The role of categorical speech perception and phonological processing in familial risk children with and without dyslexia

Hakvoort, B.; de Bree, E.; van der Leij, A.; Maassen, B.; van Setten, E.; Maurits, N.; van Zuijen, T.L.

DOI
10.1044/2016_JSLHR-L-15-0306

Publication date
2016

Document Version
Final published version

Published in
Journal of Speech, Language, and Hearing Research

JSLHR

Research Article

The Role of Categorical Speech Perception and Phonological Processing in Familial Risk Children With and Without Dyslexia

Britt Hakvoort,[a] Elise de Bree,[a] Aryan van der Leij,[a] Ben Maassen,[b] Ellie van Setten,[b] Natasha Maurits,[c] and Titia L. van Zuijen[a]

Purpose: This study assessed whether a categorical speech perception (CP) deficit is associated with dyslexia or familial risk for dyslexia, by exploring a possible cascading relation from speech perception to phonology to reading and by identifying whether speech perception distinguishes familial risk (FR) children with dyslexia (FRD) from those without dyslexia (FRND).

Method: Data were collected from 9-year-old FRD (*n* = 37) and FRND (*n* = 41) children and age-matched controls (*n* = 49) on CP identification and discrimination and on the phonological processing measures rapid automatized naming, phoneme awareness, and nonword repetition.

Results: The FRD group performed more poorly on CP than the FRND and control groups. Findings on phonological processing align with the literature in that (a) phonological processing related to reading and (b) the FRD group showed the lowest phonological processing outcomes. Furthermore, CP correlated weakly with reading, but this relationship was fully mediated by rapid automatized naming.

Conclusion: Although CP phonological skills are related to dyslexia, there was no strong evidence for a cascade from CP to phonology to reading. Deficits in CP at the behavioral level are not directly associated with dyslexia.

Dyslexia is characterized by severe and persistent difficulties in reading fluency and accuracy and/or spelling skills that are not caused by sensory deficits, low intelligence, or environmental factors such as poor educational opportunities (e.g., Vellutino, Fletcher, Snowling, & Scanlon, 2004). One of the main factors that is commonly thought to contribute to reading problems is a phonological core deficit (Protopapas, 2013; Vellutino et al., 2004): Poor phonological skills may ultimately impede the phoneme-to-grapheme mapping process, which is at the core of reading ability. Phonological deficits can roughly be divided into three dimensions (Ramus & Szenkovits, 2008; Wagner & Torgesen, 1987): (a) phonological awareness (PA; e.g., Boets et al., 2010; de Jong & van der Leij, 2003), (b) verbal short-term memory (VSTM; often measured by nonword repetition [NWR]; Snowling, Goulandris, Bowlby, & Howell, 1986; de Bree, Rispens, & Gerrits, 2007), and (c) rapid automatized naming (RAN), which mainly indicates slower (timed) lexical retrieval (e.g., Wolf, Bowers, & Biddle, 2000). Speech perception has been suggested to underlie phonological processing skill (Fitch, Miller, & Tallal, 1997; Tallal, 1980; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). Deficits in speech perception may be at the basis of a cascade of problems ranging from speech perception, through phonology, to reading (Goswami, 2015).

The relation between speech perception and reading has been investigated extensively in categorical speech perception studies (CP; see Noordenbos & Serniclaes, 2015). CP targets listeners' capacity to categorize or discriminate stimuli on an acoustic continuum, for example, from /ba/ to /da/. Although the stimuli lie on an acoustic continuum, they are perceptually dichotomous. In categorization tasks, listeners indicate whether they hear /ba/ or /da/, from

[a]Research Institute of Child Development and Education, Faculty of Social and Behavioral Sciences, University of Amsterdam, Amsterdam, the Netherlands
[b]Centre for Language and Cognition Groningen (CLCG) & University Medical Centre Groningen, University of Groningen, Groningen, the Netherlands
[c]Department of Neurology, University Medical Centre Groningen, University of Groningen, Groningen, the Netherlands

Correspondence to Britt Hakvoort: b.e.hakvoort@gmail.com

Editor: Rhea Paul
Associate Editor: Ann Tyler
Received September 2, 2015
Revision received January 15, 2016
Accepted May 9, 2016
DOI: 10.1044/2016_JSLHR-L-15-0306

Disclosure: The authors have declared that no competing interests existed at the time of publication.

which the perceptual category boundary can be identified. In discrimination tasks, the perceptual boundary is identified by presenting listeners with pairs of stimuli. The acoustic distance between each pair of stimuli is kept constant. This results in pairs that do not cross the perceptual category boundary (within-category contrasts, more difficult to discriminate) and pairs that cross the perceptual category boundary (between-category contrasts, easier to discriminate). Listeners have to indicate whether a pair consists of the same or different stimuli. Both in identification and discrimination tasks, accuracy and reaction times (RT) are recorded. Often, an increase in RT and a decrease in accuracy are found when the presented stimuli include tokens that straddle the phoneme boundary, since uncertainty is highest in that area (Noordenbos & Serniclaes, 2015; Pisoni & Tash, 1974; Poeppel et al., 2004).

CP has previously been linked to dyslexia; if categorization of a speech sound is inaccurate, this may impede the formation of accurate representations of phonemes, which may have a detrimental effect on reading ability (Serniclaes, Sprenger-Charolles, Carré, & Demonet, 2001). Yet, the way in which a CP deficit manifests itself in dyslexia is debated in the literature (Bogliotti, Serniclaes, Messaoud-Galusi, & Sprenger-Charolles, 2008; Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009; Maassen, Groenen, Crul, Assman-Hulsmans, & Gabreëls, 2001; Messaoud-Galusi, Hazan, & Rosen; 2011; Noordenbos, Segers, Serniclaes, Mitterer, & Verhoeven, 2012a; Serniclaes, van Heghe, Mousty, Carré, & Sprenger-Charolles, 2004; Vandermosten et al., 2010). On one hand, studies show that (subgroups of) people with dyslexia perform more poorly than controls on tasks measuring CP (e.g., Vandermosten et al., 2010; Hazan et al., 2009; Messaoud-Galusi et al., 2011; Maassen et al., 2001). These outcomes indicate poor readers to have a diminished ability to categorize and discriminate between phonemes, indicating poorer speech perception. This is reflected in lower discrimination and identification scores. On the other hand, some studies demonstrate people with dyslexia to have better discrimination of within-category phonemes. They perceive within-category tokens as isolated phonemes instead of generalizing them to one phonemic category, which is not useful to the listener, because within-category differences are not phonemic in nature. This phenomenon, allophonic perception, is shown through good discrimination and shallow identification functions (e.g., Bogliotti et al., 2008; Noordenbos et al., 2012a; Serniclaes et al., 2001, 2004).

The evidence regarding the role of a CP deficit in the cascade of problems from speech perception to phonology to reading has been inconclusive. For a cascade to be present, a relation between CP and reading is a prerequisite. Although correlations between CP and reading (Maassen et al., 2001) have been found, the observed deficits in CP in participants with dyslexia differ across studies (e.g., Hazan et al., 2009; Messaoud-Galusi et al., 2011; Noordenbos & Serniclaes, 2015). Defining the relation between CP and reading is therefore challenging. Furthermore, a cascade from CP via phonological processing to reading needs to be attested. Although correlations between CP and PA have been found (Boets et al., 2011; Boets, Wouters, Van Wieringen, & Ghesquière, 2007; Hazan et al., 2009; Messaoud-Galusi et al., 2011; Noordenbos et al., 2012a), results are inconsistent, as correlations were absent in some studies (Ramus et al., 2003; Serniclaes et al., 2004). Task differences might be at the root of these differing results. Relations between CP and NWR and CP and RAN have, to our knowledge, not been addressed. In the current study, the possible cascade from CP to phonology to reading was investigated on PA, NWR, and RAN. All three contribute to the phonological deficit.

