CONTRIBUTION OF AUDITORY TASKS TO DYSLEXIA SCREENING

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ABSTRACT

Dyslexia is a specific disorder of language. Research on the origin of dyslexia has led to multiple hypotheses and various rehabilitation treatments. This paper evaluates the ability of different auditory tasks to screen dyslexia. Three tasks are tested: a temporal modulation transfer function task where the detection thresholds of sinusoidal amplitude modulation applied to a noise carrier are measured and identification and discrimination tasks of two natural syllables /ba/-/pa/ to evaluate the categorical perception skills in children with developmental dyslexia. The results obtained in dyslexics and normal readers are compared. Statistical analyses (Mann-Whitney test and logistic regression model) are performed in order to evaluate the contribution of these tasks to dyslexia detection. This study includes 35 dyslexic children and 78 normal readers.

1. INTRODUCTION

Developmental dyslexia affects about 5% of school age children in France. It is traditionally defined as an enduring and heavy impairment of reading ability in spite of normal intelligence and adequate educational opportunities [1]. Dyslexics can have some associated deficits like: attention deficit, visuo-attentional deficit, auditory and memory deficits. Researches led on dyslexia origin have conducted to multiple theories (phonological theory [2], auditory theory [3], cerebellum theory [4], magnocellular theory [5]). The aim of this study is to identify the contribution of auditory tasks to dyslexia screening. Auditory hypothesis is based on the empirical finding that 25-35% of dyslexic children are impaired in their ability to discriminate rapidly presented acoustic stimuli [3]. According to this hypothesis, this impairment disrupts the ability of children to develop the perception of the fast acoustic patterns of speech and leads to prejudice phonological processing. A temporal modulation transfer function (TMTF) based method [6] has already shown that the perception of the temporal cues may not be preserved in dyslexic children who have poor speech identification. The speech intelligibility depends heavily on the integrity of the temporal envelope (low frequency amplitude modulations in speech, the average syllabic rate being 3-4 Hz). Moreover, previous studies have shown that children suffering from developmental dyslexia have a deficit in categorical perception of speech sounds [7]. The categorical perception corresponds to the degree to which acoustic differences between variants of the same phoneme are less perceptible than differences of the same acoustic magnitude between two different phonemes [8]. In this work, we tested the contribution of three auditory tasks to identify dyslexia.

2. METHOD

2.1 Participants

Ninety one children from 5 classes of French elementary school (1 class of 2nd year and 4 classes of 3rd year) took part in this study during class hours. Thirteen children of this group had a poor reading level (more than 18 months below their chronological age). They were excluded from the study in order to keep a group of normal readers. The average age of the 78 remaining normal readers (38 boys and 40 girls) was 9 years (Standard Deviation (SD) = 7 months), their lexical age was 9 years and 3 months (SD = 1 year and 4 months). Their reading level was estimated by the "Alouette test" [9], which evaluates a lexical age (reading level) from the reading of a test in 3 minutes. The level is evaluated by the speed and the accuracy of reading.
Thirty-five dyslexic children (22 boys and 13 girls) were diagnosed during a specialized hospital consultation. Their average age was 9 years and 7 months (SD = 7 months) and their lexical age was 7 years and 6 months (SD = 12 months). All the children included in this study were exempt of any major deficit of attention, oral language, motility, visual or auditory acuity. Their Intellectual Quotient (IQ) is above 80 points.

2.2 Perception of temporal cues (TMTF task)

We propose to assess dyslexics' sensitivity to the temporal envelope in measuring the auditory temporal modulation transfer function (TMTF) which consists in determining the modulation depth threshold above which the listener detects the sinusoidal amplitude modulation applied to a noise carrier as a function of modulation frequency. As modulation of white noise does not affect its long term magnitude spectrum, the detection is only based on temporal envelope cues.

2.2.1 Stimuli

Participants had to detect the presence of a sinusoidal amplitude modulation applied to a white noise carrier, for three modulation frequencies f_m (f_m = 4, 16 and 128 Hz). Two signals (standard stimulus and target stimulus) were successively randomly produced. The standard stimulus was a white noise $n(t)$ (without modulation) and the target stimulus was the amplitude modulated white noise. The equation of the target $s(t)$ is:

$$s(t) = c[1 + m\sin(2\pi f_m t)]n(t) \qquad (1)$$

where m is the modulation depth ($0 \le m \le 1$) and c the multiplicative compensation term [10] to keep the same overall power for target and standard stimuli. These two stimuli had a 500 ms duration including 25 ms rise/fall times shaped as a raised cosine function. The inter-stimulus interval was 500 ms.

