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Research Article

Another Temporal Processing Deficit in Individuals With Developmental Dyslexia: The Case of Normalization for Speaking Rate

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Purpose: Developmental dyslexia (DD) has mostly been attributed to arise from phonological impairments; however, several theories indicate a temporal processing deficit as the underlying cause of DD. So far, research examined the influence of temporal cues on concurrent speech sound categorization in DD, but effects of temporal information from a context (e.g., speaking rate) on the perception of subsequent sounds (i.e., "rate normalization") have not been considered. This study examined whether individuals with DD are capable of implicitly extracting temporal information embedded in context and use it for phoneme categorization to the same extent as healthy readers.
Method: Fifteen individuals diagnosed with DD and 16 healthy readers, all native speakers of Hebrew, listened to context sentences followed by target words. They had to indicate whether the target word sounded more like *taam* ("taste"; a long-vowel response) or *tam* ("naïve"; a short-vowel response). Temporal information of the context was manipulated (slow vs. fast speaking rate sentences) as well as the vowel duration of the target in a 5-step continuum.
Results: Listeners with DD did use the rate context to inform their decisions but to a significantly lesser extent than healthy listeners. In addition, their categorization of the vowel duration continuum was somewhat less distinct than that of the control group.
Conclusions: Individuals with DD are impaired not only in tasks involving direct temporal processing, as shown in previous studies but also in the use of temporal information of a context that impacts the perception of subsequent target words. This inability to fully utilize rate normalization processes may influence the formation of abstract phonological representations in individuals with DD.

Developmental dyslexia (DD) is a specific and significant deficiency in the development of reading skills that is not solely accounted for by mental age, visual acuity problems, or inadequate schooling (World Health Organization, 2001). DD is one of the most frequent neurodevelopmental disorders and has been identified to affect roughly 7% of the population (Peterson & Pennington, 2015). DD has mostly been attributed to arise from a deficit in direct access to and manipulation of phonemic language units (sounds that differentiate between the meanings of words) retrieved from long-term declarative memory (the phonological deficit hypothesis; Ramus & Szenkovits, 2008; Snowling, 2001). Accordingly, phonological impairments are among the central symptoms associated with DD. Phonological awareness (sensitivity to the sound structure in a word), phonological short-term memory, and lexical retrieval are impaired in DD (Melby-Lervåg, Lyster, & Hulme, 2012).

Deficits that characterize individuals with DD extend far beyond the phonological domain (Démonet, Taylor, & Chaix, 2004). Problems also occur, for instance, in temporal processing (Protopapas, 2014). In particular, individuals with DD have trouble with perceiving temporal order (Ben-Artzi, Fostick, & Babkoff, 2005; Reed, 1989; Rey, De Martino, Espesser, & Habib, 2002; Tallal, 1980) and exhibit impairments in time estimation tasks, that is, in judging whether a stimulus is longer or shorter compared with a standard stimulus (Khan, Abdal-hay, Qazi, Calle, & Castillo, 2014; Nicolson, Fawcett, & Dean, 1995). They are also impaired in implicitly learning temporal information (Gabay, Schiff,

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& Vakil, 2012; Gabay, Thiessen, & Holt, 2015; Howard, Howard, Japikse, & Eden, 2006; Lum, Ullman, & Conti-Ramsden, 2013; Singh, Walk, & Conway, 2018) and in adapting to time-compressed speech (Gabay, Karni, & Banai, 2018). Furthermore, more and more literature indicates problems with categorizing speech and nonspeech sounds based on their temporal cues in individuals with DD. In particular, individuals with DD have problems categorizing continua between spoken syllables that differ in rapid spectral changes over a very brief temporal time window (Vandermosten et al., 2010, 2011). These findings have led some researchers to hypothesize that a temporal processing deficit leads to speech perception deficiencies, resulting in impoverished phonological representations and subsequent reading difficulties in those with DD (Goswami, 2011; Tallal, 1980).

Notably, studies in support of temporal processing deficits in DD mostly examined the influence of temporal information on concurrent speech perception. That is, they considered temporal aspects of the segments that listeners should identify or discriminate (Vandermosten et al., 2011). Yet in real-world listening environments, the perception of speech sounds rarely occurs in isolation. Importantly, acoustic information in the context in which a sound occurs (i.e., word or sentence) can influence the perception of this sound. Healthy listeners are capable of implicitly extracting spectral and temporal information embedded in a context and use this information for the identification of subsequent speech sounds (i.e., concerning temporal context, this effect is termed *rate context effect* or *normalization for speaking rate*). However, given that, for individuals with DD, temporal processing is a major source of difficulty, the question arises whether and to what extent they can use temporal context information in speech perception. This question is the main topic of the current investigation. Before turning our attention to describing the rate context effect in more detail, temporal processing theories of DD will be briefly introduced.

Temporal Processing Accounts of DD

Several theoretical accounts have been proposed to specifically account for the temporal processing deficits observed in DD, most prominently the rapid temporal processing deficit theory (Tallal, 1980) and the temporal sampling framework (Goswami, 2011). The rapid temporal processing deficit theory suggests that DD arises from problems in the ability to process rapidly presented sounds in the order of tens of milliseconds. This deficit is presumed to interfere with the fine-grained analysis that is required to process acoustic differences at the level of the phoneme, resulting in the poor phonemic segmentation and decoding skills typical of DD. This account is based on a seminal study by Tallal (1980), who showed that children who failed to develop language properly were also impaired in sequencing and discriminating brief nonspeech sounds when the stimuli were closely spaced in time. Further studies revealed auditory temporal processing problems in both adults and children with DD while using either speech or nonspeech stimuli (Cohen-Mimran & Sapir, 2007; Farmer & Klein, 1995; Reed, 1989; Rey et al., 2002; Van Ingelghem et al., 2001) and found a predictive relationship between auditory processing and reading-level attainment (Boets et al., 2011).

