations, as evaluated by rapid automatized naming (RAN) of pictures, and phonological short-term memory, as measured by a short term memory task (STM, i.e., repetition of quadruplets of words). If beat perception deficits are universal, we should obtain a significant relationship between sensitivity to AM-driven beats and reading ability, and between beat perception and phonological processing abilities. As in the previous study [15], two rapid temporal processing tasks, the rapid frequency discrimination task (RFD) [19] and the temporal order-judgment task (TOJ) [4], were included to investigate similarities and differences between the P-center and the rapid temporal processing hypotheses.

MATERIALS AND METHODS

Participants: Eighteen dyslexic children (mean age ($\pm$s.d.), 137 ± 7 months) were recruited from a special boarding school for dyslexics (Les Lavandes, Orpierre, France). All had normal IQ (>85). None of the dyslexics had other language impairments or attention deficit hyperactivity disorder, as measured by standard tests (e.g. Conners scales, trail finding, Stroop test). Twenty fifth-graders (age 134 ± 8 months) were matched for chronological age with the dyslexic children ($F<1$). Eighteen first-graders (mean age 86 ± 4 months) were matched for reading age with the dyslexic children ($F<1$). Reading scores were obtained with a standardized reading test (Alouette test) [20].

Auditory processing tasks: The beat perception task was that described by Goswami *et al*. [15]. The rise times of the amplitude modulation of a 500 Hz sine tone was manipulated. The amplitude modulation was at a rate of 0.7 Hz and a depth of 50%. The underlying modulation envelope was based on a square wave. The fall time was fixed at 350 ms. Rise times varied from 15 to 300 ms (logarithmically spaced over a continuum of 40 stimuli). Sound sequences lasted for 7.857 s each. Fast increases (i.e. short rise times) lead to the percept of a beat occurring rhythmically at the same rate as the modulation. Slow increases (long rise times) lead to the percept of a single sound getting louder and softer (for examples of stimulus waveform see Fig. 1).

Performance was measured using Levitt's adaptive procedure with modifications to increase efficiency [21]. Two independent adaptive tracks were used to estimate the points on the rise time continuum at which stimuli were identified as having long rise times, 29 and 71% of the time, with a maximum of 40 trials. Tracks started at the endpoint of the continuum, with rise times of 15 and 300 ms. The categorization function was derived from all trials in a particular test, and summary statistics for slope estimated by probit analysis [22]. Flat slopes indicate less sensitivity to the rise time changes that yield the percept of beats. For testing, children indicated simply if the auditory stimulus was formed by one or two sounds [15]. As in the original study, we used cartoon characters (Asterix and Obelix) to represent the two response conditions.

The RFD task described by Tallal and Piercy [19] was used. The stimuli were two vowel-like 50 ms complex periodic tones (rise and fall times of 5 ms) with fundamental frequencies of 100 and 305 Hz. Every trial consisted of two stimuli presented sequentially with an interstimulus interval ranging from 5 to 500 ms. The task was to tell whether stimuli were the same or different. The same adaptive procedure was used as for beat perception task, but children responded by indicating same or different. Flat slopes indicate greater difficulties to discriminate stimuli with short ISI.

For the TOJ task, two stimuli readily identifiable without prior training as a dog bark and a car horn were used. The dog bark was aperiodic, whereas the car horn was periodic with a fundamental frequency of 400 Hz. Starting from sounds accompanying a children's computer game, various manipulations of amplitude envelope and duration were used to create stimuli with a total duration of 115 ms each, with rise and fall times of 5 ms. The continuum of sounds consisted of 204 stimuli in which the stimulus onset asynchrony varied from +405 ms (horn leading dog) to −405 ms (dog leading horn) in 4 ms steps. Stimuli were allowed to overlap to the degree necessary to create the specified stimulus onset asynchronies. For testing, the same adaptive procedure was used as for the beat perception task, but children indicated simply which sound they heard first. Flat slopes indicate poor discrimination performance.

Phonological processing tasks: In the non-word reading task, children had to read 60 non-words as quickly and accurately as possible. Non-words were randomly presented on a computer screen. Errors and response times were collected.

For the oddity task, children listened to a set of three words binaurally over headphones and had to find the odd word. The odd word was either the word which did not rhyme with the two others (oddity rime task; e.g. /rar/, /gar/, /*fam*/), or the word which did not begin with the same consonant (oddity onset task; e.g. /lak/, /lim/, /*pan*/). Accuracy data were collected. The oddity rime task and the oddity onset task, composed of 18 triplets each, were performed in two separate sessions.

