PHONEME BOUNDARY PERCEPTION IN RELATIONSHIP TO DEVELOPMENTAL DYSLEXIA

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ABSTRACT

The present paper concerns a study of auditory perception of phonemes and phoneme boundaries in adults with developmental dyslexia. Categorical perception experiments were done to establish whether dyslexics process phoneme boundaries differently from normal readers. In a first experiment discrimination skills were tested on a stop-consonant continuum (/bɑk/-/dɑk/) and on a stop-consonant-approximant continuum (/bɑk/-/wɑk/). The stimulus material was based on natural speech of a female voice. The results of 12 dyslexic adults and 12 control subjects show that the dyslexic group is less skilled and slower in discriminating between stimulus pairs as compared to the control group. The procedure and results of the discrimination experiment are described. Next, some important methodological aspects for follow-up experiments are addressed. Better understanding of the role of these aspects is necessary for planned brain activity measurements (MMN ERP) during auditory perception of the speech stimuli and for a replication of the discrimination experiment.

1. INTRODUCTION

Developmental dyslexia is a disability touching on many aspects of human brain functioning, which makes it a complex matter to study. One of the contributing factors to dyslexia seems to be a deficiency in auditory perception and processing. Auditory perception of speech has repeatedly been found to correlate with reading performance. As compared to normal readers, dyslexic children as well as adults generally show lower discrimination acuity and deviant identification performance on categorical perception tasks on stop-consonants (e.g. [6, 10]) and on some other phoneme contrasts [7, 2]. This suggests that dyslexics have less distinct phoneme boundary representations. Multiple questions remain, however, as to what causes this abnormal perceptual organization. Is it a problem in general auditory temporal processing [9] or is it a problem to be traced to a phonological processing deficit [4]? The present paper describes work that is part of a project, which has several links to the recently started long term Dutch national research program named "Identifying the Core Features of Developmental Dyslexia: a Multidisciplinary Approach". Our project aims at elaborating categorical perception and temporal order processing tasks as a tool for studying aspects of dyslexia. Initially, adult dyslexic subjects are tested but as soon as possible 10-year-olds and pre-reading-age children are to be tested as well. Categorical perception experiments, in combination with additional paradigms and neurophysiological data, can provide a better understanding of what is going on in the brain during speech and language processing in dyslexic individuals. The categorical perception paradigm is merely used as a tool for studying deviant behavior in dyslexic readers compared to normal readers. Therefore, we do not elaborate issues that concern speech perceptual theories as such.

1.1. Objectives

Many of the categorical perception experiments described in literature have made use of synthesized speech stimuli not nearly approaching the quality of natural speech. One of the objectives of the present study is to develop and test speech material that sounds as natural as possible. Another aspect concerns the nature of the Dutch language. Subjects may react differently to stop-consonant(-approximant) contrasts than English subjects do. Replications in Dutch of earlier experiments done in English speaking environments are therefore useful, especially with more natural sounding speech stimuli. A third concern of this study is that data of dyslexic subjects on other than stop-consonant phoneme contrasts is desirable to investigate whether anomalies in auditory perception are limited to phonemes that are characterized by very brief cues.

In our project, originally three speech continua were constructed and used for discrimination and classification experiments, /bɑk/-/dɑk/, /bɑk/-/wɑk/, and /bɑk/-/zɑk/ [3]. In the present paper we focus on the /bɑk/-/dɑk/ and the /bɑk/-/wɑk/ continuum, since the results on the third continuum evoked too many methodological questions. Furthermore, instead of describing both the classification and the discrimination experiment, we limit ourselves to discussing the discrimination experiment because this seems to be the most valuable paradigm. We subsequently address some important methodological aspects, such as step-size and interstimulus interval (ISI) duration, that deserve close attention in follow-up experiments. Finally a short description is given of an experiment that is presently conducted measuring brain activity during auditory perception of the /bɑk/-/dɑk/ continuum.

2. DISCRIMINATION EXPERIMENT

2.1. Stimulus material

Natural speech of a female speaker was recorded. She pronounced a series of one-syllable words, among which the target words /bɑk/, / dɑk/, and /wɑk/, all being normal Dutch words, meaning *'tray'*, *'roof'*, and *'hole in the ice'*, respectively. Ten-point continua were constructed using a spectral interpolation and a signal editing method.

