Title: Categorical phoneme labeling in poor readers does not depend on stimulus duration

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1 ABSTRACT

2 It is established that individuals with dyslexia are less consistent at auditory phoneme
3 categorization than typical readers. One hypothesis attributes differences in phoneme labeling to
4 differences in auditory cue integration over time, suggesting that dyslexics' performance would
5 improve with longer exposure to informative phonetic cues. Here, the relationship between
6 phoneme labeling and reading ability was investigated while manipulating the duration of
7 steady-state auditory information available in a consonant-vowel syllable. Dyslexics obtained no
8 more benefit from longer cues than did typical readers, suggesting that poor task performance is
9 not explained by deficits temporal integration or temporal sampling.

10 I. INTRODUCTION

11 A popular hypothesis is that dyslexia, a learning disorder that affects reading skill
12 development, is in fact the result of a subtle impairment in the way speech sounds are processed
13 (Farmer and Klein, 1995; Van Ingelghem et al., 2005; Poelmans et al., 2011; Tallal, 1980). It is
14 well-established that dyslexic adults and children both tend to perform worse than their non-
15 dyslexic peers on phoneme categorization tasks, in that (1) their performance reflects shallower
16 psychometric functions and (2) they tend to be less consistent labeling speech sounds that are
17 clear category exemplars (Brandt and Rosen, 1980; Hakvoort et al., 2016; O'Brien et al., 2018;
18 Serniclaes et al., 2004; Zhang et al., 2012). Across studies employing a variety of experimental
19 paradigms, moderate effect sizes are typically found (estimated to be 0.66 standard deviations on
20 average by Noordenbos & Serniclaes, 2013), suggesting a reproducible group difference, albeit
21 with considerable overlap between dyslexic and control groups.

22 It has been posited by several authors that individuals with dyslexia are specifically impaired
23 at temporal processing, which has been argued to affect the processing of briefly presented
24 sounds (Gaab et al., 2007; Lehongre et al., 2011; Richardson et al., 2004; Tallal, 1980) and the
25 processing of rapidly changing acoustic cues like formant transitions (Vandermosten et al., 2010,
26 2011). In previous work we investigated the possibility that dyslexics' abnormal performance on
27 phoneme identification tasks was driven by the presence of dynamic speech cues. We replicated
28 the study design of Vandermosten and colleagues, comparing identification performance on two
29 different stimulus continua: one featuring a steady-state cue carried by a spectral envelope and
30 the other containing a dynamic formant transition cue (O'Brien et al., 2018). In our study, the
31 duration of the informative cues was equated (i.e., the formant transition and spectral envelope
32 cue were both present for 100 ms), whereas in Vandermosten and colleagues' original studies
33 they were not (i.e., the formant transition lasted 100 ms and the spectral envelope cue was
34 present for 350 ms). We found an equivalent deficit in task performance for the dyslexic subjects
35 on both conditions whereas the original studies (Vandermosten et al., 2010, 2011), found deficits
36 only for dynamic cues.

37 Our results indicated that dyslexics are not specifically impaired at categorizing speech
38 sounds on the basis of dynamic auditory information. However, the discrepancy between the
39 results for steady-state cues did not rule out the possibility that many dyslexics could be impaired
40 at categorizing on the basis of *any* "brief" cue. This would be consistent with the hypothesis of
41 Tallal and colleagues, who proposed that dyslexics perform poorly whenever rapid auditory
42 processing is involved (Merzenich et al., 1996; Tallal et al., 1996). It would also be consistent
43 with the hypothesis of Goswami and colleagues, who proposed that dyslexics irregularly sample
44 auditory information (Goswami, 2011). If insufficient sampling were the primary problem, then

allowing a listener to acquire more samples by providing a longer exposure to the cue should reduce the gap between dyslexic and typical readers' performance. Agnostic of these two temporal processing hypotheses, it is also conceivable that some dyslexics weight sensory information differently than their typically developing peers (Nitttrouer, 1999), and require more evidence acquired over more "looks" at a signal to make consistent judgments about category.