In exploring whether deficits in CP are associated with reading problems, addressing the role of CP and phonological processing in the context of familial risk (FR) is of interest. Dyslexia is a highly heritable disorder (Snowling & Melby-Lervåg, 2016; Van Bergen, de Jong, Plakas, Maassen, & van der Leij, 2012; for a review, see Carrion-Castillo, Franke, & Fisher, 2013). Whether children at FR of dyslexia succumb to literacy difficulties depends on the presence of and interaction between multiple genetic and cognitive risk and protective factors (Pennington, 2006). FR-dyslexic (FRD) children often possess multiple risk factors, of which poor speech perception might be one. If CP deficits are related to reading problems, it is expected that a CP deficit shows specifically in FRD children but not in nondyslexic FR children (FRND). However, FRND children may still show subclinical deficits. This point has been exemplified by studies assessing phonological processing in the context of FR. It has been found that FRND children outperform FRD children on tasks that measure PA but perform worse than control children (Boets et al., 2007; de Bree, Wijnen, & Gerrits, 2010; Snowling, Gallagher, & Frith, 2003; Van Bergen, de Jong, Maassen, & van der Leij, 2014; Van Bergen et al., 2012). Such stepwise patterns are also observed on NWR (de Bree et al., 2010; Melby-Lervåg & Lervåg, 2012; Moll, Loff, & Snowling, 2013).

RAN seems to play a different role. Studies investigating RAN have shown that it is not impaired in FRND children (e.g., Moll et al., 2013; Van Bergen et al., 2012) and is one of the main predictors for literacy outcomes past age 6 (Thompson et al., 2015). The differences between FRND and FRD children may stem from the fact that RAN taps mechanisms similar to the ones needed for fluent reading. Hence, being good at rapid naming might protect against reading difficulty. RAN could be considered a microcosm of reading because it is reliant on speed as well as accuracy (Norton & Wolf, 2012) and therefore may even reflect actual reading ability. Based on these studies, it can be stated that deficits in PA and NWR are factors that are associated with FR status, whereas RAN is a factor associated with reading status. It must be noted, however, that the presence of stepwise patterns may depend on age, native tongue, and orthography, as a stepwise pattern for PA was not found in 11-year-old Dutch children (Hakvoort, van der Leij, Maurits, Maassen, & van Zuijen, 2015): Only FRD children showed deficits in PA (i.e., it was associated with reading status).

Previous studies have addressed the role of CP as a possible risk factor for dyslexia by examining FR populations in a prereading stage (e.g., Boets et al., 2011; Gerrits & de Bree, 2009; Noordenbos et al., 2012a). Gerrits and de Bree (2009) showed that 3-year-old FR children as a group were less consistent in labeling presented phonemes on a continuum from /p/ to /k/, but not all FR children displayed a deficit in CP. Boets et al. (2011) found a marginally significant difference on a CP task in favor of the control group at prereading age. Analyses of individual participants showed a subgroup of FR children to have diminished CP. Noordenbos et al. (2012a) suggested allophonic perception is present in FR children in kindergarten but disappears after a year of formal reading instruction. Findings from Noordenbos, Segers, Serniclaes, Mitterer, and Verhoeven (2012b), however, suggest that allophonic perception in dyslexia is still visible on a neural level after reading onset. Similar patterns were found in a study investigating the sensitivity to grammatical violations in dyslexia, in which participants with dyslexia performed at ceiling in a behavioral task but still showed diminished neural responses compared with the control group (Rispens, Been, & Zwarts, 2006). This implies that although differences between groups might not be observable on a behavioral level, different neural responses might still be present.

Taken together, previous studies suggest that not all FR children have a (long-lasting) deficit in CP that is measurable on a behavioral level. However, these studies did not investigate which FR children ultimately became poor readers. It is possible that CP problems, like problems in RAN, ultimately surface only in FRD children, in which case deficits in speech perception are associated with reading status. Alternatively, FRND children may show subclinical CP deficits similar to the ones observed in phonological processing measures NWR, and sometimes PA, in which case a CP deficit is associated with FR status.

Previous research has indicated the presence of attention deficits (e.g., Breier et al., 2001; Moll, Göbel, Gooch, Landerl, & Snowling, 2016) and poorer executive functions in dyslexia (e.g., Helland & Asbjørnsen, 2000). For example, Moll et al. (2016) have shown verbal memory skills and processing speed in poor readers to vary as a function of varying attentional skills. Given the complex nature of psychophysical tasks such as CP identification and discrimination tasks, behavioral CP outcomes might be the result of underlying deficits in attention. It might even (partly) explain the large variety of findings. Yet no studies to date have, to our knowledge, assessed the influence of attention on CP performance. Investigating the role of attention in this context is therefore of interest to the current study.

Current Study

The goal of this study is to investigate the cognitive underpinnings of dyslexia by examining whether there is a relation between speech perception and reading fluency in Dutch 9-year-old control, FRND, and FRD children who took part in the Dutch Dyslexia Programme (DDP; van der Leij et al., 2013). If CP is associated with reading, it is hypothesized that (a) CP is related to reading status and not to FR status and (b) there is a cascading relation from speech perception through phonological processing to reading. Moreover, it is expected that both steps in the cascade behave the same; that is, if CP relates to reading status, phonological processing will also relate to reading status. If these expectations hold, it would provide substantial evidence for CP to be at the basis of reading fluency.

CP performance is measured through accuracy as well as RT. The cascading relation between CP and the three dimensions of phonological processing and reading are addressed through correlation and regression analyses. To determine whether CP and phonological processing are factors associated with reading or FR status, a comparison is made between FRND, FRD, and control children. Furthermore, to rule out an alternative explanation, an additional measure was taken into account, sustained attention (SA). To avoid confounding effects of SA on CP outcomes, SA was included as a covariate in our analyses.

Method

Participants

A sample of 136 children was included, comprising a subsample of children who participated in the DDP (Van der Leij et al., 2013) from birth onward. All children who had taken part in the measurements in Grade 2, Grade 3, and Grade 6 and completed all tasks reported in this study were included in our sample. A child was assigned to the FR group if (one of the) parents was dyslexic (Hakvoort et al., 2015). Parents were presented with Dutch norm-referenced tests for word and pseudoword reading to assess their reading fluency (see the Materials section). A child was included in the FR group when the parent scored below the 15th percentile on either test and below the 50th on the other or below the 20th percentile on both tests. Children in the FRD group (a) performed poorly on a word and pseudoword reading test in Grade 6 (i.e., approximately age 12) and (b) had performed poorly on these tasks at least on one of the two times these tasks were administered earlier (i.e., end of Grade 2 and Grade 3). Poor performance was defined as a score below the 10th percentile on either the word or pseudoword reading test and below the 40th percentile on the other or below the 25th percentile on both tests. These criteria were considered strict enough to ensure a severe and persistent deficit in word-reading fluency. Background characteristics on reading fluency, verbal and nonverbal IQ, and SA results are displayed per group in Table 1.

Control and FRND children (fluent readers) differed significantly from the FRD group on all reading fluency tasks but not on nonverbal and verbal IQ. A significant main effect of group was found for SA. However, Bonferroni post hoc tests yielded only marginally significant differences between C and FRD children ($p = .061$) and between FRND and FRD children ($p = .072$).

Table 1. Background variables per group and statistical group comparisons.