The RAN task required children to name familiar pictures as quickly and accurately as possible. Two sets of five pictures were semi-randomly presented ten times each on a paper sheet. The time taken to name the fifty pictures was measured. The STM task required children to repeat a set of four words read aloud by the experimenter. Twenty sets were randomly presented. Errors were collected.

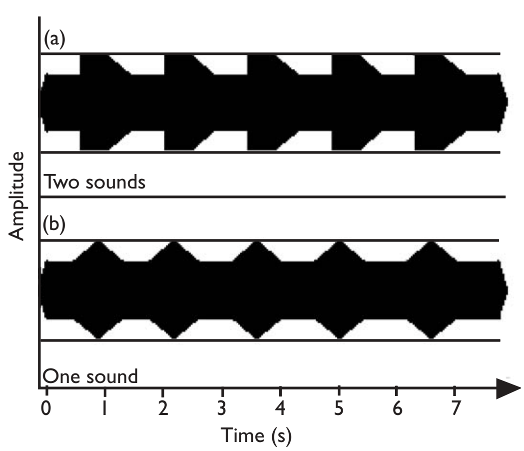

Fig. 1. Examples of the stimulus wave form for rise times of 15 ms (**a**) and 300 ms (**b**).

RESULTS

Mean values on all tasks are presented in Table 1 for dyslexic children, and controls matched for reading level (RL) and chronological age (CA). Separate statistical analyses were performed to compare dyslexics with either RL or CA controls.

Dyslexics were significantly worse than CA controls on all but two critical variables, TOJ and RFD. However, on the RFD task, differences between dyslexics and CA controls approached significance ($p < 0.10$). In comparison with RL controls, only non-word reading produced significant differences (probably because the dyslexics were receiving individual phonological remediation). Importantly, dyslexics exhibited significantly flatter slopes in beat perception than CA controls. Figure 2a presents a scatter plot showing how well the slopes separate the three groups. Figure 2b shows the relationship between beat perception and reading performance.

It was of crucial interest to evaluate the extent to which deficits in beat perception and RFD processing predicted reading and phonological processing. In addition, it was of interest to see whether one task still accounted for significant amounts of variance in reading and/or phonological performance once the contribution of the other task had been partialled out. Thus, a series of two-step fixed-entry multiple regressions was computed on the data set (56 children). The dependent variables were reading ability, oddity errors, non-word reading errors and latencies, RAN and STM. The independent variables were either (1) RFD slopes, (2) beat perception slopes or (1) beat perception slopes, (2) RFD slopes. All analyses are presented in Table 2.

Beat perception slopes accounted for a greater amount of variance in reading than did RFD slopes (36% *vs* 16% of the variance). Moreover, beat perception performance strongly predicted phonological awareness (oddity), nonword reading, STM, and RAN even if RFD was partialled out. In

Table 1. Mean (±s.d.) performance for dyslexics (DYS) and controls matched for reading level (RL) and chronological age (CA) in all tasks.

	DYS	RL	CA	DYS-RL	DYS-CA
Reading score	85.72±10.25	94.39±28.06	141.75±19.95	ns	$p<0.0001$
Beat perception (slope)	−0.056±0.057	−0.026±0.040	−0.121±0.061	ns	$p<0.001$
RFD (slope)	−0.249±0.938	−0.241±0.939	−1.107±1.657	ns	ns
TOJ (slope)	−0.045±0.043	−0.033±0.026	−0.041±0.027	ns	ns
Reading non-word (%Err)	30.98±17.64	23.63±11.22	7.03±3.70	$p<0.001$	$p<0.0001$
Reading non-word (ms)	1782±444	1578±446	888±137	$p<0.001$	$p<0.0001$
Oddity (%Err)	21.14±15.37	19.29±10.71	4.58±4.53	ns	$p<0.0001$
RAN RT (sec.)	74.38±16.07	76.44±16.08	40.04±6.91	ns	$p<0.001$
STM (%Err)	8.78±6.15	12.12±9.25	5.46±9.66	ns	$p<0.05$