The studies of Vandermosten et al. (2010, 2011), in particular, assessed auditory temporal processing in DD by asking adults and children with DD to categorize speech and nonspeech sounds from different types of sound continua. Results showed that individuals with DD were impaired in categorizing a continuum with rapidly changing spectral cues, as in /ba/–/da/ (and the respective nonspeech analogue), but not the long, stable cues in /u/–/y/ (or the respective nonspeech analogues) relative to control participants. These and similar previous findings led to the conclusion that the processing of rapid temporal information is impaired in individuals with DD. Notably, the studies by Vandermosten et al. and others tested the use of short and rapidly changing versus long and stable spectral cues. However, sounds in many languages may be differentiated mainly by their temporal information. For instance, the English words *say* and *stay* are differentiated by the duration of the gap between the /s/ and the vowel. Interestingly, Nittrouer (1999) did not find any difference in the categorization of duration continua of the type *say–stay* in children with DD compared to a control group of healthy readers. However, other studies reported impaired ability of individuals with DD to use durational cues for speech categorization of vowels (Groth, Lachmann, Riecker, Muthmann, & Steinbrink, 2011; Steinbrink, Klatte, & Lachmann, 2014). Therefore, the results are mixed with regard to how temporal information in the form of sound duration influences speech categorization in DD.

In contrast to the rapid temporal processing deficit theory, the temporal sampling framework suggests that DD arises from deficits in processing sensory temporal information of speech in the range of seconds (Goswami, 2011). It rests on the assumption that temporal coding in the brain involves the sampling of the incoming auditory signal at different rates through neural oscillations at different frequencies (Giraud & Poeppel, 2012). Specifically, these frequency bands appear to correspond to different linguistic units in the speech signal such that phonemes, syllables, and linguistic phrases roughly correspond to the periods of gamma, theta, and delta oscillations in the brain (Ghitza, 2011; Poeppel, 2003). The temporal processing deficit in individuals with DD is then assumed to arise from problems in time sampling and/or phase locking of phonological processing to one or more of these frequency bands (Goswami, 2011), with specific impact on the perception of syllable rate amplitude modulations (Goswami et al., 2002). Research in favor of the temporal sampling hypothesis has shown problems in discriminating and categorizing amplitude-modulated sounds that differ in the abruptness of the amplitude increase, termed *rise time* among DD readers (Goswami et al., 2002; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Richardson, Thomson, Scott, & Goswami, 2004). In addition, in a study carried out by Corriveau, Goswami, and Thomson (2010), preschoolers' sensitivity to amplitude rise time was significantly correlated with their emerging phonological and reading skills.

The rapid temporal processing deficit theory (Tallal, 1980) and the temporal sampling framework (Goswami, 2011) share the notion that DD can be attributed to difficulties in auditory processing, which leads, through impaired speech perception, to phonological deficits that are then linked to reading impairments. The theories differ, however, in terms of what sorts of auditory processing deficits are attributed to DD and specifically what temporal parameters are impaired in DD (i.e., stimulus duration and rapidity of stimulus change according to the rapid temporal processing deficit theory vs. dynamic changes within longer stimuli according to the temporal sampling framework). Although there is evidence in support of each of these two accounts, there are several questions that remain unclear with regard to what type of auditory processes are affected, their causal link to reading, and whether auditory processing is a consequence of DD rather than the cause of it (Halliday, Tuomainen, & Rosen, 2017; Protopapas, 2014). Importantly, most studies in support of one or the other theory have addressed the use of acoustic information on concurrent speech perception. As mentioned above, this study's goal is to extend the question about temporal processing deficits in those with DD to the domain of subsequent speech perception.

Temporal Information Influences Subsequent Speech Categorization

Speech perception in real-world listening environments does not occur in isolation but with strong contextual support. That is, the acoustic characteristics of a preceding sentence or word are used to interpret subsequent sounds. For example, listeners interpret speech sounds relative to the phonetic context in which they appear (i.e., adjacent segments; e.g., Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967) and the talker who is perceived to have produced it (e.g., Ladefoged & Broadbent, 1957). Such context-dependent speech perception processes have been termed perceptual normalization according to the nature of the contextual information that is being used (Francis, Ciocca, Wong, Leung, & Chu, 2006). The process of using context that is related to temporal information is termed normalization for speaking rate or rate context effect. That is, sounds that are cued by duration (e.g., in a vowel duration contrast such as /a/ vs. /a:/ in German words such as bahnen vs. bannen "to channel"–"to ban"; Reinisch, 2016a) are interpreted relative to the speaking rate of the preceding context (for recent studies including summaries of past research, see Heffner, Newman, & Idsardi, 2017; Reinisch, 2016b; Reinisch, Jesse, & McQueen, 2011; Reinisch & Sjerps, 2013; Toscano & McMurray, 2015). The direction of the effect is contrastive, that is, following a fast (i.e., short/compressed) context sentence, a target sound tends to be perceived as relatively longer than following a slow context sentence. In this way, the sentence context can shift the perception of a target sound and hence word meaning if duration is used in a linguistically contrastive fashion. Therefore, the rate context effect is an example of how temporal information of a context influences subsequent speech categorization.

The information in the context is perceptually weighted such that speaking rate information closer to a given target sound is more important than a more distal context (e.g., Reinisch et al., 2011; Summerfield, 1981). Normalization for speaking rate has been argued to involve general auditory processes related to auditory contrast effects (Diehl & Walsh, 1989), as it occurs with nonspeech context (Bosker, 2017; Wade & Holt, 2005), and arises very early during processing (Reinisch & Sjerps, 2013; Toscano & McMurray, 2015) prior to other perceptual processes such as perceptual learning from lexical context (Sjerps & Reinisch, 2015) or talker-selective processing (Bosker, 2017; Newman & Sawusch, 2009). Using the speaking rate of the context to interpret a durationally cued sound contrast is an implicit automatic process that does not require attention (Bosker, Reinisch, & Sjerps, 2017; Kösem et al., 2018). Neurobiologically, rate normalization has been hypothesized to arise from neural entrainment at the syllable level (i.e., theta oscillation; Bosker, 2017; Bosker & Ghitza, 2018).