2.2.2 Procedure

On each trial, for a given modulation frequency, the target stimulus and the standard one were presented to the listener who had to identify the modulated stimulus (target stimulus). The modulation depth *m* was estimated using the adaptive forced-choice method on two intervals: 2down-1up and 2up-1down interval (noted 2I-2AFC). No feedback was given after each trial. The *m* variation (between two consecutive trials) depends on the response of the listener to the previous trial. The adaptive method is a successive variation of the *m* level (up-down variation). The 2down-1up criterion consists in reducing the *m* level after two consecutive correct responses (good identification of the target) and in increasing it after a wrong response (identification of the standard stimulus instead of the target stimulus). The step size of *m* variation was initially 4 dB and was reduced to 2 dB after the two first reversals. This procedure estimates the modulation depth *m* necessary to obtain 70.7% of correct detection [11]. The TMTF task stops after 14 inversions and the threshold *m* for detecting sinusoidal amplitude is calculated by the mean of the last 10 reversals. For each frequency, this threshold was determined twice and only the best was retained in this study. The worst threshold is 0 dB which corresponds to a modulation depth of 1 (100% modulated noise). The more negative *m* in decibels, the better the detection depth threshold.

2.3 Categorical perception skills (VOT tasks)

To evaluate categorical perception skills in dyslexic children, two exercises were proposed: an identification task where children had to identify syllable, /ba/ or /pa/, and a discrimination task where they had to discriminate a pair of /ba/-/pa/ syllables along a voice onset time (VOT) continuum. VOT is the time between the release of the consonant and the start of vocal fold vibration (voicing); it is measured in milliseconds and quantifies the degree of phonetic voicing.

2.3.1 Stimuli

Categorical perception skills were evaluated using a VOT continuum whose extremities are constituted of two syllables /ba/ and /pa/ which differ by their VOT and intermediate syllables which allow to link the extremities using a progressive variation of 10 ms. By convention, when voicing starts before the release of the consonant, VOT is negative; when voicing and consonant release happen simultaneously, VOT equals 0 ms; when voicing starts after the release of the consonant, VOT is positive. A difference of 20 ms between VOT values of two syllables is perceptible only if the syllables belong to distinct phonemic categories. The syllables /ba/ and /pa/ differ by respectively negative and positive VOTs. The production of several intermediate VOT values generates a continuum of syllables perceived as either /ba/ or /pa/. In this study, the continuum ranged from -40 ms to 40 ms and was generated using 3 reference French natural syllables: /ba/, /pa/ and /pha/ with respectively a VOT of -117 ms, +13 ms and +70 ms (see Figure 1).

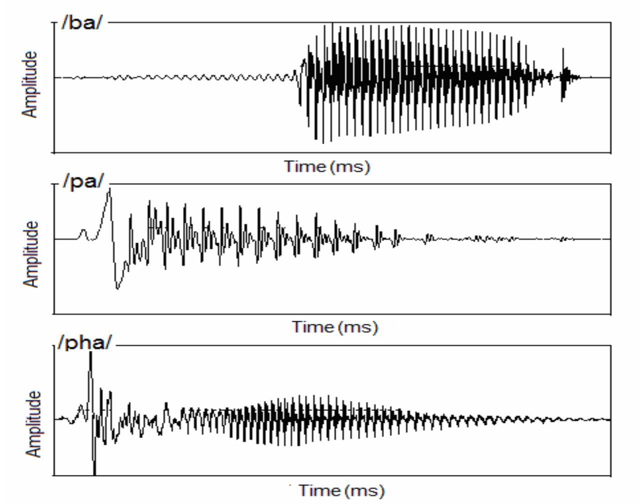

Figure 1 – French natural syllables, respectively /ba/, /pa/ and /pha/.