To investigate these possibilities, we sought to determine whether (a) children with dyslexia and (b) struggling readers who do not meet the criterion for dyslexia benefit from longer exposure to steady-state acoustic cues in the context of phoneme identification task compared to children with typical reading skills. As in our earlier study, we employed a fricative continuum that spans from [s] to [ʃ]. We tested two conditions: one in which the steady-state fricative is available to listeners for 100 ms (short cue duration), and one in which it is present for 300 ms (long cue duration). As before, we recruited children with a range of reading abilities to participate.

II. METHODS

A. Participants

A total of 83 native English-speaking school-aged children ages 8-12 were recruited for the study. Children without histories of neurological or auditory disorders were recruited from a database of volunteers in the Seattle area (University of Washington Reading & Dyslexia Research Database; <http://ReadingAndDyslexia.com>). Parents and/or legal guardians of all participants provided written informed consent under a protocol that was approved by the University of Washington Institutional Review Board. All subjects demonstrated normal or corrected-to-normal vision. Participants were tested on a battery of cognitive and literacy assessments, including the Woodcock-Johnson IV (WJ-IV) Letter Word Identification and Word Attack sub-tests, the Test of Word Reading Efficiency (TOWRE), and the Wechsler Abbreviated Scale of Intelligence (WASI-II). All participants underwent a hearing screening to ensure pure tone detection at octave frequencies between 500 Hz and 8000 Hz in both ears at 25 dB HL or better.

One subject who was initially recruited did not pass the hearing screening and was not entered in the study, and seven others did not meet the inclusion criterion for IQ (performance no less than 2 SD below the population mean on the age-normed WASI-II FS-2 and nonverbal IQ measures). One subject was unable to complete training for the experimental task and so did not participate further. Another two subjects yielded data that could not be well fit with a psychometric function and were excluded from further analysis on the basis of low confidence in the psychometric parameter estimates, thus yielding data from 72 children in total. The guidelines for exclusion are described in greater detail in the following sections.

B. Demographics

In order to understand the relationship between phoneme categorization ability and reading ability, we selected our cohort of participants to span the continuum from impaired to highly skilled readers. Although we treat reading ability as a continuous measure in our statistical analyses, for the purpose of recruitment and data visualization we defined three groups based on the composite Woodcock-Johnson Basic Reading Score (WJ-BRS) and TOWRE index. As both the WJ-BRS and TOWRE indices are scored on the same standardized scale, a composite reading skill measure was created by averaging the two scores for each participant. The "Dyslexic" group comprised participants whose reading score fell 1 standard deviation or

more below the mean (standardized score of 100); Above Average readers were defined as those with scores above the population mean; and Below Average readers were defined as participants who fell between the Dyslexia and Above Average groups. This definition is consistent with our previous work (O'Brien et al., 2018, similar to (Rimrodt et al., 2010; Shaywitz et al., 2002)). We used both the WJ-BRS and TOWRE index in our criterion to improve the confidence of our group assignments since they are highly correlated measures ($r = 0.91$, $p < 2e-16$). There were 36 subjects in the Dyslexic group, 17 in the Below Average group, and 19 in the Above Average group. There were no significant differences in age between groups (Kruskal-Wallis rank sum test, $H(2) = 2.28$, $p = 0.32$), nor was there a significant correlation between age and reading score ($r = -0.009$, $p = 0.57$). We did not exclude participants with ADHD diagnoses from the study because ADHD is highly comorbid with dyslexia, so this inclusion leads to a more representative sample of children. However, we did account for the presence of ADHD diagnosis in our statistical models. Of our 72 participants, 20 had a formal diagnosis of ADHD: 4 in the Above Average group, 5 in the Below Average group, and 11 in the Dyslexic group. The difference in prevalence of ADHD across groups was not significant (Kruskal-Wallis rank sum test, $H(2) = 0.71$, $p = 0.70$).

Table 1

Summary statistics and group differences on various demographic, reading and cognitive measures. Summary statistics show means and (sample standard deviations). Significance assessed by the Wilcoxon rank-sum test. Stars indicate p-values that meet threshold for significance ($\alpha = 0.05$) after Bonferroni correction for 24 comparisons.