The /bɑk/-/dɑk/ continuum was constructed by performing an interpolation of the F_2 transition using the Praat software package [1]. We implemented linear transitions in the original /bɑk/ signal with F_2 onset ranging from 1100 to 1800 Hz and F_2 offset being 1100 Hz. The manipulated part of the signal was a 100 ms' interval at the beginning of the vowel. The interpolation and additional processing resulted in a 10-point continuum; the total length of each item was 600 ms, consisting of (a) a vocal murmur 170 ms; (b) burst 10 ms; (c) vowel [ɑ] 250 ms, divided into 100 ms transition duration and 150 ms steady state; (d) occlusion period [k] (silence) 55 ms; (e) release [k] 115 ms. The [bɑk]-starting point was characterized by a constant level of the F_2 at 1100 Hz. For each intermediate signal, the F_2 onset was gradually situated at higher frequencies, making the fall of the transition steeper in every step. At the [d]-endpoint of the continuum the transition was falling from 1800 Hz to 1100.

The /bɑk/-/ʋɑk/ continuum, which contains a *labio-dental* approximant in standard Dutch, whereas it contains a *bilabial* approximant in English, was constructed by a signal editing method using the original /bɑk/ and /ʋɑk/ signals. To obtain a /bɑk/-endpoint the approximant in /ʋɑk/ was cut off from the vowel at point "A" in the waveform and was replaced by the vocal murmur and burst of the original /bɑk/ utterance, which resulted in a very natural /bɑk/ realization. The procedure now to create the intermediate signals was to shift point "A" increasingly to the left, first deleting the burst and inserting a period of the original [ʋ] signal, then replacing gradually every period of the vocal murmur of [b] by a period of the original waveform of [ʋ]. This resulted in a signal with a total length of 600 ms, consisting of (a) a voiced labial consonant 180 ms; (b) vowel [ɑ] 250 ms; (c) occlusion period [k] (silence) 55 ms; (d) release [k] 115 ms. All stimuli of both continua were thus of equal duration. The audio files are available at http://fonsg3.hum.uva.nl/caroline.

2.2. Perceptual tests

2.2.1. Design. Apart from a screening test for dyslexia, the experimental design consisted of a same-different discrimination test and a classification test on the speech continua. Response registration included reaction time measurements. In the discrimination task two interstimulus intervals were used (25 and 400 ms), since we were interested in the influences of temporal aspects on discrimination performance of our subjects.

2.2.2. Subjects. Twelve adult dyslexic subjects (8 male and 4 female) and twelve adult control subjects (4 male and 8 female) participated in the listening tests. Except for 3 dyslexics all subjects were students; they were paid for their participation. None of the subjects reported auditory problems.

2.2.3. Experimental procedure. The perception tests were conducted in a room with three sound-attenuated booths. Each booth contained a computer screen, headphones, and a panel of buttons that the subjects had to press to indicate their responses. The buttons were labeled with words and with a corresponding picture or symbol, to avoid lexical confusions. Each session began with a same-different discrimination task followed by a forced choice classification task. For both discrimination and classification the continua were presented separately. The order of presentation of the continua was balanced across subjects.

The discrimination task required subjects to discriminate between two stimuli that were always three continuum steps apart (e.g. 1-4, 2-5, 3-6, etc.). The 7 stimulus pairs were presented 12 times. The internal order of a stimulus pair was balanced. In addition to 'different' trials, ten 'same' trials (1-1, 2-2, etc.) were presented, each pair twice. The stimulus pairs were presented in four blocks of 52 stimuli ($6 \times 7 + 1 \times 10$), while the interstimulus interval remained constant within one block. The first and third block always contained the stimulus pairs separated by a 25 ms ISI, the second and fourth block stimuli were separated by 400 ms ISI. So there was a short-long-short-long ISI-pattern for each continuum. Within blocks stimuli were randomized. The task was preceded by 24 practice stimuli. No direct feedback was given. Subjects were instructed to listen to the two words presented and to determine whether they sounded 'the same' or 'different'. They were urged to react as adequately and as quickly as possible by pushing the corresponding button. The discrimination task took about 45 minutes.

2.2.4. Results. Figure 1 displays the average scores on the same-different discrimination task by both the dyslexic and the control subjects for the long and short interstimulus intervals. The dyslexic group performs significantly less well on both continua. Reaction times were on average longer for the dyslexic subjects as compared to the control subjects. The reaction times show no marked differences between within-category and between-category stimulus pairs.

The average scores as presented in Figure 1 provide a clear indication of the effects that are found. To get the full picture, of course, it is important to inspect the individual scores as well. Classification results are not given although they are also interesting in the sense that they display differences between dyslexics and controls. These differences are in accordance with the results described in literature and with our discrimination results. These discrimination results show more effectively than the classification scores what is going on in the perception of the speech continua. For more information on the classification data the reader is referred to [3, 8].