To make a positive VOT, a part of /pha/ VOT was selected and inserted in /pa/ syllable. For the negative VOT, a part of /ba/ VOT was introduced in the beginning of the /pa/ syllable. The 0 point of continuum was realized in deleting the burst of /pa/ syllable. Nine stimuli with respectively a VOT of -40 ms, -30 ms, -20 ms, -10 ms, 0 ms, +10 ms, +20 ms, +30 ms, and +40 ms were created.

2.3.2 Procedure

Two exercises were proposed to the participants: an identification task and a discrimination task. In the identification task, the nine stimuli of the continuum were randomly presented 10 times to the listener. For each stimulus, the listener indicated if he (she) heard /ba/ or /pa/ syllable. In the discrimination task, 7 pairs of syllables which differ by a VOT of 20 ms and 9 pairs of syllables which have the same VOT value were randomly presented 8 times each. For each pair, the listener indicated whether the syllables were identical or not.

2.3.3 Variables

- Identification variables

Identification task was evaluated through two variables: the slope of the identification function adjusted by a sigmoid function and the identification threshold.

- *Slope*

This task provides the number σ of given /pa/ responses according to the VOT values. To determine the slope of the curve $\sigma(x)$ (where x represents the value of the VOT) at the phonemic boundary, the curve was adjusted by a sigmoid function (Equation 2).

$$\sigma(x) = \frac{a}{\left(1 + b.e^{-c.x}\right)}. \qquad (2)$$

The 3 parameters of this function (*a*, *b* and *c*) are estimated by using Nelder-Mead algorithm [12]. The parameter *c* corresponds to the slope of the curve.

- *Identification threshold (T)*

It is measured at the inflexion point of the slope by Equation 3.

$$T = -a.b.\frac{-e^{-c.q} + e^{-c.(q+10)}}{\left(1 + b.e^{-c.(q+10)}\right)\left(1 + b.e^{-c.q}\right)} \qquad (3)$$

where *a*, *b* and *c* are the parameters of the sigmoid function and *q* the abscissa of the inflexion point. Figure 2 illustrates an example of the observed identification function and the adjusted function.

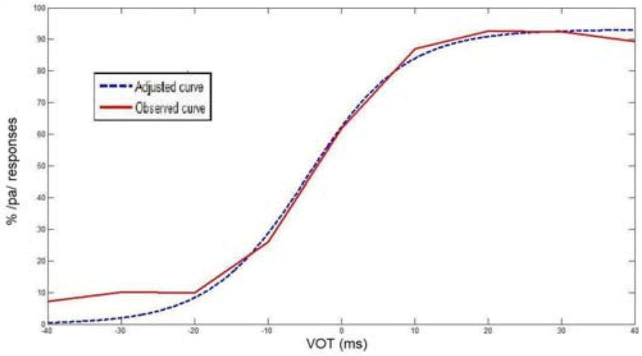

Figure 2 – Observed identification function and adjusted curve using a sigmoid function.

- Discrimination variables

The categorical perception is evaluated by the difference between the percentages of correct discrimination directly observed from the discrimination task (CD_OB) and those expected according to the results of the identification task (CD_PR).
The observed percentages of correct discrimination (CD_OB) are calculated using Equation 4.

$$CD\_OB(S_i,S_j)=\frac{16-D(S_i,S_i)-D(S_j,S_j)+2D(S_i,S_j)}{0.32} \quad (4)$$

where $D(S_i,S_j)$ is the number of responses “the syllables are different” given by the listener for each pair of syllables (S_i,S_j).
The expected scores of the discrimination task (expected number of responses “the syllables are different” for each pair of syllables) are estimated by the results obtained on the identification task (number of responses “the syllable is /pa/” for each syllable) and using Pollack and Pisoni prediction method [13] (Equation 5).

$$P(S_i,S_j)=I(S_i).(10-I(S_j))+(10-I(S_i)).I(S_j) \quad (5)$$

where $I(S_i)$ is the number of responses “the syllable is /pa/” for S_i syllable and $P(S_i,S_j)$ is the expected number of responses “the syllables are different” for each pair of syllables (S_i,S_j).
The expected percentages of correct discrimination (CD_PR) are calculated using Equation 6.

$$CD\_PR(S_i,S_j)=\frac{200-P(S_i,S_i)-P(S_j,S_j)+2P(S_i,S_j)}{4}\,. \quad (6)$$

In this way, we obtain 7 variables evaluating the difference between observed and expected percentages of correct discrimination for each pair of syllables (7 pairs of syllables).