	Dyslexic (36 subjects)	Below Average (17 subjects)	Above Average (19 subjects)	Significance (Dyslexic v. Below Average)	Significance (Dyslexic v. Above Average)
Males/Females	17m 19f	8m 9f	9m 10f		
Age	9.7(1.3)	9.5 (1.2)	10.3 (1.7)	0.962	0.172
WASI-II					
FS-2	96.0 (9.5)	106.4 (14.5)	121.3 (16.2)	0.003	7.423e-7*
Nonverbal IQ	46.5 (6.4)	52.0 (8.0)	60.0 (11.8)	0.023	6.708e-5*
WJ- IV					
WJ-BRS	77.5 (10.6)	95.5 (3.5)	113.5 (9.4)	1.400e-8*	1.484e-9*
Word reading	74.3 (12.0)	94.3 (5.4)	113.1 (10.5)	2.557e-8*	1.463e-9*
Nonword reading	83.2 (10.8)	97.5 (6.5)	112.0 (9.2)	4.692e-6*	1.742e-9*
TOWRE 2					
TOWRE Index	68.8 (8.3)	91.7 (7.0)	108.6 (9.4)	1.556e-8*	1.465e-9*
Word reading	69.9 (10.7)	93.7 (9.4)	111.8 (11.8)	2.235e-7*	1.456e-9*
Nonword reading	70.9 (7.0)	90.4 (5.7)	104.5 (7.8)	7.218e-9*	1.477e-9*
CTOPP 2					
Phonological awareness	84.2 (11.3)	92.2 (12.8)	102.2 (14.2)	0.035	3.600e-5*
Phonological memory	83.0 (11.8)	91.2 (13.8)	99.6 (19.8)	0.0628	0.001*
Rapid symbolic processing	78.6 (10.3)	92.4 (10.0)	97.5 (13.6)	2.043e-5*	1.321e-5*

Table 1 shows group comparisons on measures of reading and cognitive skills. We observed that IQ, both full-scale (incorporating verbal IQ) and nonverbal measures, varied as a function of group. Importantly, by design no subjects had a full-scale or nonverbal IQ falling more than 2 standard deviations below the population mean as measured by the WASI-II. Therefore, although there was a significant difference in IQ scores across groups, we were not concerned that abnormally low cognitive ability would prevent any child from performing the experimental task. To be certain our results were not confounded by this difference, we also included nonverbal IQ as a covariate in our statistical analyses to confirm the specificity of the relationship with reading skills as opposed to IQ.

C. Stimuli

Two 7-step speech continua were created using Praat v. 6.0.37. Both were /fa~/sa/ continua, with the sole difference being the duration of the initial fricative. The fricative duration was either 100 or 300 ms. The /fa~/sa/ continua were created by splicing synthesized fricatives onto a natural /a/ token excised from a spoken /sa/ syllable. The duration of /a/ was scaled to 250 ms using Praat's implementation of the PSOLA algorithm. Synthesized fricatives contained three spectral peaks centered at 2500, 3500, and 6500 Hz. The bandwidths and amplitudes of the spectral peaks were linearly interpolated between continuum endpoints in seven steps, and the resulting spectra were used to filter white noise. To improve the naturalness of the synthesized fricatives, a gentle cosine on- and off-ramp was imposed on the fricative envelope. The duration of the ramps was scaled proportionately to the entire duration of the fricative, with the rise occurring in the first 75% of the fricative and the fall in the last 20%. Aside from this onset/offset ramping (which was applied equally to all continuum steps), the contrastive cue (the amplitudes and bandwidths of the spectral peaks) was steady throughout the duration of each fricative.

D. Procedure

Stimulus presentation and participant response collection was managed with PsychToolbox for MATLAB. Auditory stimuli were presented at 75dB SPL via circumaural headphones (Sennheiser HD 600). Children were trained to associate sounds from the two speech continua with animal cartoons (pink and purple snakes) on the right and left sides of the screen, and to indicate their answers with right or left arrow keypresses. Throughout all blocks, each cartoon was always associated with the same stimulus endpoint. After every 35 stimulus presentations, a reminder was displayed illustrating the snake associated with each sound.

Practice rounds were administered before the first test block. In practice rounds, participants were asked to categorize only endpoint stimuli and were given feedback on every trial. Participants had to score at least 75% correct on the practice round to advance to the experiment and were allowed to repeat the practice blocks up to three times. As mentioned, 1 child from the initial recruitment did not meet this criterion and was not included in the study.