In typical development, perceptual normalization processes can help listeners maintain phoneme constancy is spite of different acoustic realizations of the same phoneme (Heald & Nusbaum, 2014). The inability to fully utilize normalization processes may hence impair the formation of the abstract representations of speech sounds necessary for robust phoneme–grapheme mapping during reading development (Perrachione et al., 2011). Surprisingly, perceptual normalization processes in the form of context effects have rarely been examined in DD, and the few studies that have been conducted reported intact ability to use a preceding context as support of phonological categorization (Blomert, Mitterer, & Paffen, 2004; Gabay & Holt, 2018). However, these studies focused on the use of spectral rather than temporal contexts and did not observe any differences in the use of context in DD individuals compared with healthy listeners. Based on temporal processing deficits found in those with DD, we hypothesized that, for individuals with DD, the ability to use speaking rate context in categorizing speech sounds may be compromised relative to healthy readers.

The Present Study

In this study, we examined the extent to which people with DD are able to use temporal information of a context (fast vs. slow speaking rate of a context sentence) to categorize a phonological speech sound contrast that is mainly distinguished by a difference in duration. In this way, two types of temporal processing demands were tested: (a) the use of the slow versus fast rate of the context sentences and (b) the use of durational cues in the vowel when categorizing a vowel duration continuum. In the current study, we asked the following questions:

1. To what extent are individuals with DD capable of implicitly extracting temporal information from a context (fast vs. slow speaking rate of a context sentence) and use it in subsequent phoneme categorization?
2. To what extent are individuals with DD capable of using concurrent temporal information (durational cues) for vowel categorization?

If people with DD are less capable of using temporal information embedded in a context than healthy readers, their phonological categorization of the vowel contrast is expected to be less affected by the rate of the context than is typically seen in rate normalization tasks (i.e., more long-vowel responses following a fast than a slow context). In addition, if people with DD were less capable of using temporal cues for vowel categorization in general, they are expected to exhibit a flatter identification curve of vowel categorization compared with healthy readers.

The answers to these questions can inform theories of temporal processing in DD, as different predictions can be made as for whether those with DD would show deficits in the use of temporal context information on subsequent phonetic categorization. Since the rapid temporal processing deficit theory (Tallal, 1980) focuses on deficits in the processing of rapid temporal information in the range of milliseconds (i.e., in the domain of sounds), deficits in normalization for speaking rate are likely not predicted. This is because the domain of rate normalization is typically seen at the syllable level, hence at longer temporal modulations. Critically, the neurobiological mechanism underlying rate normalization is assumed to relate to entrainment to syllable-level theta oscillations (Bosker & Ghitza, 2018). Therefore, given that the temporal sampling framework (Goswami, 2011) assumes the deficit underlying impaired phonological processing in DD is the ability to entrain to brain oscillations at the syllable level, this account straightforwardly predicts an atypical use of rate context in those with DD.

Method

Participants

The study consisted of 31 university students, 15 individuals with DD and 16 healthy readers. All were native speakers of Hebrew with no history of neurological disorders, psychiatric disorders, or attention deficits (according to the criteria of the American Psychiatric Association, 2013). In addition, all participants had normal or corrected-to-normal vision and had normal hearing. The DD group was recruited from the Yael Learning Disabilities Center at the University of Haifa, Israel. A documented diagnosis of a comorbid learning disability, such as attention-deficit/hyperactivity disorder or specific language impairment, or any sensory or neurological impairment was an exclusion criterion. The inclusion criteria for the dyslexia group were (a) a formal diagnosis of dyslexia by a qualified psychologist, as indicated by previous test records of the participant, and (b) a score of at least 1 *SD* below the average of the local norms in a test of phonological decoding (nonword reading). This test was part of the psychometric test battery that was administered to participants in this study. Since there are no standardized reading tests for adults in Hebrew, the selection was based on local norms, using similar criteria to other studies conducted on Hebrew readers with DD (Weiss, Katzir, & Bitan, 2016; Yael, Tami, & Tali, 2015). Scores of 1 *SD* below the mean of the local norms were chosen following the standard practice in the Hebrew literature (Breznitz & Misra, 2003; Shany & Breznitz, 2011). The control group consisted of individuals with no reading problems (i.e., above the inclusion criteria of the DD group on the nonword reading test) and the same level of cognitive ability (i.e., reaching a scaled score of 7 or above in Similarities and Block Design subtests from the Wechsler Adult Intelligence Scale; Wechsler, 1997). Based on these criteria, one participant with DD and five control participants were replaced to yield the sample of 31 participants listed above. In particular, the reading scores of the replaced controls were below the inclusion criteria for the DD group. Reading scores of the replaced participant with DD were above the exclusion criteria for the dyslexia group. All participants completed a battery of tests to assess multiple indicators of language skills and general cognitive ability (see below). Participants were compensated for their participation in the study (120 New Israeli Shekel, approximately 30 USD). Written informed consent was obtained from all participants. The study was approved by the faculty ethics committee at the University of Haifa and conducted in accordance with the Declaration of Helsinki.

Cognitive and Literacy Measures

Intellectual ability was assessed by means of two subtests from the Wechsler Adult Intelligence Scale (Wechsler, 1997). Verbal intelligence was assessed by the Similarities subtest. This test requires participants to indicate how alike various pairs of words (e.g., dog/cat) are. This test consists of 19 pairs. Task administration is discontinued when a participant fails to provide the correct answer on four consecutive pairs. Nonverbal intelligence was measured by the Block Design subtest. In this test, participants are required to rearrange blocks with different color patterns according to a stimulus presented to them on a card.

Verbal working memory was assessed by the Digit Span subtest from the Wechsler Adult Intelligence Scale (Wechsler, 1997). In this task, participants are required to recall the names of digits presented auditorily in the order they appeared, with a total raw score of 28. Task administration is discontinued after a failure to recall two trials with a similar length of digits.

Word reading and decoding skills were examined by the One-Minute Test of Words (Shatil, unpublished test for Hebrew) and the One-Minute Test of Nonwords (Shatil, unpublished test for Hebrew), which assess the number of words and nonwords accurately read aloud within 1 min. The One-Minute Test of Words contains 168 nonvowelized Hebrew words of an equivalent level of difficulty, listed in columns, ranging from high to low lexical frequency. The One-Minute Test of Nonwords contains 86 successively difficult vowelized Hebrew nonwords listed in seven columns. It assesses participants' ability to read nonwords varying in complexity with a maximum total raw score of 45. Both accuracy (number of correct words read per minute) and speed (number of items read per minute) were measured.