Variable	Controls (n = 49)	FRND (n = 41)	FRD (n = 37)		Cohen's d		
	M (SD)	M (SD)	M (SD)	F(2, 124)	C-FRND	C-FRD	FRND-FRD
Age (months)	96.65 (5.08)$_a$	97.73 (4.27)$_a$	97.38 (5.02)$_a$	.59	–0.23	–0.14	0.08
WRF Grade 2	69.78 (16.74)$_a$	68.59 (18.82)$_a$	31.43 (12.57)$_b$	69.81***	0.07	2.59	2.32
PWF Grade 2	38.94 (11.57)$_a$	38.76 (12.50)$_a$	16.62 (6.53)$_b$	56.54***	0.01	2.38	2.22
WRF Grade 3	60.98 (11.02)$_a$	58.83 (13.62)$_a$	34.24 (10.60)$_b$	62.80***	0.17	2.47	2.01
PWF Grade 3	46.10 (14.04)$_a$	43.56 (13.96)$_a$	20.78 (7.09)$_b$	50.24***	0.18	2.27	2.06
Grade 6	80.27 (12.12)$_a$	80.29 (11.68)$_a$	56.29 (10.99)$_b$	55.57***	–0.001	2.07	2.12
PWF Grade 6	71.12 (13.38)$_a$	69.51 (14.42)$_a$	40.76 (9.81)$_b$	70.26***	0.12	2.59	2.33
Nonverbal IQ	40.25 (10.69)$_a$	44.41 (11.13)$_a$	41.05 (9.03)$_a$	1.94	–0.38	–0.08	0.33
Verbal IQ	31.90 (5.26)$_a$	32.66 (5.94)$_a$	29.89 (4.66)$_a$	2.78	–0.14	0.40	0.52
SA	4.00 (0.57)$_a$	4.01 (0.67)$_a$	3.69 (0.62)$_a$	3.48*	–0.02	0.52	0.50

Note. FRND = familial risk nondyslexic children; FRD = familial risk dyslexic children; C = controls; WRF = word-reading fluency; PWF = pseudoword reading fluency; SA = sustained attention. Group differences were attested using analyses of variance with Bonferroni post hoc comparisons. Shared subscripts indicate no significant difference.

*p < .05. ***p < .001.

Materials

Word-Reading Fluency

Word-reading fluency (WRF) was measured by the "Een-minuut-test" (1-min test; Brus & Voeten, 1973) in parents and in children in Grade 3 and in Grade 6. In Grade 2, it was measured by the second list of the "Drie Minuten Toets" (3-min test; Verhoeven, 1995). The 1-min test consists of a list of 116 mono- and polysyllabic words, increasing in difficulty. The administered list of the 3-min test consists of 150 monosyllabic words. The score was the number of words read correctly in 1 min for both tests. Standardized scores were used for the categorization of participants (see the Participants section).

Pseudoword-Reading Fluency

The Dutch norm-referenced task De Klepel (van den Bos, Lutje Spelberg, Scheepstra, & de Vries, 1994) measured pseudoword-reading fluency in parents and children. It was administered in Grades 2, 3, and 6. It consists of a list of 116 mono- and polysyllabic pseudowords. The score was the number of words read correctly within 2 min. Standardized scores were used for the categorization of participants.

Phonological Awareness

PA was assessed in Grade 3 and Grade 6 using a phoneme deletion task (de Jong & van der Leij, 2003). In Grade 3, the task consisted of three parts, and answers were given orally. The first part consisted of nine monosyllabic pseudowords (e.g., deleting /t/ from *tral*) and the second of nine bisyllabic pseudowords (e.g., deleting /l/ from *memslos*). During the third part, children were presented with nine bisyllabic pseudowords. The consonant they were asked to delete occurred twice (e.g., deleting /χ/ from *gepgral*). When six consecutive items were answered incorrectly in the first or three items in the second part, the test ended. The score on this task was the total number of items correct. The maximum score was 27. In Grade 6, the test was computerized and shortened. Each of the three parts now consisted of four items. Two practice items preceded the first and third parts of the test. The score on this task was the total number of items correct. The maximum score was 12. Scores were transformed to percentage correct to compare scores on both PA tasks.

Rapid Automatized Naming

RAN in Grade 3 was assessed using a digit-naming task. Children were asked to name a total of 50 digits as quickly and as accurately as possible. The digits included on the list were 2, 4, 5, 8, and 9. They were presented in five columns of ten digits each. Time in seconds and errors were recorded. These were used to calculate the total number of digits read correctly within 1 min.

Nonword Repetition

NWR is used as a measure of VSTM and was measured in Grade 3. Children were asked to listen to 36 nonwords. They had to repeat each item as accurately as possible; any mispronounced phoneme was recorded as erroneous. The nonwords consisted of at least three (e.g., *kummigar*) and at most five syllables (e.g., *nammonniffumnem*) and were presented in a fixed order. The score was the total number of words repeated correctly (Scheltinga, van der Leij, & Struiksma, 2010).

Categorical Perception

CP in Grade 3 was measured using a 10-step continuum of stimuli ranging from /bAk/ 'bak' [container] to /dAk/ 'dak' [roof]. The stimuli were recorded by a female native speaker of Dutch. To create the steps within the continuum, the second formant was manipulated using Praat (Boersma & Weenink, 1996). For a more detailed description of the phoneme manipulation and intermittent steps, see Van Beinum, Schwippert, Been, Van Leeuwen, and Kuijpers (2005). Two tasks were administered using these stimuli: a discrimination task and an identification task.

The identification task required children to identify one stimulus from the continuum that was presented to them as /bAk/ or /dAk/, by pressing a button that corresponded to an image of a box and one of a roof. In total, participants completed 20 trials. Each step of the continuum was presented twice. Both accuracy and RT were recorded. In the discrimination task, children were presented with two words from the continuum (either always three steps apart [called different trials, e.g., from Step 7 to Step 10] or identical [called same trials, e.g., two times Step 1]) via a computer. They had to indicate whether two stimuli were the same or different by pressing the corresponding button. Both accuracy and RT were recorded. Pairs were presented randomly in a nonadaptive design. In total, participants completed 48 trials, 20 of which were same trials and 28 different trials. Each pair of different trials was presented four times (seven contrasts, stimuli from Steps 1–4, 2–5, 3–6, 4–7, 5–8, 6–9, and 7–10 of the continuum). The proportion of accurate responses on different trials (i.e., the percentage of times participants answered "different" on trials such as 1–4, 4–1) and times that participants answered "same" on trials that consisted of identical stimuli (e.g., 1–1, 4–4) per stimulus pair was calculated, in this manner accounting for response bias, which is the tendency to favor one response over the other (e.g., Bogliotti et al., 2008; Wood, 1976). For RT, categories were created following the same procedure but additionally split into RTs for items that were correct versus items that were not. On the endpoint trials (1 and 7), a lower percentage of accurate responses is reflective of a better performance, because these trials are within-category. Control children are ideally expected to identify them as being the same, resulting in a lower percentage of "different" answers. Thus, for the purpose of comparing performance on within-category and between-category items, the percentages obtained on Contrasts 1 and 7 were averaged to form a within-phoneme category score, and items on Contrasts 2, 3, 4, 5, and 6 were averaged to form a between-phoneme category score (Messaoud-Galusi et al., 2011). The choice for these categories was supported by carrying out a mixed-design repeated-measures analysis of covariance (ANCOVA) on the identification data of the control group with within-subject factor percentage bak answers per stimulus type (1, 2, 3, 4, 5, 6, 7, 8, 9, and 10) and SA as a covariate. A significant main effect for stimulus type was found, $F(5.92, 278.61) = 3.07$, $p = .006$. Post hoc comparisons revealed Stimuli 1 and 4 to not differ from each other significantly. Both yielded a similar amount of bak classifications. The same held true for Stimuli 7 and 10.

Sustained Attention

To address the possible influence of SA on CP, a continuous performance task was administered in Grade 3. Children completed four blocks each containing 100 trials, comprising a total of 400 trials. Each trial was presented for 150 ms, at a slow pace with an inter-stimulus interval of 1,650 ms. The task took approximately 15 min. The assignment throughout the task was to press the spacebar when an X was preceded Xs were also presented to measure response inhibition (no-go condition). Other letters in the task served as distractors. Accuracy and RTs were recorded on both target trials and trials that could elicit false alarms (isolated Os, targets immediately following isolated Os, and isolated Xs). Scores on the continuous performance task were determined as follows. The total number of hits (go trials) and false alarms (no-go trials) were calculated. These were transformed into proportional values and standardized using a z-transform. The standardized proportion of false alarms on no-go trials was subtracted from the standardized proportion of hits on go trials to calculate d-prime.

Nonverbal IQ

To measure nonverbal IQ in Grade 3, the Block Design subtest of the Wechsler Intelligence Scale for Children–Third Edition (WISC-III) was used and administered following the manual. The reliability of this test in Grade 3 is $\alpha = .79$ (Kort et al., 2005).