In each test block, participants heard a single syllable and decided which category it belonged to by selecting an animal (no text labels were used). Generally, this was not difficult for our participants. Three subjects (one Above Average and two Dyslexic) lost track of the animals associated with the endpoints after succeeding at the practice rounds. In these cases, the experimenter provided written labels taped to the computer monitor to assist. Each block contained 5 presentations of each step on the continuum, for a total of 35 randomly ordered trials.

Six blocks were administered in total. In each block, only one kind of stimulus (100 ms or 300 ms long fricatives) was presented, and the type of stimulus tested was alternated on each block. The order of presentation was counterbalanced across participants such that half began with the 100 ms fricative continuum and half began with the 300 ms fricative continuum.

E. Psychometric curve fitting

Modeling of response data was performed with Psignifit 4.0, a MATLAB toolbox that implements Bayesian inference to fit psychometric functions (Schütt et al., 2015). We fit a logistic curve with four parameters, modeling the upper and lower asymptotes, the width of the psychometric, and the threshold. The width parameter was transformed to the slope at the threshold value.

To determine the most appropriate priors for fitting the two asymptotic parameters, we utilized a cross-validation approach previously demonstrated in O'Brien et al. 2018. Four-parameter fits of each experimental block were performed with each of 7 possible priors: a prior that fixed the lapse rate at zero (in line with the approach in most previous studies of auditory processing in dyslexia), and six uniform distribution priors with lower bound zero and upper bound ranging from 5% to 30% in steps of 5% (e.g., a lapse rate of 20% corresponds to constraining the lower asymptote between 0 and 0.2, and the upper asymptote between 0.8 and 1). Next, the optimal prior was chosen using ten-fold cross-validation. Specifically, for each of the psychometric functions measured for each participant in each condition (long and short fricative), psychometric curves were fit to all but the held-out fold of behavioral data. Then, the summed log-likelihood of the participant's selection on the held-out data points was calculated under the model. This process was repeated for each of the ten folds, for each of the possible prior widths. The estimated likelihoods of the held-out data points were used as a goodness-of-fit metric and pooled across blocks and cross-validation runs to determine the median likelihood for each prior width. The goodness-of-fit metric was normalized for comparison across participants by subtracting out each individual's median likelihood with a two-parameter model. The optimal prior was determined to be a maximum lapse rate of 15%, using the standard error rule (selecting the most restrictive prior width at which the standard error does not encompass 0). As expected, when the asymptotes were fixed at 0 and 1 as in the two-parameter model, the psychometric fits had the poorest fit to the data.

Having determined the optimal prior for the asymptote parameters, models were re-fit on the full dataset for each combination of participant and cue continuum to obtain final estimates of the four parameters. Any cases where the best-fit threshold parameter was not in the range of the stimulus continuum steps (1 through 7) were excluded from further analysis. Additionally, one Dyslexic subject performed the labeling consistently backwards and produced a sharp psychometric function in the reverse direction, despite repeated reminders about the sound associated with each animal throughout the experiment. The psychometric functions were particularly ill-fitting for this subject and were removed from further analysis. As previously stated, 72 subjects in total yielded behavioral responses that could be fit with psychometric functions.

F. Stepwise model selection procedure

Once the psychometrics had been fit for each subject/condition, the parameter estimates were used as dependent variables in a series of generalized linear models, to determine the relationship between reading ability and the parameters of the psychometric fit. Specifically, we used the psychometric slope, the average offset of the upper/lower asymptotes (i.e., their deviations from zero/one, respectively), and the first component of a principal components

analysis of the slope and the two asymptotes. Fixed-effect predictors with sum coding were used for the continuum (short /fa~/sa/ versus long) variable. Reading ability (the average of the WJ-BRS and TOWRE Index) was entered as a continuous fixed-effect predictor except where otherwise stated. Nuisance predictors were added for presence/absence of ADHD diagnosis (treatment coding) and for non-verbal IQ (WASI-III Matrix Reasoning; continuous predictor). A random intercept for participant was also included. For all model analyses, we began with a fully specified model of reading score as a function of the parameters of interest plus the two nuisance predictors and a random intercept for subject identity. All model fitting was done using the lme4 library for R (Bates et al., 2015). The contributions of nuisance parameters were first tested using parametric bootstrapping using the pbkrtest library for R (Halekoh and Højsgaard, 2014), which is robust to non-normally distributed residuals. Model terms were retained if the bootstrapped p-value of the parameter being nonzero was less than 0.1. In all cases, the nuisance terms failed this test and were dropped from the model. Next, terms of interest for the study (psychometric function parameters, duration, and interactions) were tested similarly.