Phonological awareness was assessed by the Phoneme Deletion Test (Breznitz & Misra, 2003). This test consists of 25 words. The experimenter reads a word and a phoneme aloud, and the participant is required to indicate how the word sounds after deletion of this phoneme as fast and as accurately as possible. Due to experimenter error, only accuracy scores, but not response speed, was obtained for this measure.

Naming skills were assessed through the Rapid Naming Test (RAN; Breznitz, 2003) using letters and objects. Five (nonfinal) Hebrew letters—ס, א, ד, ג, ל—in the Letter-Naming Test (RAN letters) and five objects—flower, cat, book, watch, and flag—in the Object-Naming Test (RAN object) were presented 10 times in random order. Participants were asked to read the 50 letters and name the 50 objects aloud as quickly and accurately as they could. The accuracy rates and the time for naming the entire list were measured.

Groups did not differ according to age or intelligence according to *t* tests for independent samples. However, compared with the group of healthy readers, the DD group showed a clear profile of reading disability, conforming to the symptomatology of DD. They differed significantly from the control group on word reading and decoding skills. Results are reported in Table 1.

Rate Normalization Task

Since rate normalization has never been investigated in Hebrew, a first step was to examine whether and to what extent the effect is observed in healthy Hebrew native listeners (i.e., to norm our material) before comparing it to people with DD. For this purpose, in this study, participants performed a phonetic categorization task in which they were asked to decide whether they hear the Hebrew word *tam* ("naive") or *taam* ("taste"; where the /a/ in *taam* is relatively longer) preceded by 30 different sentences between five and 19 syllables in length at a slow or fast speaking rate (approximately five vs. eight syllables per second as implemented by linear compression of the original speech signal). If rate context influences phoneme categorization in Hebrew, we expect that participants' perception will shift toward more long-vowel (i.e., *taam*) responses if the word is preceded by sentences spoken at a fast speaking rate and toward more short-vowel (*tam)* responses if the word is preceded by sentences at a slow speaking rate.

The Hebrew minimal word pair "*tam*"–"*taam*" (English "naïve"–"taste," respectively) was selected for target categorization since duration is the main acoustic cue for distinguishing between these words. This was confirmed by acoustic measures on 30 recordings of the minimal word pair *tam–taam* and another minimal word pair that differed in the same phoneme contrast (e.g., *ram–raam,* "tall" vs. "thunder," respectively; note that for the main experiment only *tam–taam* was used). Word pairs were recorded by a male native speaker of Hebrew at the end of the context sentences that were later used for the speaking rate experiment. The vowel in *taam* and *raam* was consistently produced as longer than in *tam* and *ram* (mean duration of long vowels = 193 ms, SD = 22; mean duration of short vowels = 115 ms, SD = 14).

A pilot experiment demonstrated that Hebrew listeners rely on duration to distinguish between these words when categorizing a vowel duration continuum in the word pair *tam–taam*. For this pilot, a 15-step duration continuum was created from one recorded token of *taam* (i.e., the word containing the long vowel). The consonants were set to fixed durations of 41 ms for /t/ and 130 ms for /m/. These durations were based on the average duration of these sounds across all recordings of *tam* and *taam* and judged as appropriate for both words so that the vowel information was the only cue to differentiate between the words (in natural recordings, the durations of the other sounds in the words, specifically the /m/, may covary with vowel duration). A native speaker of Hebrew confirmed through informal listening that the chosen consonant durations sounded natural for both *tam* and *taam*. The vowel duration continuum was created to range from 47 to 206 ms, hence enhancing the natural durations on both sides of the continuum.

Based on this pretest, for the main speaking rate experiment, another vowel duration continuum was created. It spanned a shorter range of durations from 145 to 206 ms. These new end points were selected since the pretest showed that any durations shorter than 145 ms were perceived as short vowel (*tam*). A vowel duration of 206 ms consistently led listeners to perceive the long vowel (*taam*). In this way, the continuum used in the main experiment ranged from a clearly short to a clearly long vowel, with the most ambiguous durations approximately centered on the continuum. This perceptual scaling and centering is useful since context effects can typically be expected to be largest in the ambiguous region of the continuum. For the final version of the experiment, five continuum steps were selected, with durations of 145, 167, 176, 185, and 207 ms. That is, we reduced the number of continuum steps to shorten the whole experiment, and we used a denser sampling of steps in the ambiguous region, again, because ambiguous durations can be expected to be most strongly influenced by the speaking rate of a preceding context sentence.

Thirty semantically neutral Hebrew sentences were created of the type "The third term in the dictionary is called…" (i.e., the target could not be predicted from the content of the sentences; see Appendix). The sentences were based on a list of sentences that had previously been

Table 1. Performance of the developmental dyslexia (DD) and control groups on psychometric measures.

Measurement	Controls	DD	*t*	*p*
Age	26.87	30.2	–1.58	*ns*
Oral word letter decoding				
Oral words recognition speed	111.06	67	5.99	< .001
Oral words recognition accuracy	102	63.86	3.73	< .001
Oral nonwords recognition speed	71.87	43.66	5.89	< .001
Oral nonwords recognition accuracy	66.18	25.46	11.3	< .001
Rapid naming measures				
Naming letters	23	25.73	–1.45	*ns*
Naming objects	33.75	41.6	–3.56	< .01
Phonological processing				
Phoneme deletion (accuracy)	21.5	18.4	1.78	.07
Short verbal working memory				
Digit span	11.31	9.4	1.91	.06
Intellectual ability				
Similarities (verbal intelligence)	10.8	12.4	–1.63	*ns*
Block design (nonverbal intelligence)	10.37	11.33	–1.48	*ns*

Note. *ns* indicates nonsignificant.