An ANOVA was conducted for each continuum, the independent variables being subject group (control and dyslexic), interstimulus interval (25 and 400 ms), and stimulus pair (seven 3-step pairs) and the dependent variable being the same-different discrimination scores. Significant main effects ($p<.001$) were found for subject groups (dyslexics performing worse) and for stimulus pairs, whereas the main effect of ISI was moderately significant ($p<.05$). The interaction between ISI and subject groups, however, was not significant. This indicates that for both control subjects and dyslexic subjects a longer ISI yielded better discrimination scores to the same degree. An ANOVA with reaction times as the dependent variable also revealed significant differences between the dyslexic and the control group, dyslexics reacting on average 100 ms slower.

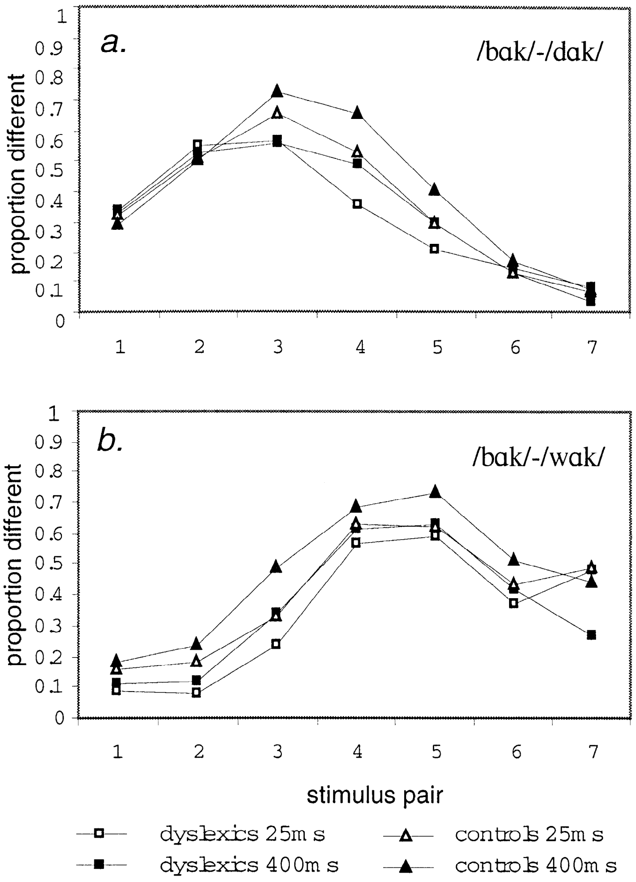

Figure 1. Mean discrimination functions of the dyslexic and control subjects for the /bak/-/dak/ and /bak/-/wak/ continua, separated for interstimulus interval.

3. THEORETICAL ASPECTS

Before continuing experimenting with this speech material the influence of some parameter settings needs to be better understood. Therefore some additional experiments are set up to shed more light on the role of the physical step-size used in the discrimination experiment. Furthermore, the influence of the duration of the interstimulus interval and of the stimulus onset asynchrony are subject to closer analysis.

3.1. Step-size

In the same-different discrimination experiments done so far, we used a 10-point /bak/-/dak/ continuum and we presented all combinations of items that were 3 steps apart, e.g. 1-4 or 3-6. Looking at the results, however, we ask ourselves whether this step-size yields the optimal physical distance for measuring phoneme boundary effects in control subjects and more importantly in dyslexic subjects. As can be observed in Figure 1. clear discrimination peaks are observed for both groups. The control subjects identify a higher proportion of across category pairs correctly than the dyslexics do. However, both curves never come close to the maximum score. This suggests that the physical differences between the stimuli were hard to perceive. The question now is whether a larger physical step-size enhances discrimination of all stimulus pairs to the same degree or whether it only enhances discrimination of the across category pairs. In the latter case, a more pronounced discrimination peak will be found. In the first case, the same curve may be found, shifted vertically only. We would, of course, be most interested in finding relatively higher discrimination peaks reflecting a high degree of categoricalness of perception. This could allow finding clearer differences between control and dyslexic subjects. As for the reaction times, they might get shorter for larger physical step-sizes. This could cause differences between dyslexics and controls to become less salient, which is undesirable.

An experiment is presently conducted measuring discrimination performance of adult normal readers on the /bak/-/dak/ and /bak/-/wak/ continuum presenting stimulus pairs with step-sizes of 3 and 4 to find out what are the differences between the step-size conditions and how large they are. If considerable differences are found the same experiments will be done with dyslexic subjects to obtain the optimal step-size for further experimenting.

3.2. Interstimulus interval duration

It is important to find out what is the optimal value for ISI duration and for stimulus onset asynchrony. Several factors related to the interval between two cues may interfere with discrimination performance. If the interstimulus interval is too long, performance may decrease because of memory decay; if the interval is too short, context or masking effects may obscure discrimination ability of the subjects. Stimulus and cue duration also play a role. In our /bak/-/dak/ continuum the stimulus consists of 600 ms, in which the cue is located at the beginning of the vowel (after the relatively faint signal of the vocal murmur) and lasts 100 ms. Such a long stimulus duration is rather exceptional in categorical perception literature especially in combination with short interstimulus intervals as used in this study and as such little is known about its influence on the task.