G. Data availability statement

The de-identified datasets reported and analyzed in the current study, as well as the code for stimulus presentation, data analysis, and figure generation, is available at https://github.com/YeatmanLab/link_upon_publication.

III. RESULTS

A. Phoneme categorization and reading skill

After model selection, the most parsimonious model of psychometric slope contained a continuous predictor of reading ability (reading score), a main effect for stimulus duration, and a random intercept for each participant (see Table 2). The interaction of slope and stimulus duration was not significant and did not survive the model selection procedure.

The same initial model specification and simplification procedure used in the model predicting psychometric slope was also used for the model predicting the average asymptote offset. The final model of asymptote offset contained a continuous predictor for reading ability (see Table 2); there was no evidence for a significant main effect of duration or interaction. Higher reading ability was associated with smaller asymptotic parameters (about 0.08% smaller per 1-unit increase of reading score).

Thus, compared to strong readers, poor readers show shallower psychometric slopes and are also more likely to inconsistently label stimuli even near the continuum endpoints. On average, subjects show a steeper psychometric function when provided a longer cue irrespective of their reading ability. There was no evidence to suggest that the degree of within-category consistency depended on the cue duration (short or long fricative).

Table 2

The results of model selection for three dependent variables: psychometric function slope, asymptote, and PC1.

Model	Parameter	β	SE	p
1 st principal component	Reading score	0.271	0.006	$3.178e-5$
	Duration (long)	0.509	0.157	0.0002

Slope	Reading score	0.020	0.007	<i>0.003</i>
	Duration (long)	0.504	0.111	<i>1.986e-5</i>
Asymptote	Reading score	-0.0008	0.0002	<i>0.002</i>

One challenge in interpreting psychometric function parameters is that it is difficult (if not impossible) to fit both the slope and asymptotic parameters without incurring bias in one domain due to these parameter's trading relationship in the optimization space of sigmoidal functions (Treutwein and Strasburger, 1999). Moreover, data that are best fit with non-zero asymptotes are often treated as indicative of lapses of attention, but in fact may (in part) reflect aspects of the deficit under study (O'Brien et al., 2018; Serniclaes et al., 2004). Therefore, ideally we would model slope and asymptotes simultaneously using a single measure of the psychometric shape that takes all parameters into account. Hence, we use the first principal component (PC1) of the psychometric function's four parameters (slope, threshold, lower and upper asymptotes) as a summary measure of the psychometric function's shape. We have previously shown this measure to be an effective predictor of reading ability in children that is possibly a more sensitive probe than either slope or asymptotic parameters alone (O'Brien et al., 2018).

Computing a principal component analysis (PCA) of four parameters of the psychometric function revealed that the first component explained 46.5% of the variance in the data reflecting a linear combination of the slope and both asymptotes (slope: -0.628; lower asymptote: 0.588; upper asymptote: -0.510). The most parsimonious model of PC1 contained predictors for reading skill and duration, but the interaction of these variables was not significant and did not survive model selection (see Table 2). Individual PC1, slope, and asymptote measures are shown in Figure 1. The effect of stimulus duration on PC1 for each individual is plotted in the third column as a function of reading score, illustrating the lack of evidence for a significant interaction. Thus, there is no evidence suggesting that poor task performance is attributable to stimulus duration.

Figure 1. Plots of model parameter estimates versus reading score (figure appears in color online). Each point corresponds to parameter estimates for one subject in one condition (100 ms or 300 ms fricative duration). Lines indicate the best fit regression line with 95% confidence intervals in shaded regions.

B. Group differences in phoneme categorization

For ease of comparison with prior studies, we also modeled our dependent variables with reading ability as a categorical predictor rather than as a continuous covariate. Because we are specifically interested in how dyslexics compare to strong readers, these analyses were carried out using data from our subjects in the Dyslexic and Above Average groups (omitting the “below average” group).