used for speaking rate experiments in Dutch (Bosker et al., 2017) and German (Bosker & Reinisch, 2017). Multiple sentences were preferred over single-context sentences (as in Reinisch & Sjerps, 2013) to make the experiment more engaging for participants and—importantly—to increase ecological validity as any effects found for multiple items are less likely to be item specific. The sentences recorded included one of the target words, of which one was selected to create the continuum as described above. To create the rate-manipulated context sentences, the target words were cut out of the recordings. All sentences were then normalized and matched for root-mean-square amplitude to the selected targets of the *tam–taam* continuum. The rate manipulation was implemented using the pitch synchronous overlap and add (PSOLA) method as implemented in the phonetics software PRAAT (Boersma & Weenink, 2017). This method divides the speech waveform into small overlapping segments of which parts are duplicated if the speech signal is to be made longer/slower and of which parts are deleted if the speech signal is to be shortened/compressed/made faster. The duration or speaking rate is hence changed linearly, that is, the same manipulation is applied to all segments equally. Since the recorded sentences were spoken rather slowly (i.e., at a rate of, on average, five syllables per second), the slow version of the sentences to be used in the experiment was a simple PSOLA resynthesis with a manipulation of 1% of the original duration. Applying the manipulation even without substantial changes was to control for the presence of any artifacts that could be introduced due to the manipulation for the fast sentences. Fast sentences were created by PSOLA resynthesis by compressing them to 60% of their original duration (i.e., a rate of approximately eight syllables per second). The fast and slow versions of each of the 30 sentences were then combined with all five selected steps of the *tam–taam* continuum. A silent gap of 250 ms was inserted between the sentences and the target to prevent masking effects without introducing the perception of a break before the target.

Procedure

The procedure followed previous experiments on speaking rate normalization in other languages (Bosker & Reinisch, 2017; Bosker et al., 2017; Reinisch, 2016a, 2016b). Listeners were tested individually in a sound-attenuated booth. On each trial, two response alternatives (“tam”–“taam”) were presented orthographically on a screen throughout the trial, with *tam* always presented on the left side of the screen and corresponding with the left button. After 200 ms, listeners were presented the carrier sentence followed by the target word. Stimuli were presented over headphones at a comfortable listening level. The listeners’ task was to indicate, by pressing a button, which of the two words they heard. Listeners were not informed that the critical issue was the perception of vowel length. The next trial started 4,000 ms after the participants’ response. No feedback was given. All combinations of fast and slow carrier sentences with the five steps of the continuum were presented twice for a total of 600 trials (i.e., 30 sentences × 2 rates × 5 continuum steps of the target × 2 repetitions). Trials were presented with a different randomization for each participant and the restriction that all stimuli were presented once before they were repeated. Given the large number of different stimuli resulting from all combinations of sentences, rates, and continuum steps, a randomized design was considered preferable over blocked designs because (a) the choice of which factors to block would not have been obvious (e.g., by sentence, by rate, by step), (b) counterbalancing all possible orders of blocks over participants would not have been possible, and (c) experiments on speaking rate normalization are prone to effects of blocking (e.g., see Baese-Berk et al., 2014; Maslowski, Meyer, & Bosker, 2019). After every 65 trials, participants were allowed to take a short break. The experiment was controlled by

E-Prime software (Schneider, Eschman, & Zuccolotto, 2002), which allowed for automatically randomized stimulus presentation and recording of answers. It took approximately 40 min to complete.

Analyses

Statistical analyses were conducted using linear mixed-effects models as implemented in the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in R (Version 3.4.3, R Core Team; Pinheiro, Bates, DebRoy, & Sarkar, 2017). Mixed-effects models were deemed appropriate as our design includes repeated measures over 31 participants and 30 items (i.e., sentences). Mixed models allow the raw input to be analyzed without prior aggregation over repeated measures. They further allow to simultaneously specifying participants and items as random factors, which would amount to an F1 versus F2 analysis using traditional analyses of variance (ANOVAs; i.e., once analyzing effects by averaging over items and once over participants). Importantly, by simultaneously taking into account variation by participants and items, mixed models have been shown to be preferable over traditional ANOVAs, as they are less susceptible to Type I errors in such cases (Quené & Van den Bergh, 2008). The specification of random factors allows us to take into account that participants and items may differ idiosyncratically, and by estimating participant and item idiosyncrasies, they also allow an estimate of how likely it is that the same result would be replicated with different participants and items.

Importantly, in mixed-effects models, the random effects structure includes the specification of random intercepts and slopes. Random intercepts estimate participant or item variation around the average. Random slopes capture differences in the sensitivity to the fixed effects (for more detailed discussions of mixed-effects models, see Baayen, Davidson, & Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013; Field, Miles, & Field, 2012).

For the present analyses, we fitted a linear mixed-effects model with a logistic linking function (Jaeger, 2008) to account for the binomial nature of our dependent variable (i.e., long-vowel response *taam* coded as 1, short-vowel response *tam* coded as 0). The random effects structure included random intercepts for participants and items (i.e., sentences), each with random slopes for continuum step and rate. The interaction between these two factors was not included in the random effects structure as model comparisons using log likelihood ratio tests showed that the more complex models did not fit the data better. Random slopes for participant group were not included since it is a between-participants factor (Barr et al., 2013) and over items again did not improve the model fit.