Verbal IQ

To measure vocabulary in Grade 3, the Vocabulary subtest of the WISC-III was used. It was administered following the manual. The reliability of this test in Grade 3 is $\alpha = .80$ (Kort et al., 2005).

Procedure

All children were tested by a trained research assistant in a quiet room at the university lab. The tests were part of a larger battery that was administered in Grade 3. Tests were administered in a fixed order. The session took approximately 2 hr, with breaks in between. Children were given a small present once the session was finished.

Analyses

To assess whether CP and phonology relate to reading or FR status, group differences on CP and phonological tasks were addressed by means of analyses of variance (ANOVAs). On the background measures, effect sizes were addressed using Cohen's *d,* where effects around .20 are regarded as small, between .30 and .50 as moderate, and greater than .50 as large (Cohen, 1988). Regression analyses were carried out to investigate whether FR or reading status significantly predict outcomes on CP and phonology tasks. To explore a possible cascading relation between CP and phonology and reading, correlations between CP, phonological tasks, and reading were run, where correlations less than .30 are regarded as weak, around .50 as moderate, and around .70 as strong. In addition, regression and mediation analyses were run to address the role of CP and phonology as predictors of reading outcome.

Results

Data Screening

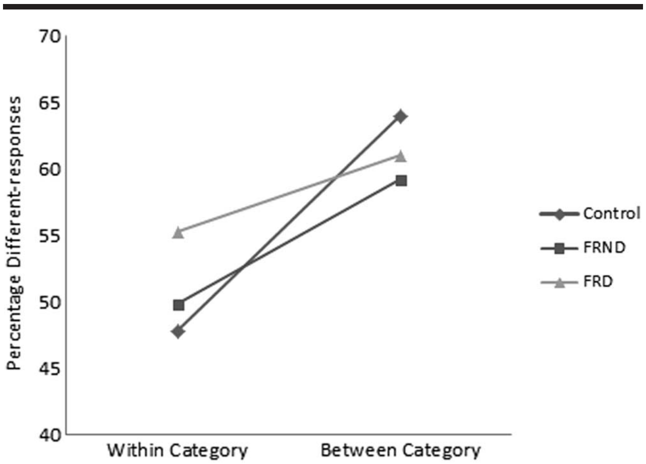
Prior to analysis, data were screened. For CP, children's RTs and corresponding responses on individual trials were coded as missing if latencies were more than three standard deviations from a participant's mean. Data were screened for multivariate and univariate outliers on the dependent variables NWR, PA, and RAN; general outcome measures of the CP task (mean RT in the classification task, total number of items correct in the classification task, mean RT in the discrimination task, and total number of items correct in the discrimination task); and SA. Three multivariate outliers were found and removed. These children belonged to the FRD group. In addition, six univariate outliers (four FRD and two FRND) were identified on the basis of z-transformed scores of the dependent variables and CPT (i.e., scores exceeding −3.29 or +3.29) and excluded from the analysis. The final sample consisted of data of 127 children: 49 C, 41 FRND, and 37 FRD children.

Categorical Perception

Discrimination Task

The mean proportion of different responses on within-phoneme category contrast (1 and 7) and the mean proportion of different responses on between-phoneme category contrasts (2, 3, 4, 5, and 6) were entered into a mixed-design repeated-measures ANCOVA with within-subjects factor category (within, between), between-subjects factor group (C, FRND, and FRD), and SA as a covariate. Greenhouse–Geisser corrections were applied when necessary. Results are displayed in Figure 1. A main effect was found for category, $F(1, 123) = 6.76$, $p = .01$. Overall, while controlling for response bias, between-category items yielded a larger mean percentage of different responses (61.57%) compared with within-category items (50.64%).

Figure 1. Percentage of different responses for within- and between-category items.



Within-category tokens were thus less often regarded as being different from each other. No effects were found for group or the covariate. However, an interaction between category and group was present, $F(2, 123) = 8.41$, $p < .001$. Control (47.74%) and FRND children (49.85%) showed a lower percentage of different responses on within-category trials compared with FRD children (55.24%, $p < .001$, and $p = .015$, respectively). No differences were found between control and FRND children. No differences were found on the between-category trials.

For the analysis of the RTs, a mixed-design repeated-measures ANCOVA was run on the mean RT in milliseconds of all different and same responses on the within-phoneme and between-phoneme category different trials, with within-subjects factor category (within, between), different (yes, no), between-subjects factor group (control children, FRND, and FRD), and SA as a covariate. An overview of RT outcomes per stimulus category is available in Table 2. The analysis yielded a main effect of different, $F(1, 123) = 28.74$, $p < .001$: Items that were answered to with *same* were responded to more slowly, compared with items that were answered to with *different*. No further main or interaction effects were found.

Identification Task

To address correct identification of *bak* on each step of the continuum, all answers were transformed into percentage *bak* answers per stimulus type (Trials 1 to 10), allowing identification curves to be plotted. Curves in Figure 2 reflect the percentage of trials that participants identified as *bak* for each stimulus type on the continuum. To assess differences in identification slope values, participants' data were fitted to a sigmoid curve using a logistic function (cf. Medina, Hoonhorst, Bogliotti, & Serniclaes, 2010). A univariate ANCOVA with dependent variable slope, independent variable group (C, FRND, FRD), and SA as a covariate yielded no significant effects, indicating that the identification curves of each group were equally steep, total M (SD) = −0.78 (0.19), and that SA did not affect the outcomes. To assess differences in classification on endpoint trials, a mixed-design repeated-measures ANCOVA with within-subject factor percentage *bak* answers per stimulus type (1, 2, 3, 4, 5, 6, 7, 8, 9, and 10), between-subjects factor group (control vs. FRND vs. FRD), and SA as a covariate was carried out. Given the absence of a slope difference, the analysis revealed no significant main effect for group or Group × Stimulus type interaction. Stimuli were not identified differently between groups. Post hoc comparisons revealed stimulus Types 1 through 3 to yield significantly higher percentages of *bak* classifications than stimulus Types 4 to 10 (all $p < .001$) and stimulus Types 7 through 10 to yield a significantly lower percentage of *bak* classifications compared with stimulus Types 1 through 6 (all ps < .001).

Next, a mixed-design repeated-measures ANCOVA was run on the RTs with within-subjects factor stimulus type (1, 2, 3, 4, 5, 6, 7, 8, 9, 10), between-subjects factor group (control vs. FRND and FRD), and SA as a covariate. No

Table 2. Descriptive statistics for the RT data on the CP discrimination task.

	Within-Phoneme Category		Between-Phoneme Category	
	Different	Same	Different	Same
Group	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*
C (n = 49)	853.45 (124.86)	1,125.51 (132.93)	865.28 (70.96)	1,207.03 (105.89)
FRND (n = 41)	862.74 (121.03)	1,168.34 (147.74)	896.61 (89.72)	1,234.46 (121.97)
FRD (n = 37)	909.43 (227.35)	1,152.34 (122.65)	907.35 (143.57)	1,194.61 (78.36)

Note. RT = reaction time; CP = categorical perception; different = trials answered with *different*; same = trials answered with *same*; C = controls; FRND = familial risk nondyslexic; FRD = familial risk dyslexic.

main effects or interactions were found, indicating that the participants did not differ in how fast they answered in response to each stimulus in the identification task, $F(2, 123) = 1.67$, $p = .19$. In sum, whereas all groups are equally apt at identification of stimuli in the identification task, the control and FRND children perform more poorly at distinguishing within-category items compared with the FRD group.