Using a mixed model analysis with group as a categorical predictor with Above Average as the reference group, subject as a random factor, and following the same model selection procedure as before, we found a significant main effect of group ($F(1,50.79) = 7.26, p = 0.0095$) and duration ($F(1,65.85) = 14.96, p = 0.0003$) on psychometric slope. The interaction of duration and group was eliminated by model selection. The estimated Cohen’s d for the separation of slope by group was 0.78, with a 95% confidence interval ranging from 0.19 to 1.38.

Next, we considered a model of average psychometric asymptote offset. The most parsimonious model contained only a main effect of group, which was significant ($F(1, 51.04) = 6.54, p = 0.014$). Group separability by lapse rate was measured with Cohen’s d , giving an effect size of 0.73 with a 95% confidence interval ranging from 0.14 to 1.32.

Lastly, we confirmed the relationship between group and psychometric PC1 ($F(1,50.35) = 15.13, p = 0.0003$, degrees of freedom estimated via the Kenward-Rogers approximation). The

selected model also included a main effect of duration ($F(1,51.71) = 11.07, p = 0.001$). A candidate model including the interaction of duration and group indicated that this term was not significant ($F(1,66.78) = 0.13, p = 0.725$). To assess the separability of the groups, we calculated Cohen's d for a group comparison where each individual's PC1 estimate is averaged across the two test conditions (combining long and short durations). We found a large effect size for the comparison between the Dyslexic and Above Average groups ($d = 1.1$, with the 95% confidence interval spanning from 0.50 to 1.72).

IV. Discussion

Our results replicate and extend previous findings about the nature of phoneme categorization deficits in struggling readers. We confirm that reading ability is moderately predictive of the extent to which a child applies consistent labels to repeated presentations of the stimuli. We found that this effect occurs whether the child has relatively long or short exposure to the identifying phonetic cue, which was in this case the spectral envelope of a fricative consonant. Our findings rule out the possibility that the performance of poor readers on the identification is limited by a general difficulty processing brief auditory cues (Merzenich et al., 1996), as well as the more recently posed hypothesis that they do not properly sample or integrate auditory information at the phonetic-cue scale (Goswami, 2011). Although we cannot make claims about temporal sampling or processing in all contexts, our results suggest that difficulty making categorical judgments about speech sounds is not primarily driven by temporal features of the stimulus. The benefit of increasing cue duration was roughly equal across the spectrum of reading abilities. If poor readers were unable to form clear categories of speech sounds because they did not properly sample phonetic information (the spectral envelope), then we would have expected to find a significant interaction of stimulus duration and reading ability. This would occur because increasing the duration of phonetic cue availability would give poor readers a greater chance of perceiving the cue, improving their performance on the labeling task relative to strong readers. Conversely, we might expect an interaction in the opposite direction if poor readers were so profoundly impaired at processing the phonetic cue that they derived little or no benefit from increased duration while controls did. In any case, the fact that we did not find evidence for such an interaction for any of the psychometric function parameters tested—including slope, asymptote, and the first principal component of these measures—argues that poor readers' well-established difficulty with phoneme identification is unlikely to be a consequence of poor temporal processing.

At this juncture, there have been nearly forty studies of phoneme identification with reading-disabled children. There is no clear consensus on stimulus features that induce or remedy struggling reader's impairments with the task: the deficit has been variously found for synthetic and naturalistic speech, stop consonants and fricatives, brief and long stimulus presentations, and spectral, temporal, and spectrotemporal cues. Although some studies have shown group differences on certain continua but not others (Nitttrouer, 1999; Vandermosten et al., 2010), no reliable pattern seems to emerge for a specific acoustic feature that distinguishes controls from poor readers across identification studies.

In light of this, future research concentrating on general aspects of decision making and cognition relevant to the identification task may be warranted. It is important to remember that categorical labeling is a general feature of sensory perception, and the task design we employ exercises working memory, statistical learning capacity, and auditory attention (Ramus and

Ahissar, 2012). Furthermore, it is controversial whether categorical labeling is a necessary stage of analysis in speech processing (Cleary and Pisoni, 2001). Rather than treating identification tasks as probes of speech processing in everyday environments or auditory acuity, it may be more fruitful to turn our attention to the domain-general functions that are tapped by such laboratory tasks.

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