2.4 Statistical analysis

2.4.1 *Analysis of discriminatory properties of individual variables*

A Mann-Whitney test was used to compare the results obtained by normal reader children and children with dyslexia on each auditory variable. This nonparametric test compares the distributions of a variable in two independent samples. A 0.1 significance level was chosen to state whether each variable was discriminative: $p > 0.1$ indicates that the medians are equal in both groups (the variable is not discriminative), $p < 0.1$ indicates that the medians differ between both groups (the variable is discriminative).

2.4.2 *Logistic regression*

The logistic model was chosen for modelling the probability of being dyslexic: the logit of the conditional probability of being dyslexic was modelled by a linear combination of the scores obtained on the different tasks (represented by vector *X* in Equation 7).

$$\log\left[\frac{P(dyslexic/X)}{1-P(dyslexic/X)}\right]=\alpha+\beta X+\varepsilon\,. \quad (7)$$

This model is robust to non-normal distributions of explanatory *X*. For each individual of the sample, the probability of being dyslexic is estimated from the model as:

$$P(dyslexic/X)=\frac{\exp[\alpha+\beta X]}{1+\exp[\alpha+\beta X]}\,. \quad (8)$$

The decision rule derived from this function was as follows: if the probability of being dyslexic is greater than 0.5, the subject is classified as dyslexic, otherwise he (she) is classified as non-dyslexic.
All the variables derived from the auditory tasks are not necessarily linked to the dyslexia status of the children, so that some of them may induce confusion in the predictive model and reduce its predictive accuracy. Moreover, our objective is to measure in which manner the auditory tasks can globally screen dyslexia but also, which of them are the most relevant. For that purpose, a selection procedure based on Akaike's Information Criterion (AIC) [14] was implemented. This criterion allows comparing models with different numbers of estimated parameters by using a complexity-penalized likelihood to evaluate the goodness of fit of the models. The model with the lowest AIC is the best. In the stepwise selection process, the variable introduced into the model at each step is the variable which minimizes AIC. As in any stepwise selection, variables that were previously introduced may be removed after each new variable is introduced, if they are no more significant.

2.4.3 *Performance estimation*

As the purpose was to predict group membership, the classification accuracy of the resulting function of logistic regression was assessed through the classification matrix which compares classification groups to actual groups. The overall percentage of children correctly classified (hit ratio), the sensitivity (detection rate of dyslexic children), the specificity (detection rate of non-dyslexic children), the false-positive rate (percentage of children classified as dyslexic who are actually not dyslexic) and the false-negative rate (percentage of children classified as non-dyslexic who are actually dyslexic) were estimated using cross validation.

3. RESULTS

3.1 Descriptive abilities of auditory tasks

3.1.1 Detection thresholds of sinusoidal amplitude modulation

For each group, we computed the mean of modulation thresholds, expressed in decibels. The results obtained for each frequency (4, 16 and 128 Hz) are not significantly different. For the two groups, the TMTF displays a typical band-pass characteristic. This result is not completely in accordance with Lorenzi's study [6], where results detected low-pass characteristic for normal readers, but only 6 participants were tested within each group (dyslexics and normal readers). Moreover, TMTFs results were highly heterogeneous within each group.

Figure 3 shows the probability density functions for each group and each frequency (4, 16, 128 Hz). Given a frequency, the two groups display the same shape of probability density function. These results confirm that there is no significant difference between these two groups.

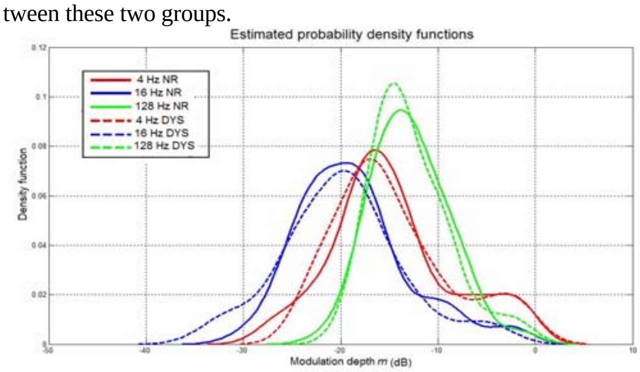

Figure 3 – Probability density functions estimated for Normal Readers (NR – continuous line) and DYSlexics (DYS – dotted line) and for each frequency (4, 16, 128 Hz).