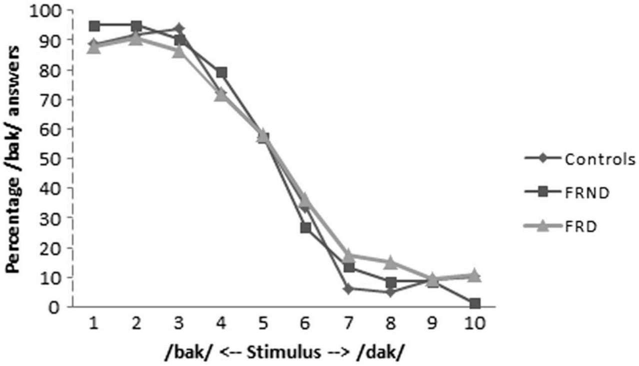
Phonology

Group means and standard deviations on the percentage of items answered correctly on the PA tasks in Grade 3 and 6, the accuracy scores on NWR, and scores on RAN in Grade 3 were assessed using ANOVAs with post hoc Bonferroni tests. Fluently reading children with and without FR outperformed FRD children on all phonological processing tasks, both in Grade 3 and in Grade 6. Results are displayed in Table 3.

Categorical Perception, Phonology, and FR Versus Reading

To investigate the relation between CP and phonological processing to FR versus reading, reading status and FR status were used as predictors for performance on CP and phonological tasks in complementary regression analyses. These were run with the mean percentage of "different" responses per category (within-phoneme category and between-phoneme category) on the discrimination task and the phonological processing measures as dependent variables, and FR status and dyslexia status as predictors. To this end, dummy variables were created, indicative of the reading status (0 for average readers, 1 for dyslexia) and the FR status of the child (0 for controls, 1 for FR children). For all dependent variables, FR status was entered in Step 1 (Model 1) and dyslexia status was added in Step 2 (Model 2; e.g., Moll et al., 2013). The results (see Table 4) suggest that performance on within-category items is significantly predicted by dyslexia status as well as performance on PA, NWR, and RAN. Performance on between-category items is not related to reading or FR status.

Figure 2. Percentage of times that participants have identified a stimulus as /bak/.



Investigating the Relation Between CP, Phonology, and Reading

Correlations

Correlations were calculated between all reading, phonological, and CP measures and SA. In addition, partial correlations were calculated between all reading, phonological, and CP measures to control for SA (see Table 5). Differences between the two types of correlational analyses were small. With respect to the relation between CP and phonological processing, significant weak negative correlations were obtained between the accuracy on CP discrimination within-category items and RAN. Lower scores on within-category accuracy relate to a higher number of correctly named digits per minute. There were no significant correlations between CP within-category items and PA or NWR. However, when controlling for SA, a weak negative correlation was found between within-category items and PA and between within-category and WRF. Lower scores on within-category accuracy relate to higher scores on WRF. With regard to the relation between reading and phonological processing, significant moderate to strong positive correlations were observed between all phonological processing measures and reading.

Regression Analyses

On the basis of the correlation analyses, the relation between CP discrimination within-category scores, phonology,

Table 3. Descriptive statistics for all phonological processing measures and statistical group comparison outcomes.

	C (n = 49)	FRND (n = 41)	FRD (n = 37)		Cohen's d		
Task	M (SD)	M (SD)	M (SD)	F(2, 124)	C-FRND	C-FRD	FRND-FRD
PA Grade 3	74.15 $(14.88)_a$	70.73 $(18.64)_a$	48.05 $(17.42)_b$	28.07*	0.20	1.61	1.26
PA Grade 6	88.95 $(11.71)_a$	84.96 $(11.82)_a$	71.85 $(18.04)_b$	16.82*	0.34	1.12	0.86
NWR Grade 3	17.24 $(4.74)_a$	15.68 $(5.54)_a$	12.38 $(4.57)_b$	10.29*	0.30	1.04	0.65
RAN Grade 3	112.18 $(20.41)_a$	115.76 $(24.13)_a$	96.14 $(19.35)_b$	9.26*	−0.16	0.80	0.90

Note. C = controls; FRND = familial risk nondyslexic children; FRD = familial risk dyslexic children; PA = phonological awareness (percentage correct); NWR = nonword repetition; RAN = rapid automatized naming (items/minute). All values are given as mean (standard deviation). Group differences were attested using analyses of variance. Shared subscripts are indicative of no significant difference.
*p < .01.

and WRF was further explored using a mediation analysis. We did not include SA in this model as this did not relate to CP. Conforming to Step 1 of the mediation model (Baron & Kenny, 1986), three separate regression analyses were conducted to assess whether CP individually predicted PA, NWR, and RAN. As expected, on the basis of the absence of correlations, CP did not significantly predict scores on NWR. Despite the presence of a weak correlation between CP and PA when controlling for SA, CP did not predict PA. For NWR and PA, no mediation was possible. However, CP significantly predicted RAN ($\beta = -.28$), $t(125) = -3.26$, $p < .001$. In the second step, we found that CP also significantly predicted word reading ($\beta = -.24$), $t(125) = -2.72$, $p = .008$. The third step of the mediation model, in which both CP and RAN are entered as predictors for reading skill, revealed that only RAN significantly predicted Grade 3 reading skill ($\beta = .39$), $t(125) = 4.68$, $p < .001$. As direct effects of CP on reading disappeared when RAN was entered into the model, effects of CP on reading are fully mediated by RAN. This was attested by a significant Sobel test (Baron & Kenny, 1986; $z = -2.67$, $p = .007$; see Figure 3). To compare the role of CP within- versus between-category items, we assessed whether the scores on between-category items predicted phonological skills and reading using a mediation analysis. As expected, on the basis of the correlations, between-category scores predicted neither phonological nor reading skill; hence, no mediation was possible.

Correlations were present between CP discrimination within-category items accuracy and reading and between all individual phonological processing measures and reading. To assess the individual contribution of each dimension of phonological processing and CP to the variance in reading fluency separately, a hierarchical regression analysis was run. The dependent variable was WRF in Grade 3. SA was entered into the model as a control variable in Step 1. CP was added to the model in Step 2, and RAN, NWR, and PA were added in Step 3. Results (see Table 6) show that once PA, RAN, and NWR are entered, CP ceases to predict WRF outcomes. PA, RAN, and NWR are all individual predictors for reading skill.

Discussion

This study aimed to gain more insight into the way in which categorical speech perception and phonological processing relate to dyslexia and FR, by comparing FR children with and without dyslexia on CP and phonological processing measures and by exploring whether a cascading relation between CP, phonology, and reading could be found. Findings show that CP and phonological processing (PA, RAN, and NWR) related to reading status. Yet findings do not point toward a clear cascade from CP to phonological processing to reading: Although there was a relation between the dimensions of phonological processing and reading, we found a predictive relation only between CP and RAN.

The role of CP as a factor that relates to reading status or to FR status was investigated by comparing the

Table 4. Outcomes of linear regression analyses with dependent variables PA, NWR, RAN, and CP.

	PA		NWR		RAN		CP Within		CP Between	
Predictor	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	.12***		.08***		.02		.05*		.03	
FR		−.34***		−.28***		.14		. 22*		−.16
Step 2	.19***		.06**		.09***		.04*		.004	
FR		−.08		−.14		−.04		.10		−.20
Dys		−.51***		−.28**		.36***		.20*		.07

Note. PA = phonological awareness; NWR = nonword repetition; RAN = rapid automatized naming; CP = categorical perception; CP within = categorical perception, discrimination task within-category; CP between = categorical perception discrimination task between-category.
*p < .05. **p < .01. ***p < .001.

Table 5. Correlations between WRF, PWF, CP, and phonological processing measures while controlling for SA (below diagonal) and without controlling for SA (above diagonal).