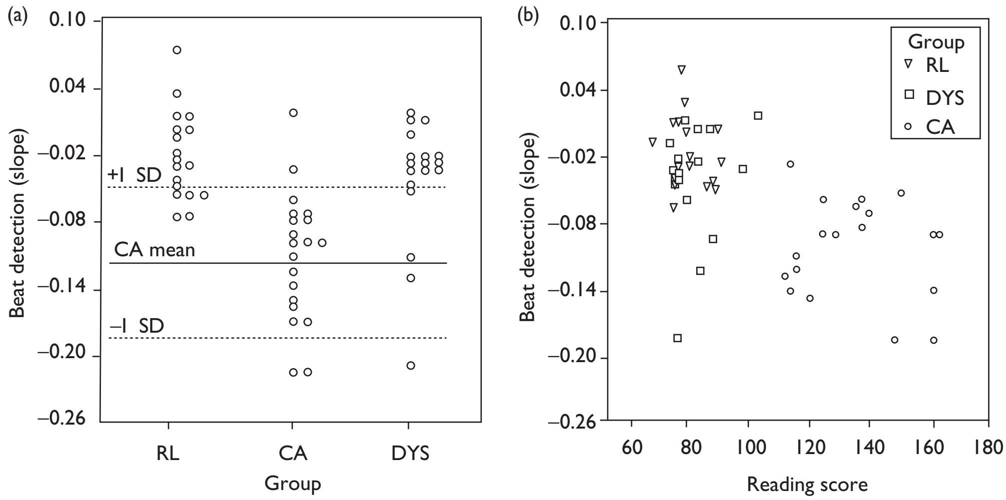

Fig. 2. Individual scatter plots of beat detection performance across the three groups (**a**) and correlations between beat detection and reading (**b**).

Table 2. Percentage of variance in reading, phonological awareness (oddity), non-word reading, STM, and RAN explained by the different independent variables in separate fixed-entry multiple-regression equations.

	Dependent variable (columns show separate equations), R^2					
	Reading	Oddity	Reading non-word (Err)	Reading non-word (RT)	STM	RAN
Step 1: RFD	0.16**	0.10*	0.08*	0.03	0.08*	0.08*
Step 2: Beat perception	0.31***	0.14**	0.11**	0.24***	0.02	0.16**
Step 1: Beat perception	0.36***	0.17**	0.14**	0.26***	0.07*	0.19**
Step 2: RFD	0.10*	0.06*	0.05	0.01	0.04	0.05

*$p<0.05$; **$p<0.01$; ***$p<0.0001$.

contrast, RFD exhibited only weak correlations with reading and oddity once beat perception was partialled out.

DISCUSSION

Results clearly show that French dyslexics exhibit a beat perception deficit. The magnitude of this deficit was strikingly similar to that previously found in English dyslexic children [15]. Moreover, beat perception strongly predicted word and nonword reading, and this was even the case when other temporal processing variables, such as RFD, were partialled out. RFD predicted a smaller amount of variance than did beat perception and did not differ significantly between groups. This suggests that beat perception measures tap more strongly into processes that are important for reading development than rapid temporal processing measures.

At this point, we can only speculate that detecting cues important for speech rhythm, such as the AM-driven beats investigated here, plays a different role in word representation than rapid temporal processing. Our hypothesis is that the changes in rise time that yield the percept of beats are intimately linked with the perceptual moments of occurrence of vowels. Thus, these beats provide information about the structure of the syllable specifying which vowel is being heard, and which phoneme(s) precede(s) or follow(s) this vowel. This may be important for the initial setting-up of well-specified phonological representations, long before the child learns to read. Recent electrophysiological evidence from German kindergartners at risk for dyslexia supports the view that early phonological representations are degraded [24], with related evidence that atypical neural representation continues into adulthood [25]. To the extent that onset-rime awareness is causally related to reading progress in normal children [2,3], a perceptual deficit in beat perception would inevitably cause impaired phonological representations to develop, with subsequent difficulties in representing phonemes.

CONCLUSION

The goal of the present study was to test whether beat perception deficits found in English dyslexic children [15] were due to the particularities of the stress-timed English language. Our results show a reliable beat perception deficit in French, a language with different rhythmic properties. A recent study with Norwegian dyslexics also shows that the accurate perception of slower frequency and amplitude changes is indeed a strong predictor of reading skill regardless of the language that is being learned [23]. Altogether, these findings suggest that deficits in the perception of speech rhythm and contour, as reflected in the slow modulations of the temporal envelope, are universal in developmental dyslexia.

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