3.1.2 Identification task

Figure 4 shows the mean scores of "pa" responses for each group, reported as a function of VOT and their adjusted curves obtained using Nelder-Meald algorithm. The slopes of these curves differ between groups. For the normal reader group, the slope is steeper (slope of 0.15) than that of the dyslexics (slope of 0.08), which indicates higher precisions for normal readers than for dyslexics.

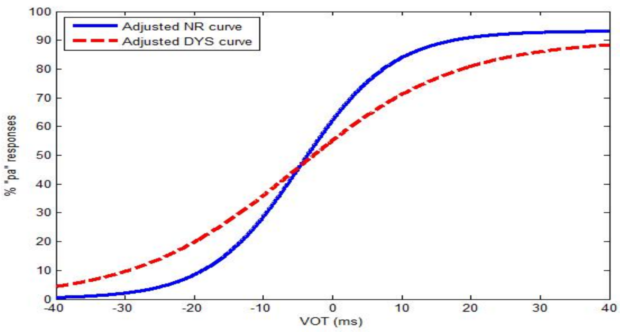

Figure 4 – Average adjusted identification curves along of a /ba/-/pa/ continuum in Normal Readers (NR) and DYSlexics (DYS). The ordinate is the percentage of /pa/ responses.

The results on the identification thresholds (*T*) suggest that normal children (average of $T = 3.48$) have a better capacity to identify /ba/ and /pa/ syllables than dyslexics (average of $T = 2.83$). The expected curve from the identification task of the percentage of correct discrimination (left part of Figure 5) shows a peak slightly different between the two groups. Normal readers have a higher peak than dyslexics.

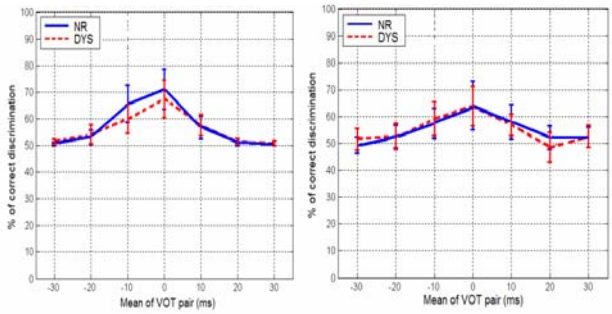

Figure 5 – Left part: average expected curves from the identification task within each group (DYSlexics and Normal Readers). Right part: average observed curves for the discrimination task within each group. These curves represent the percentage of correct discrimination for each pair of /ba/-/pa/ syllables.

3.1.3 Discrimination task

Right part of Figure 5 suggests no difference between groups in the discrimination task. The smaller the difference between observed and expected discrimination scores, the higher the degree of categorical perception. If we refer to Figure 6, for dyslexic children, the differences are higher than for normal readers only for two pairs of syllables (VOT mean of -30 ms and -20 ms) and lower for pairs of syllables located in the phonemic boundary (VOT mean of -10 ms and 0 ms). These results indicate that dyslexics preserve categorical perception in phonemic boundary and have a poorer performance than normal readers in pairs of syllables located at the beginning of the continuum.

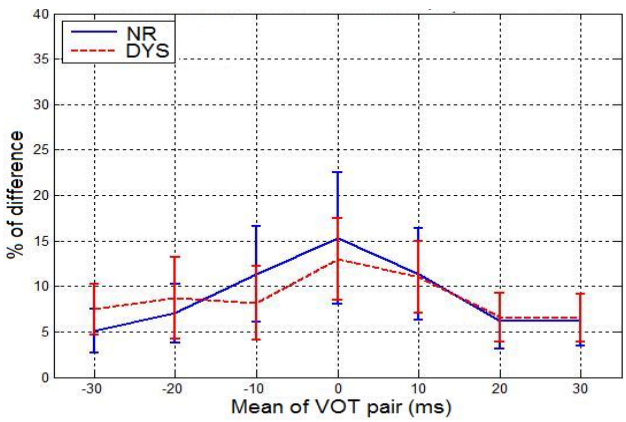

Figure 6 – Average difference between expected and observed scores in Normal Readers (NR) versus DYSlexics (DYS).