Short interstimulus interval duration degrades the performance of dyslexic subjects in the temporal processing of stop-consonants and tones, while normal readers are not influenced by this parameter [4, 6]. The same effect is found for discrimination between two stop-consonants [4]. Based on these findings, we expected dyslexic subjects to perform worse at short interstimulus intervals whereas control subjects were thought not to be sensitive to varying interstimulus intervals. Instead, performance was worse for both the dyslexics and the controls on the 25 ms ISI condition compared to the 400 ms ISI condition. Apparently ISI variation evoked the same response in both groups, suggesting no difference in the processing of events with a very brief interval between them. This is an interesting result, which does not correspond to the findings of earlier studies. The very subtle nature of the differences between the stimuli that our subjects had to detect possibly caused these deviant results. The presence of a context effect may have a stronger influence when such small differences have to be detected than in tasks as described in the above-mentioned studies. Therefore it is considered as a possibility that a context effect masks the differences between dyslexics and controls in the 25 ms condition. The signal had a duration of 600 ms of which the 100 ms transition part contained the cue for discriminating between /bɑk/ and /dɑk/. The remaining part of the signal, the /ɑk/ part, may have influenced the processing of the initial consonant.

4. ERP MEASUREMENTS

An experiment is presently set up in which normally reading adult subjects listen to stimuli from the /bɑk/-/dɑk/ continuum while electrical activity of the brain is recorded from electrodes placed on the scalp. Changes in the electroencephalogram (EEG) time-locked to events or stimuli are called event-related potentials (ERPs). Such ERPs elicited by visual, auditory or somato-sensory stimuli are regarded as manifestations of the cortical activity evoked by those stimuli. Different waveforms can be identified in the ERP according to their polarity (positive of negative) and their latency, i.e., the point in time at which they occur. ERPs can reflect the activity of the brain before overt responses are generated (such as reaction times or discrimination between types of stimuli) and can thus reveal aspects of information processing that took place in the millisecond range. The mismatch negativity (MMN) is the brain's automatic change detection response [5]. It is a negative component of the event-related potential (ERP) with a peak latency around 200 ms post stimulus onset and maximum amplitude over fronto-central areas of the brain. MMN can be used as a 'tool' to assess the automatic discrimination between successively presented auditory stimuli, including phonemic sound features, even when these sounds are not attended to.

In the present within-subjects study, MMN is measured in response to 5 different, paired contrasts of the /bɑk/-/dɑk/ continuum. The physical step-size between the stimuli forming a pair is identical. In each of these pairs one CVC syllable is frequently presented as the standard stimulus (80%). The occasional 'deviant' syllable is randomly presented on the remaining 20% of the trials. The duration of a single syllable is 600 ms. Subsequent stimuli are presented with an interstimulus interval of 400 ms. A total of 200 stimuli are presented in each block. The 5 different blocks are presented in random order. Subjects are silently reading (they are watching a silent video) and are instructed to ignore the auditory stimuli presented to them by headphones. Electrocortical activity is recorded with a 21 electrode montage. Electrodes are placed at scalp locations according to the '10-20' system and include Fz, F3, F4, Cz, C3, C4, T3 and T4. Sampling with a rate of 256 Hz starts 100 ms before stimulus onset and lasts 2000 ms. The ERP measurements are followed by an AX-discrimination experiment on the same stimulus pairs. This allows us to compare discrimination performance (at a conscious level) with detection of differences between the stimuli of a pair at an unconscious, pre-attentional level.

5. CONCLUSION

The present study on categorical perception using Dutch stimuli based on natural speech confirms results from earlier studies on categorical perception in dyslexia [4, 7, 10]. Dyslexic subjects are generally less skilled in discriminating between the stimuli of a stop-consonant continuum such as [bɑ]-[dɑ]. In addition, they are slower in responding. Surprisingly, longer ISI are equally profitable for dyslexic and control subjects in our study.

We are presently investigating in normally reading adults whether the /bɑk/-/dɑk/ continuum is suitable for brain activity measurements. In a later stage, then, we will explore whether ERP measurements can show differences between dyslexics and controls in how the auditory system distinguishes between two stimuli of the /bɑk/-/dɑk/ continuum at a pre-attentive level. However, before doing ERP measurements and before continuing experiments with dyslexic children, additional tests need to be done to verify the role of the interstimulus interval, stimulus onset asynchrony (SOA) and step-size.

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