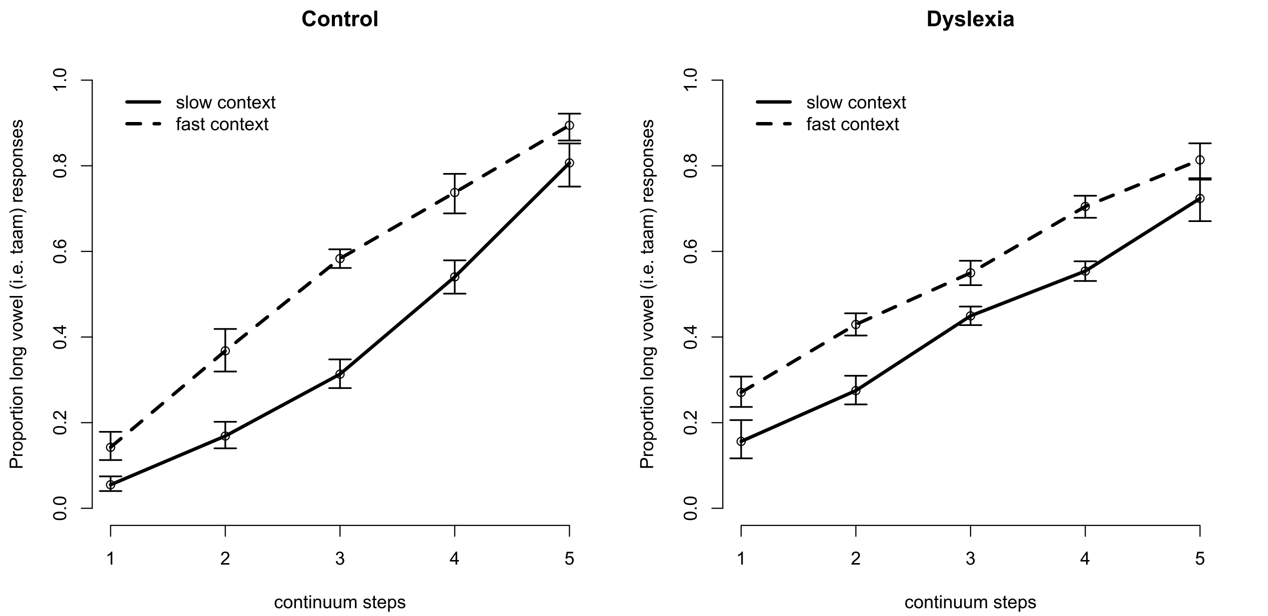
Fixed effects were continuum step (centered on zero, ranging from −2 to 2; the lower the number, the shorter the vowel), rate (fast coded as 0.5, slow coded as −0.5), listener group (individuals with DD coded as 0.5, controls coded as −0.5), and all interactions. Note that with this coding the grand mean is mapped onto the intercept, and effects can be interpreted as main effects comparable to ANOVA with the magnitude of the regression weight indicating the effect size and the direction of the regression weights (i.e., positive vs. negative) indicating the direction of the effect.

Results

Figure 1 illustrates the proportion of long vowel (i.e., *taam*) responses averaged over participants and sentences for the five continuum steps. Results for the control group are plotted in the left panel, whereas results for the DD group are plotted in the right panel. Responses following a fast sentence are presented in dashed lines, following a slow sentence in solid lines. Error bars indicate 1 *SE*. It can be observed that, for both groups, the higher the continuum step (i.e., the longer the vowel), the more long-vowel responses were given. That is, listeners used the duration cue in the vowel to base their decision on (i.e., concurrent speech perception). Moreover, the dashed lines are above the solid lines, suggesting a rate effect such that more long-vowel responses were given following a fast than a slow context. Dashed and solid lines appear to differ for both groups, indicating an effect on context on subsequent speech perception. However, the difference between the solid and dashed lines appears somewhat smaller for the DD group than the control group, suggesting a diminished effect of context for the DD group.

Results of the statistical model confirm these observations from Figure 1. They show a main effect of continuum step ($b_{(\text{Step})} = 0.41$, $SE = 0.05$, $z = 7.91$, $p < .001$; $b_{(\text{Intercept})} = -0.15$, $SE = 0.11$, $z = -1.39$, $p = .166$) with more long-vowel responses the longer the duration of the vowel and a main effect of rate ($b_{(\text{Rate})} = 0.79$, $SE = 0.06$, $z = 10.49$, $p < .001$) with more long-vowel responses following a fast than a slow rate. These are the two main effects that indicate that, overall, our manipulation worked. Listeners used the duration cue in the vowel (effect of step) and the rate context as the basis for their decisions. The main effect of group was not significant ($b_{(\text{Group})} = -0.23$, $SE = 0.16$, $z = -1.41$, $p = .159$), indicating that listeners in the two groups did not differ in their overall amount of long-vowel (i.e., *taam*) responses. Importantly, both significant effects were modulated by two-way interactions with listener group. The interaction between rate and listener group ($b_{(\text{Rate:Group})} = 0.392$, $SE = 0.14$, $z = 2.76$, $p = .006$) shows that individuals with DD had a smaller effect of rate (smaller difference in the proportion of long-vowel responses between fast and slow context sentences) than listeners in the control group. This finding concerns the first research question and implies that the ability to implicitly extract temporal information in a context for subsequent speech perception is carried out less effectively in those with DD. The marginally significant interaction between continuum step and listener group ($b_{(\text{Step:Group})} = 0.185$, $SE = 0.10$, $z = 1.78$, $p = .07$) suggests that individuals with DD had somewhat shallower categorization functions than the control group. That is, individuals with DD were somewhat less decisive in categorizing the

Figure 1. Proportion of long-vowel (i.e., "taam") responses (*y*-axis) over continuum steps (*x*-axis) for the fast versus slow rate context for the two listener groups. Dashed lines indicate the fast rate context; solid lines indicate the slow rate contexts. Results for the control group are presented in the left panel, and results for the dyslexia group are presented in the right panel. Error bars indicate 1 *SE* and are corrected for the manipulation of rate as a within-participant factor (see Morey, 2008).



middle (i.e., acoustically ambiguous) steps of the duration continuum. This finding concerns the second research question and suggests problems with using temporal information in concurrent speech perception in DD. The third possible two-way interaction between rate and continuum step and the three-way interaction between all three factors were not significant ($b_{(Rate:Step)} = -0.02$, $SE = 0.01$, $z = -1.51$, $p = .132$; $b_{(Group:Rate:Step)} = -0.035$, $SE = 0.03$, $z = -1.29$, $p = .196$).

To follow up on the interaction between group and rate (i.e., pertaining to Research Question 1) and to specifically test whether individuals with DD would show an effect of rate on their own despite it being smaller than for the control group, two additional mixed-effects models were run, one for each participant group. Both models had random intercepts for participants and items with random slopes for rate and step over participants and a random slope for rate over items. These were the best fitting models as again established in model comparisons using log-likelihood ratio tests. Fixed factors were continuum step, rate, and their interaction, coded as described above.