Variable	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
1. WRF Grade 3		.84***	.43***	.60***	.37***	−.24**	−.07	−.13	−.25**	−.13	−.26**	.23*
2. PWF Grade 3	.83***		.35***	.63***	.30***	−.18*	−.07	−.17	−.16	−.07	−.18*	.20*
3. RAN Grade 3	.42***	.34***		.19*	.01	−.28***	−.16	−.13	−.20*	−.15	−.20*	.09
4. PA Grade 3	.57***	.61***	.17*		.46***	−.16	.005	−.08	−.05	−.07	−.07	.26**
5. NWR Grade 3	.37***	.29***	.01	.46***		−.07	.13	−.05	−.17	−.17	−.17	.07
6. CP within	−.28**	−.21*	−.30***	−.20*	−.08		−.30**	−.07	.02	.24**	.21*	.13
7. CP between	−.09	−.09	−.17	−.02	.13	−.29***		−.04	.13	.21*	.20*	.07
8. CP within RT	−.16	−.19*	−.14	−.11	−.06	−.06	−.05		.36***	−.11	.39***	.07
9. CP between RT	−.27**	−.18*	−.20*	−.07	−.18*	.009	.13	.36***		−.12	.39***	.08
10. CP ident slopes	−.12	−.06	−.15	−.05	−.16	.23**	−.21*	−.11	−.12		−.23**	.09
11. CP ident RT	−.28**	−.19*	−.20*	−.09	−.17	.21*	.19*	.39***	.39***	−.23**		.03
12. SA	—	—	—	—	—	—	—	—	—	—	—	—

Note. WRF = word-reading fluency; PWF = pseudoword reading fluency; CP = categorical perception discrimination task within-category scores; SA = sustained attention; PA = phonological awareness; RAN = rapid automatized naming; NWR = nonword repetition; RT = reaction time.

*$p < .05$. **$p < .01$. ***$p < .001$.

performance of 9-year-old Dutch FRD, FRND, and control children on CP, PA, RAN, and NWR. CP results were not clear-cut. As opposed to previous findings regarding RTs on CP (Pisoni & Tash, 1974; Poeppel et al., 2004; Van Beinum et al., 2005), no group differences were found on the identification or discrimination task. No group differences were found on accuracy in the identification task. On the accuracy measure of the discrimination task, however, significant differences were found between good readers (controls and FRND children) and FRD children. FRD children were more sensitive to within-category contrasts, reflective of poorer CP. Groups performed equally well at discerning between-category contrasts. Poor CP performance on the discrimination task thus seems related to dyslexia, rather than to FR status.

The CP results extend those of Boets et al. (2011) and Gerrits and de Bree (2009), who showed poor CP performance for the FR group in a prereading stage. Our results suggest that poor CP performance extends into third grade, when children have already started to read, and becomes specific to poor readers. Our results are also in line with studies observing CP deficits in adults (see Noordenbos & Serniclaes, 2015). This contrasts findings by Noordenbos et al. (2012a), who found that difficulties in CP at the behavioral level disappeared after a year of formal reading instruction (but see Noordenbos et al., 2012b). The outcome that within-category contrasts are better discerned by FRD children are in line with, for example, Serniclaes et al. (2001), suggesting that within-category items are perceived as allophones of the same phoneme. Yet, because no differences between controls, FRD, and FRND children are found on the identification task, and because there were no differences between these groups on between-category items and on RTs of within- and between-category performance, our results do not fully support the allophonic perception theory.

Figure 3. Standardized regression coefficients for the relationship between categorical speech perception (CP) within-category scores and reading skill as mediated by rapid automatized naming (RAN). The outcome in parentheses refers to the standardized regression coefficient for CP and reading when both CP and RAN were predictors in the model.

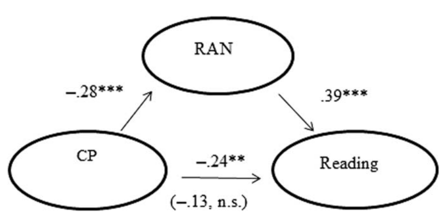


Table 6. Hierarchical regression analyses with dependent variable word-reading fluency Grade 3.

Predictor	ΔR^2	β
Step 1	.05*	
SA		.23*
Step 2	.07**	
SA		.26**
CP		−.27**
Step 3	.37***	
SA		.09
CP		−.08
PA		.43***
RAN		.31***
NWR		.16*
Total R^2	.49***	

Note. SA = sustained attention; CP = categorical perception discrimination task within-category scores; PA = phonological awareness; RAN = rapid automatized naming; NWR = nonword repetition.

*$p < .05$. **$p < .01$. ***$p < .001$.

Moll et al. (2013), using a parental questionnaire, have previously shown attention to relate to tasks tapping processing speed and verbal working memory. We used an experimental task to measure SA. SA was anticipated to relate to CP, as CP taps into processing speed. The relationship was, however, not attested for either RT or accuracy. This could be due to the design of our study: Other studies have used adaptive CP designs, increasing task demands (e.g., Messaoud-Galusi et al., 2011) or have used more trials to determine CP performance, increasing task length (e.g., Van Beinum et al., 2005). Our task was nonadaptive and contained few trials, which might account for these different findings.

Regarding the relation between reading and phonological processing, the results show that deficits in phonological processing relate to reading status. As expected, FRD children were outperformed by both FRND and control children on all three phonological dimensions. FRND children did not perform more poorly than control children on the phonological tasks, in line with previous findings by Snowling et al. (2003) and Snowling, Muter, and Caroll (2007). Often, however, a stepwise pattern in performance is found on phonological tasks, in which FRND children outperform FRD children but perform more poorly compared with controls (e.g., Moll et al., 2013). This was also true for Dutch children in Grade 2 (Van Bergen et al., 2012). Similarly, de Bree et al. (2010) showed that both poorly and averagely reading FR children perform more poorly on NWR than controls. Possibly, the absence of a difference between FRND and control children in our study is due to the declining predictive value of phonology for reading in Dutch as a function of age (de Jong & van der Leij, 2003). This interpretation is further supported by our finding that differences in PA are not visible between controls and FRND children in Grade 6 either. Although a stepwise pattern is present in another DDP study at Grade 2 (Van Bergen et al., 2012), it does not surface in later grades. However, different diagnostic criteria or moment of measurement might explain the difference, because participants in the study by Van Bergen and colleagues were categorized on Grade 2 and 3 reading scores only. In all, our results suggest that deficits in PA, RAN, and NWR at this point in development all relate directly to reading fluency and, thus, that they are factors related to reading status rather than to FR.

To explore whether a cascading relation between CP, phonology, and reading was present, correlation and regression analyses were conducted. In line with literature on phonology and dyslexia (e.g., Vellutino et al., 2004) and the group comparisons reported in this study, we found a clear association between phonology and reading, confirming the results from the group comparisons. Phonological skills significantly predicted reading skills. Unexpectedly, given the previously reported relation between CP within-category discrimination scores and dyslexia, the relation between CP and phonological processing was not clear-cut. Relations between CP and NWR were absent, which does not align with the expectations of a cascade. We found a weak correlation between CP and PA, in line with other studies that have reported relations between CP and PA (Boets et al., 2007; Hazan et al., 2009; Messaoud-Galusi et al., 2011; Noordenbos et al., 2012a). However, although a correlation was present, no clear evidence for a cascading relation from CP to PA to reading was found in a follow-up mediation analysis, because CP was not a significant predictor for PA.

Surprisingly, correlations were found between CP within-category accuracy and RAN: Lower scores on within-category accuracy implicate a higher number of digits named per minute on RAN. Findings of a mediation analysis indicate that reading skill is significantly predicted by CP, but RAN fully mediates the effects of CP on reading. One explanation could be that processing speed is involved in both CP and RAN. RAN tasks are timed, and in CP, stimuli are fleeting and require a fast reaction. Both tasks require fast access to representations stored in memory. Hence, both RAN and CP demand processing speed, which has previously been shown to be a risk factor for poor reading skill (McGrath et al., 2011). Poor readers are poor at RAN and show allophonic perception even at this age, whereas normal readers do not. Allophonic representations create interference with the activation of phoneme representations, also affecting RAN. Phrased differently, RAN performance might index the timing of phoneme and allophonic activation. This may provide an explanation for the mediation effect. The relation between RAN and CP within-category scores is difficult to interpret, however, especially because the RTs on CP within-category items were not related to RAN or reading and considering that we used RAN digits and not RAN letters. Possibly, effects would have been different if letters were used instead of digits, because lexical retrieval is targeted more in digit naming than in phoneme retrieval.