3.2 Screening capacities of auditory tasks

3.2.1 Individual auditory variables

Table 1 shows the results of the Mann-Whitney test and suggests that the scores of modulation thresholds in the TMTF task do not have any screening capacity, contrary to auditory hypothesis. These results suggest that the high modulation thresholds measured in children with dyslexia concern probably a minority of dyslexics. For the identification task, all variables show a significant difference between the two groups ($p < 0.07$) but for the discrimination task only two variables are discriminative ($p < 0.08$). These results show a poor categorical precision in dyslexic children but the categorical perception does not seem to be affected for a majority of them.

Variables	p-value
TMTF task	
Modulation depth threshold (*m*) at 4 Hz	0.99
Modulation depth threshold (*m*) at 16 Hz	0.43
Modulation depth threshold (*m*) at 128 Hz	0.84
VOT identification task	
Slope	0.066*
Identification threshold	0.016*
VOT discrimination task	
Difference between expected and observed scores	
VOT mean of -30 ms	0.03*
VOT mean of -20 ms	0.51
VOT mean of -10 ms	0.07*
VOT mean of 0 ms	0.85
VOT mean of 10 ms	0.83
VOT mean of 20 ms	0.68
VOT mean of 30 ms	0.83

(*) p-value < 0.1, the variable is discriminative.

Table 1 - Mann-Whitney comparisons between normal reader children and children with dyslexia.

3.2.2 Capacity of auditory tasks to detect dyslexia

Using the stepwise AIC logistic regression with auditory variables, three variables out of the 12 variables (recalled in Table 1) were selected: modulation depth threshold at 16 Hz, identification threshold and difference between expected and observed discrimination scores with a VOT mean of -30 ms. Figure 7 gives the performance obtained with these variables. The quality of decision rules is not very high (70.8% of individuals correctly classified) and contrary to the rate of specificity (92.31%), the sensitivity is poor (22.86%).

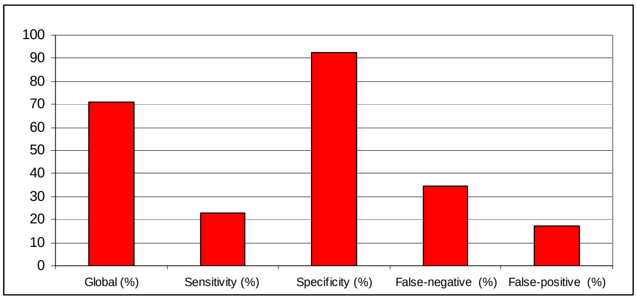

Figure 7- Predictive accuracy (global percentage of correct classification, sensitivity, specificity false-negative rate and false-positive rate) for the auditory model of dyslexia detection (3 variables included: modulation depth threshold at 16 Hz, identification threshold and difference between expected and observed discrimination scores with a VOT mean of -30 ms).

These results suggest that 22% of the dyslexic population were identified as dyslexic according to their deficit in auditory tasks. This proportion is consistent with the prevalence observed when the auditory hypothesis is stated [3].

4. CONCLUSION

This study tested the relevance of three screening tasks based on auditory hypothesis. No significant deficit was found in dyslexic group for TMTF task. However, some abnormalities were noted in phoneme categorization (deficit in precision and categorical perception) evaluated by two auditory tasks which tested the capacity to discriminate syllables along a /ba/-/pa/ continuum. These results suggest that dyslexic children may have deficit in speech perception but not in the perception of temporal cues. Moreover, this study presented a method (AIC criterion based on stepwise logistic regression) to identify a model to estimate the children who could be identified as dyslexic only by their auditory deficit (22%) and in the same time to determine the importance of auditory deficits in the manifestation of dyslexia. Among the auditory tasks, three relevant variables have been selected for the model: identification threshold, modulation depth threshold at 16 Hz and the difference of pair of syllables with a VOT mean of -30 ms between expected and observed scores and this model may be used to screen auditory deficits in dyslexia.

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