Results for the group of individuals with DD showed a main effect of continuum step ($b_{(Step)} = 0.31$, $SE = 0.05$, $z = 5.95$, $p < .001$; $b_{(Intercept)} = -0.03$, $SE = 0.09$, $z = -0.36$, $p = .716$) with more long-vowel responses the longer the vowel and an effect of rate ($b_{(Rate)} = 0.31$, $SE = 0.05$, $z = 5.96$, $p < .001$) with more long-vowel responses following the fast than slow carrier sentences. The interaction was not significant ($b_{(Step:Rate)} = -0.006$, $SE = 0.02$, $z = -0.31$, $p = .754$). Results for the control group showed a main effect of continuum step ($b_{(Step)} = 0.51$, $SE = 0.09$, $z = 5.44$, $p < .001$; $b_{(Intercept)} = -0.27$, $SE = 0.16$, $z = -1.64$, $p = .102$) with more long-vowel responses the longer the vowel and an effect of rate ($b_{(Rate)} = 0.98$, $SE = 0.11$, $z = 8.89$, $p < .001$) with more long-vowel responses following the fast than slow carrier sentences. The interaction failed to reach significance ($b_{(Step:Rate)} = -0.037$, $SE = 0.02$, $z = -1.83$, $p = .068$) but suggests that the effect of rate was smaller the longer the vowel duration. Notably, the regression weights for rate for the two groups indicate that the effect of rate was roughly three times as large for the control group ($b_{(Rate)} = 0.98$) than the DD group ($b_{(Rate)} = 0.31$). That is, regarding Research Question 1, these results show that individuals with DD are able to use speaking rate context for subsequent phoneme categorization but less effectively than healthy readers.

Discussion

The purpose of this study was to examine whether individuals with DD are capable of implicitly extracting temporal information embedded in a context and use this information in phonological categorization in a similar fashion to healthy readers. The use of acoustic context information such as the speech rate of a sentence can help listeners to overcome variability that is inherent in the acoustic signal. Based on previous studies suggesting temporal processing deficits in those with DD, we hypothesized that the use of speaking rate context might be impaired in those with DD relative to healthy listeners and that categorization of speech sounds based on durational cues will be different between the two groups.

Results of this study showed that the speaking rate of context sentences influenced the phonological categorization of a Hebrew vowel contrast in both groups of listeners. In particular, participants' perception was shifted toward long-vowel (i.e., *taam*) responses when the context was fast relative to context sentences at a slow speaking rate—in line with the many previous studies observing rate normalization effects in other languages (for recent studies including summaries of past research, see Heffner et al., 2017; Reinisch, 2016b; Reinisch et al., 2011; Reinisch & Sjerps, 2013; Toscano & McMurray, 2015). Importantly, the magnitude of this rate effect differed between listener groups such that it was significantly smaller in those with DD compared with the control group of healthy readers. At first glance, the observation that individuals with DD rely on context information to a lesser extent than the controls appears to contrast with previous findings suggesting that other types of normalization processes, such as talker normalization, do not differ between DD and healthy readers (Blomert et al., 2004; Gabay & Holt, 2018). However, previous studies focused on the use of spectral context information rather than temporal context, as was the case for this study on speaking rate normalization. Speech categorization deficits in DD have been attributed to an auditory processing deficit that is specific to temporal acoustic information (Tallal, 1980; Vandermosten et al., 2010, 2011). This can explain the discrepancies across studies.

The present results are hence consistent with other studies indicating impaired temporal processing in DD, including temporal order judgment tasks (Farmer & Klein, 1995; Tallal, 1980, 1984), understanding time-compressed speech (Freeman & Beasley, 1978; Gabay et al., 2018; Watson, Stewart, Krause, & Rastatter, 1990), and time estimation (Gooch, Snowling, & Hulme, 2011; Khan et al., 2014; Nicolson et al., 1995). The marginally significant interaction between continuum step and listener group further suggests that individuals with DD had shallower categorization functions than the control group; that is, they were less certain how to categorize the acoustically ambiguous middle part of the sound duration continuum. This finding is consistent with previous findings indicating shallower categorization functions during concurrent speech processing in people with DD for other types of acoustic cues (Godfrey, Syrdal-Lasky, Millay, & Knox, 1981; Mody, Studdert-Kennedy, & Brady, 1997; Reed, 1989; Serniclaes, Van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Tallal, 1980). Notably, the finding of a reduced magnitude of the effect of rate context in this study suggests that temporal processing deficits in those with DD extend beyond concurrent speech perception and are also evident when temporal processing needs to be implicitly extracted from a sentence context.

Our finding of diminished rate normalization effects in individuals with DD compared with healthy listeners is further consistent with accounts suggesting impaired temporal processing as the underlying cause of phonological impairment found in DD. While it could be assumed that, due to its focus on rapid temporal information in the scope of tens of milliseconds, the rapid temporal processing deficit theory (Tallal, 1980) does not specifically predict impairments in rate normalization, the temporal sampling framework (Goswami, 2011) predicts our effects. The temporal sampling framework aligns with accounts of neural entrainment during speech perception in healthy listeners (e.g., Giraud & Poeppel, 2012; Ghitza, 2011; Poeppel, 2003) but suggests that individuals with DD show poorer alignment of entrained neural oscillations during speech processing. This approach focuses on frequency bands pertaining to syllable rate in speech (i.e., delta or theta), and neural entrainment to these frequency bands has been suggested as one explanation for the observed rate normalization effects found in healthy listeners (Bosker, 2017; Bosker & Ghitza, 2018). Based on this, the impairment of this entrainment in DD straightforwardly predicts the deficits in rate normalization that we observed.

It should be noted that the present findings are also consistent with other accounts of DD arguing for a selective disruption in brain structures related to the procedural learning system (such as the basal ganglia and the cerebellum) as the underlying cause of DD (Gabay & Holt, 2015; Krishnan, Watkins, & Bishop, 2016; Nicolson & Fawcett, 2007, 2011; Ullman, 2004). The basal ganglia and the cerebellum play a significant role in timing (Nozaradan, Schwartze, Obermeier, & Kotz, 2017) and, as such, could potentially explain temporal processing deficits observed in our sample of individuals with DD. Nevertheless, future studies are needed to determine whether temporal processing deficits in DD occur alongside other deficits predicted by this account (skill acquisition deficiencies).