Our findings do not provide conclusive evidence for a cascade from speech perception to phonological processing to reading. It appears that CP, RAN, and reading skill are related. This relation may be characterized by activation timing of allophones and phonemes. However, the relation between CP, PA, and reading and CP, NWR, and reading is less evident. Risk factors assessed in the current study relate to one another and to reading, but they are not cascading as such. The different patterns of findings regarding the relation between CP and phonology highlight that different processes are tapped by different tasks and as such stress the importance of addressing multiple dimensions of phonological skill to disentangle the relationship between CP and phonological processing and reading. It must be noted that we addressed concurrent, and not developmental, relationships. Had we explored cascading relations longitudinally, the possible influence of emerging literacy skill on the relation between CP and phonology could have been addressed. However, in a previous study that addressed the relation between CP and PA longitudinally, Boets et al. (2011) did not find strong evidence for either a persistent deficit in CP or a cascading relation between CP, phonology, and reading. Taking these results into consideration, it might just be possible that in Dutch speakers, the relation between CP, phonology, and reading skill is not strong enough to surface persistently.

To conclude, categorical speech perception seems to relate to reading fluency, because deficits in CP are found in FRD children only. Attenuated phonological skills also surface only in FRD children. PA, NWR, and RAN are thus factors that relate directly to reading status at age 9, supporting the view that they are important markers for dyslexia. Furthermore, no conclusive evidence was found for a cascade from speech perception, to phonology, to reading as CP did not relate to PA and NWR. CP related only to RAN. Overall, our results suggest that a deficit in speech processing as measured by a categorical perception task is a factor that contributes to the manifestation of dyslexia. The evidence for a cascading relation between CP, phonology, and reading, however, is limited.

Acknowledgments

This research was funded by Grant 360-89-040 of the Netherlands Organisation for Scientific Research (awarded to Ben Maassen and Aryan van der Leij). We thank the parents and children enrolled in the Dutch Dyslexia Programme for their contribution to our study. We thank Sietske van Viersen and Madelon van den Boer for their valuable comments on a previous draft of this article.

References

Baron, R. M., & Kenny, D. A. (1986). The moderator–mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology, 51,* 1173–1182.

Boersma, P., & Weenink, D. (1996). *Praat, a system for doing phonetics by computer* (version 4.4.22). Amsterdam, the Netherlands: University of Amsterdam, Institute of Phonetic Sciences.

Boets, B., Smedt, B., Cleuren, L., Vandewalle, E., Wouters, J., & Ghesquière, P. (2010). Towards a further characterization of phonological and literacy problems in Dutch-speaking children with dyslexia. *British Journal of Developmental Psychology, 28,* 5–31. doi:10.1348/026151010X485223

Boets, B., Vandermosten, M., Poelmans, H., Luts, H., Wouters, J., & Ghesquière, P. (2011). Preschool impairments in auditory processing and speech perception uniquely predict future reading problems. *Research in Developmental Disabilities, 32,* 560–570. doi:10.1016/j.ridd.2010.12.020

Boets, B., Wouters, J., Van Wieringen, A., & Ghesquière, P. (2007). Auditory processing, speech perception and phonological ability in pre-school children at high-risk for dyslexia: A longitudinal study of the auditory temporal processing theory. *Neuropsychologia, 45,* 1608–1620. doi:10.1016/j.neuropsychologia.2007.01.009

Bogliotti, C., Serniclaes, W., Messaoud-Galusi, S., & Sprenger-Charolles, L. (2008). Discrimination of speech sounds by children with dyslexia: Comparisons with chronological age and reading level controls. *Journal of Experimental Child Psychology, 101,* 137–155. doi:10.1016/j.jecp.2008.03.006

Breier, J. I., Gray, L., Fletcher, J. M., Diehl, R. L., Klaas, P., Foorman, B. R., & Molis, M. R. (2001). Perception of voice and tone onset time continua in children with dyslexia with and without attention deficit/hyperactivity disorder. *Journal of Experimental Child Psychology, 80,* 245–270.

Brus, B., & Voeten, M. (1973). *Een minuut test: Verantwoording en handleiding* [One minute test: Rationale and manual]. Nijmegen, the Netherlands: Berkhout.

Carrion-Castillo, A., Franke, B., & Fisher, S. E. (2013). Molecular genetics of dyslexia: An overview. *Dyslexia, 19,* 214–240. doi:10.1002/dys.1464

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

de Bree, E., Rispens, J., & Gerrits, E. (2007). Non-word repetition in Dutch children with (a risk of) dyslexia and SLI. *Clinical Linguistics & Phonetics, 21,* 935–944. doi:10.1080/02699200701576892

de Bree, E., Wijnen, F., & Gerrits, E. (2010). Non-word repetition and literacy in Dutch children at-risk of dyslexia and children with SLI: Results of the follow-up study. *Dyslexia, 16,* 36–44. doi:10.1002/dys.395

de Jong, P. F., & van der Leij, A. (2003). Developmental changes in the manifestation of a phonological deficit in dyslexic children learning to read a regular orthography. *Journal of Educational Psychology, 95,* 22. doi:10.1037/0022-0663.95.1.22

Fitch, R. H., Miller, S., & Tallal, P. (1997). Neurobiology of speech perception. *Annual Review of Neuroscience, 20,* 331–353. doi:10.1146/annurev.neuro.20.1.331

Gerrits, E., & de Bree, E. (2009). Early language development of children at familial risk of dyslexia: Speech perception and production. *Journal of Communication Disorders, 42,* 180–194. doi:10.1016/j.jcomdis.2008.10.004

Goswami, U. (2015). Sensory theories of developmental dyslexia: Three challenges for research. *Nature Reviews Neuroscience, 16,* 43–54. doi:10.1038/nrn3836

Hakvoort, B., van der Leij, A., Maurits, N., Maassen, B., & van Zuijen, T. L. (2015). Basic auditory processing is related to familial risk, not to reading fluency: An ERP study. *Cortex, 63,* 90–103. doi:10.1016/j.cortex.2014.08.013

Hazan, V., Messaoud-Galusi, S., Rosen, S., Nouwens, S., & Shakespeare, B. (2009). Speech perception abilities of adults with dyslexia: Is there any evidence for a true deficit? *Journal of Speech, Language, and Hearing Research, 52,* 1510–1529. doi:10.1044/1092-4388(2009/08-0220

Helland, T., & Asbjørnsen, A. (2000). Executive functions in dyslexia. *Child Neuropsychology, 6,* 37–48. doi:10.1076/0929-7049(200003)6:1;1-B;FT037

Kort, W., Schittekatte, M., Bosmans, M., Compaan, E. L., Dekker, P. H., Vermeir, G., & Verhaege, P. (2005). *WISC III-NL. Wechsler Intelligence Scale for Children III-NL.* Amsterdam, the Netherlands: Pearson.

Maassen, B., Groenen, P., Crul, T., Assman-Hulsmans, C., & Gabreëls, F. (2001). Identification and discrimination of voicing and place-of-articulation in developmental dyslexia. *Clinical Linguistics & Phonetics, 15,* 319–339. doi:10.1080/02699200010026102

McGrath, L. M., Pennington, B. F., Shanahan, M. A., Santerre-Lemmon, L. E., Barnard, H. D., Willcutt, E. G., . . . Olson, R. K. (2011). A multiple deficit model of reading disability and attention-deficit/hyperactivity disorder: Searching for shared cognitive deficits. *Journal of Child Psychology and Psychiatry, 52*(5), 547–557. doi:j.1469-7610.2010.02346.x

Medina, V., Hoonhorst, I., Bogliotti, C., & Serniclaes, W. (2010). Development of voicing perception in French: Comparing adults, adolescents, and children. *Journal of Phonetics, 38,* 493–503.