As mentioned in the introduction, rate normalization is a perceptual process that listeners rely on to cope with variability in the speech signal that allows them to take into account the context in which a given sound is heard to interpret this sound. The question that now arises is how the observed impairment in this perceptual process is related to the set of reading impairments found in those with DD more generally. What does it mean that the use of (temporal) context information is impaired? The strongest interpretation would be that a decreased ability to use this perceptual process reduces the abilities of those with DD to disambiguate speech sounds in real-world listening environments where variability is ubiquitous and the use of context information strongly supports speech processing. A more specific consequence then would be that, due to the reduced contextual support, the perception of speech sounds is less categorical; that is, listeners are less sure about the identity of any given sound, leading to phonological impairments, which, in turn, cause reading difficulties. One could argue, however, that poor rate normalization is the consequence of poor phonological representations (manifested in atypical categorical perception) that characterize those with DD. Less categorical boundaries were also observed in the present sample of participants as indicated by the (marginally significant) interaction between continuum step and listener group showing that the categorization slopes of those with DD were shallower (i.e., less categorical) than for healthy listeners. This is consistent with previous findings reporting problems to use durational cues for vowel categorization in individuals with DD (Groth et al., 2011; Steinbrink et al., 2014).

However, a recent observation makes the explanation of poor rate normalization as a consequence of poor phonological categorization less probable. In particular, a recent study has shown that children who have less distinct phonological categories than adults demonstrate relatively sharper phonological categories when categories were presented in context compared to a situation in which they were presented in isolation (Hufnagle, Holt, & Thiessen, 2013). This leads to the assumption that contextual information supports categorization of less well-defined phonological representations. In that sense, we could have expected to find larger context effects in those with DD. Yet, the opposite pattern was observed in this study.

Another important thing to note is that, while the current study suggests a relation between a reduced rate context effect and reading impairments, it does not determine a causal relationship between the two. For that, developmental and longitudinal studies are needed in order to determine how poor rate normalization is related to the ability to form phonological representations. Furthermore, it may be important in the future to examine the influence of rate information of a context on DD using speech versus nonspeech stimuli. Such a comparison would help to determine whether poor use of speaking rate context arises from a domain-specific or domain-general deficiency in temporal processing. Lastly, as noted in the introduction, it may be important to distinguish between effects of acoustic context pertaining to the spectral (Blomert et al., 2004; Gabay & Holt, 2018) versus temporal domain.

To conclude, in this study, we examined whether people with DD would use similar perceptual normalization processes for speech sound categorization as healthy readers to account for acoustic variation due to speakers, accents, or—here—speaking rate. Consistent with previous observations indicating impaired temporal processing skills in those with DD, we found diminished reliance on rate context to disambiguate speech sounds in listeners with DD compared with a control group of typically developed listeners. The results are consistent with perceptual frameworks suggesting temporal processing deficits in those with DD. Atypical use of rate normalization processes may influence the ability of individuals with DD to overcome speech variability that may affect the formation of precise phonological representations.

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List of Sentences That Has Been Used in the Current Study (in Hebrew/Latin/Translation), Including Number of Syllables for Each Sentence

Sentence (Hebrew, Latin transliteration, *translation*)	**Number of syllables (in Hebrew)**
הם השתמשו במילה hem histamshu bamila They used the word	7
בסיפורו דני השתמש במונח besipuro dani hishtamesh bamunach In his story Dani used the term	12
במילון מוגדרת משמעותו של מונח בשם bamilon mugderet mashmauto shel munach beshem In the dictionary, it is defined the meaning of term named	15
הם מכנים זאת hem mechanim zot They call these things	5
יפית תמיד בחרה במונח yafit tamid bahara bamunach Yafit always chose the term	10
שם היה כתוב פירוש ל sham haya katuv perush le There was written the translation for	8
הילדים תהו לגבי פירושו של hayeladim tahu legabey perushu shel The children argued about the meaning of the word	12
בספר יש גיבור ששמו הוא basefer yesh gibor seshmo hu In the book there is a hero whose name is	9
חבר שלהם נקרא hachaver shelahem nikra Their friend is called	7
היא לא כתבה מונח בשם hi lo katva munach beshem She did not write the term named	8
זכיתי בפסלון כשאייתתי zachiti bepislon ksheiyateti I won the sculpture when spelling	11
מונח מספר שלוש במילון מכונה munach mispar shalosh bamilon mechune The third term in the dictionary is called	12
לדני יש קושי בביטוי ledani yesh koshi bebituy Danny has difficulties with expressing	9
המלכה מתחילה את סיפורה ואומרת hamalca matchila et sipura veomeret The queen begins her story and is saying	14
ישנן לפחות עוד שתי מילים טובות יותר לתיאור yeshnan lefachot od sthey milim tovot yoter leteaur There is at least another two better words for	16
אם הוא הולך קרא בקול im hu holech kra bekol If he leaves you call	8
הוא קרא להם בשם hu kara lahem bashem He called them with the name	7
היא פתרה תשבץ עם מילה דומה ל hi patra tasbetz em mila doma le She solved the puzzle using a similar word to	11
היא חיפשה סיפור שכותרתו hi hipsa sipur shecotarto She looked for a story with the title	9
שיריו הטובים ביותר מסתיימים במילה shirav hatovim beyoter mistaymim bamila His best songs end in the word	14

Appendix (p. 2 of 2)

List of Sentences That Has Been Used in the Current Study (in Hebrew/Latin/Translation), Including Number of Syllables for Each Sentence

Sentence (Hebrew, Latin transliteration, *translation*)	Number of syllables (in Hebrew)
הוא סיים במילה hu siyem bamila He ended (his speech) with the word	6
גילינו פרשנות חדשה למילה gilinu parshanut hadash lamila We found new translations for the word	12
הוא חיפש כלב ששמו הוא hu hipes kelev shshmo hu He looked for a dog named	8
ישנם מספר מילים נרדפות למילה yeshnam kama milim nirdafot lamila There are several synonyms for	12
למגמגם היה קושי בביטוי lamegamgem haya koshi bebituy The stutterer had trouble saying	11
היא שיימה זאת כ he shyma zot ke She named it as	5
התשבץ כלל מילה בשם hatasbetz kalal mila beshem The puzzle contained the word	9
חיפשתי במילון את פירושו של hipasti bamilon et perushi shel I looked/search in the dictionary the meaning of	11
מחר הקומיקאי מציג מופע הנקרא mahar hakomikai mezig mofa beshem Tomorrow the comedian presenting a show named	13
שמו של חתול זה הוא shemo shel hatul ze hu The name of this cat is	7