Melby-Lervåg, M., & Lervåg, A. (2012). Oral language skills moderate nonword repetition skills in children with dyslexia:

A meta-analysis of the role of nonword repetition skills in dyslexia. *Scientific Studies of Reading, 16,* 1–34. doi:10.1080/10888438.2010.537715

Messaoud-Galusi, S., Hazan, V., & Rosen, S. (2011). Investigating speech perception in children with dyslexia: Is there evidence of a consistent deficit in individuals? *Journal of Speech, Language, and Hearing Research, 54,* 1682–1701. doi:10.1044/1092-4388(2011/09-0261

Moll, K., Göbel, S. M., Gooch, D., Landerl, K., & Snowling, M. J. (2016). Cognitive risk factors for specific learning disorder: Processing speed, temporal processing, and working memory. *Journal of Learning Disabilities, 49,* 272–281. doi:10.1177/0022219414547221

Moll, K., Loff, A., & Snowling, M. J. (2013). Cognitive endophenotypes of dyslexia. *Scientific Studies of Reading, 17,* 385–397. doi:10.1080/10888438.2012.736439

Noordenbos, M. W., Segers, E., Serniclaes, W., Mitterer, H., & Verhoeven, L. (2012a). Allophonic mode of speech perception in Dutch children at risk for dyslexia: A longitudinal study. *Research in Developmental Disabilities, 33,* 1469–1483. doi:10.1016/j.ridd.2012.03.021

Noordenbos, M. W., Segers, E., Serniclaes, W., Mitterer, H., & Verhoeven, L. (2012b). Neural evidence for allophonic perception in children at risk for dyslexia. *Neuropsychologia, 50,* 2010–2017. doi:10.1016/j.neuropsychologia.2012.04.026

Noordenbos, M. W., & Serniclaes, W. (2015). The categorical perception deficit in dyslexia: A meta-analysis. *Scientific Studies of Reading, 19,* 340–359. doi:10.1080/10888438.2015.1052455

Norton, E., & Wolf, M. (2012). Rapid automatized naming (RAN) and reading fluency: Implications for understanding and treatment of reading disabilities. *Annual Reviews of Psychology, 63,* 427–452. doi:10.1146/annurev-psych-120710-100431

Pennington, B. F. (2006). From single to multiple deficit models of developmental disorders. *Cognition, 101,* 385–413. doi:10.1016/j.cognition.2006.04.008

Pisoni, D. B., & Tash, J. (1974). Reaction times to comparisons within and across phonetic categories. *Attention, Perception, & Psychophysics, 15,* 285–290.

Poeppel, D., Guillemin, A., Thompson, J., Fritz, J., Bavelier, D., & Braun, A. R. (2004). Auditory lexical decision, categorical perception, and FM direction discrimination differentially engage left and right auditory cortex. *Neuropsychologia, 42,* 183–200.

Protopapas, A. (2013). From temporal processing to developmental language disorders: Mind the gap. *Philosophical Transactions of the Royal Society B: Biological Sciences, 369,* 20130090. doi:10.1098/rstb.2013.0090

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Castellote, J. M., White, S., & Frith, U. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126,* 841–865. doi:10.1093/brain/awg076

Ramus, F., & Szenkovits, G. (2008). What phonological deficit? *The Quarterly Journal of Experimental Psychology, 61,* 129–141. doi:10.1080/17470210701508822

Rispens, J., Been, P., & Zwarts, F. (2006). Brain responses to subject-verb agreement violations in spoken language in developmental dyslexia: An ERP study. *Dyslexia, 12,* 134–149. doi:10.1002/dys.316

Scheltinga, F., van der Leij, A., & Struiksma, C. (2010). Predictors of response to intervention of word reading fluency in Dutch. *Journal of Learning Disabilities, 43,* 212–228. doi:10.1177/0022219409345015

Serniclaes, W., Sprenger-Charolles, L., Carré, R., & Demonet, J. F. (2001). Perceptual discrimination of speech sounds in developmental dyslexia. *Journal of Speech, Language, and Hearing Research, 44,* 384–399. doi:10.1044/1092-4388(2001/032)

Serniclaes, W., Van Heghe, S., Mousty, P., Carré, R., & Sprenger-Charolles, L. (2004). Allophonic mode of speech perception in dyslexia. *Journal of Experimental Child Psychology, 87,* 336–361. doi:10.1016/j.jecp.2004.02.001

Snowling, M., Gallagher, A., & Frith, U. (2003). Family risk of dyslexia is continuous: Individual differences in the precursors of reading skill. *Child Development, 74,* 358–373.

Snowling, M., Goulandris, N., Bowlby, M., & Howell, P. (1986). Segmentation and speech perception in relation to reading skill: A developmental analysis. *Journal of Experimental Child Psychology, 41,* 489–507. doi:10.1016/0022-0965(86)90006-8

Snowling, M., & Melby-Lervåg, M. (2016). Oral language deficits in familial dyslexia: A meta-analysis and review. *Psychological Bulletin, 143,* 498–545. doi:10.1037/bul.0000037

Snowling, M. J., Muter, V., & Carroll, J. M. (2007). Children at family risk of dyslexia: A follow-up in early adolescence. *Journal of Child Psychology and Psychiatry, 48,* 609–618. doi:10.1111/j.1469-7610.2006.01725.x

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language, 9,* 182–198. doi:10.1016/0093-934X(80)90139-X

Thompson, P. A., Hulme, C., Nash, H. M., Gooch, D., Hayiou-Thomas, E., & Snowling, M. J. (2015). Developmental dyslexia: Predicting individual risk. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 56,* 976–987. doi:10.1111/jcpp.12412

Van Beinum, F. J., Schwippert, C., Been, P., Van Leeuwen, T., & Kuijpers, C. (2005). Development and application of a /bAk/–/dAk/ continuum for testing auditory perception within the Dutch longitudinal dyslexia study. *Speech Communication, 47,* 124–142. doi:10.1016/j.specom.2005.04.003

Van Bergen, E., de Jong, P. F., Maassen, B., & van der Leij, A. (2014). The effect of parents' literacy skills and children's preliteracy skills on the risk of dyslexia. *Journal of Abnormal Child Psychology, 42,* 1187–1200. doi:10.1007/s10802-014-9858-9

Van Bergen, E., de Jong, P. F., Plakas, A., Maassen, B., & van der Leij, A. (2012). Child and parental literacy levels within families with a history of dyslexia. *Journal of Child Psychology and Psychiatry, 53,* 28–36. doi:10.1111/j.1469-7610.2011.02418.x

van den Bos, K., Lutje Spelberg, H., Scheepstra, A., & de Vries, J. (1994). *De Klepel, een test voor de leesvaardigheid van pseudowoorden. Verantwoording, Handleiding, Diagnostiek en Behandeling* [De Klepel, a test for pseudoword reading fluency. Rationale, manual, diagnosis and treatment]. Nijmegen, the Netherlands: Berkhout.

van der Leij, A., Van Bergen, E., Van Zuijen, T., De Jong, P., Maurits, N., & Maassen, B. (2013). Precursors of developmental dyslexia: An overview of the longitudinal Dutch dyslexia programme study. *Dyslexia, 19,* 191–213. doi:10.1002/dys.1463

Vandermosten, M., Boets, B., Luts, H., Poelmans, H., Golestani, N., Wouters, J., & Ghesquière, P. (2010). Adults with dyslexia are impaired in categorizing speech and nonspeech sounds on the basis of temporal cues. *Proceedings of the National Academy of Sciences, USA, 107,* 10389–10394. doi:10.1073/pnas.0912858107

Vellutino, F. R., Fletcher, J. M., Snowling, M. J., & Scanlon, D. M. (2004). Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry, 45,* 2–40. doi:10.1046/j.0021-9630.2003.00305.x

Verhoeven, L. (1995). *Drie-Minuten-Toets* [Three minutes test]. Arnhem, the Netherlands: Cito.

Wagner, R. K., & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin, 101,* 192.

Wolf, M., Bowers, P. G., & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities, 33,* 387–407. doi:10.1177/002221940003300409

Wood, C. C. (1976). Discriminability, response bias, and phoneme categories in discrimination of voice onset time. *The Journal of the Acoustical Society of America, 60,* 1381–1389.

Ziegler, J. C., Pech-Georgel, C., George, F., & Lorenzi, C. (2009). Speech-perception-in-noise deficits in dyslexia. *Developmental Science, 12,* 732–174. doi:10.1111/j.1467-7687.2009.00817.x