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Basic Auditory Processing Deficits in Dyslexia: Systematic Review of the Behavioral and Event-Related Potential/Field Evidence

Jarmo A. Hämäläinen, PhD[1], Hanne K. Salminen, MA[1], and Paavo H.T. Leppänen, PhD[1]

Abstract

A review of research that uses behavioral, electroencephalographic, and/or magnetoencephalographic methods to investigate auditory processing deficits in individuals with dyslexia is presented. Findings show that measures of frequency, rise time, and duration discrimination as well as amplitude modulation and frequency modulation detection were most often impaired in individuals with dyslexia. Less consistent findings were found for intensity and gap perception. Additional factors that mediate auditory processing deficits in individuals with dyslexia and their implications are discussed.

Keywords

auditory processing, dyslexia, neuropsychology

Developmental dyslexia is a specific learning disability manifested by difficulties in learning to read and write despite having adequate cognitive ability, motivation, access to instruction, and intact peripheral sensory mechanisms (Lyon, Shaywitz, & Shaywitz, 2003). It is widely accepted that deficits in phonological processing underlie the poor reading performance of the majority of individuals with dyslexia (Bradley & Bryant, 1983; Stanovich, 1998; Wagner & Torgesen, 1987). Two broad lines of research emphasize different cognitive-level manifestations and/or causes, either bottom-up or top-down, for the phonological processing deficit. Bottom-up explanations suggests basic auditory processing problems are the underlying basis of the phonological deficit (Farmer & Klein, 1995; Tallal & Gaab, 2006). In this account, poor auditory and speech processing leads to fuzzy or inexact speech sound representations, which in turn constrain phonological processing (Pasquini, Corriveau, & Goswami, 2007; Talcott & Witton, 2002). On the other hand, top-down explanations suggest that phonological problems are a consequence of deficits in higher level linguistic processes at lexical and sublexical levels (Ramus et al., 2003; White et al., 2006). In this view, lower level auditory processing difficulties may co-occur with a phonological deficit, but they do not contribute to phonological processing difficulties and thus play no causal role in the expression of dyslexia. The current review focuses on the empirical behavioral and neural-level evidence of auditory processing deficits in individuals with dyslexia.

Different sound features have been investigated in dyslexia depending on the theoretical paradigm. One theory that has been studied extensively is the rapid auditory processing deficit hypothesis, which posits that individuals with dyslexia have problems processing either brief auditory cues or auditory information presented rapidly, such as in stop consonants where rapid changes in formants (frequency bands) are important for phoneme identification (Farmer & Klein, 1995; Tallal & Gaab, 2006). In this view, slow processing of rapid auditory information could lead to inaccurate perception of certain phonemic contrasts and thus to the development of less precise phonological representations in individuals with dyslexia.

Another hypothesis with a slightly different emphasis states that processing of dynamic features of auditory stimuli, such as amplitude and frequency modulations (AM, FM) in a speech signal, is impaired in individuals with dyslexia (Talcott & Witton, 2002; Witton, Stein, Stoodley, Rosner, & Talcott, 2002). AM refers to the fluctuations of sound intensity in time, and FM refers to similar fluctuations of sound frequency in time.

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An alternative hypothesis suggests that detecting the longer time-scale patterns of intonation, rhythm, and stress in speech prosody is particularly problematic for children and adults with dyslexia (Goswami et al., 2002; Pasquini et al., 2007). The prosody-related sound features would include slowly varying rise times (the time from sound beginning to its maximum amplitude), AM, FM, and changes in syllable and phoneme duration. The deficit in processing these sound features is thought to constrain the segmentation of the speech stream into smaller elements. Basic auditory processing in terms of other features of the acoustic signals, that is, frequency (how high a tone is), duration (how long a tone is), and intensity (how loud a tone is) of tones (e.g., Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999; Richardson, Thomson, Scott, & Goswami, 2004), could also be atypical in individuals with dyslexia.

A growing body of evidence has associated deficits in auditory processing with impaired reading for some but not all individuals with dyslexia. This finding has led to the conclusion that auditory problems may mediate but are not necessary to cause reading problems. For example, auditory processing deficits may be associated with language learning impairments (LLI) that constrain reading development (Bishop, Carlyon, Deeks, & Bishop, 1999). In this view, auditory processing problems may exist as a deficit that constrains development of phonological and literacy skills beyond that which is expected from the language impairment alone. Alternatively, young children with LLI and reading impairments may have a maturational lag in the development of the central nervous system, which would also be reflected in the functioning of the auditory pathway (McArthur & Bishop, 2004; B. A. Wright & Zecker, 2004). In this case, auditory deficits that are present early in children's development could affect the formation of speech sound representations. However, the magnitude of this effect is expected to diminish as children grow older.

The present review focuses on findings from studies that use nonlinguistic auditory stimulation to investigate auditory perception of individuals with dyslexia. This approach is narrow in scope and contrasts with earlier reviews of research on auditory processing among diverse clinical populations that include children and adults with dyslexia (e.g., Bishop, 2007; Tallal & Benasich, 2002) or on the neural basis of dyslexia, which includes studies in genetics and neurobiology (e.g., Démonet, Taylor, & Chaix, 2004; Galaburda, Loturco, Ramus, Fitch, & Rosen, 2006). The current review both complements and extends previous summaries of research that have focused on narrow topics related to auditory processing, such as studies on rapid auditory processing, for example the capacity of those with dyslexia to make temporal order judgments or the effects of decreasing interstimulus intervals on the perception of auditory stimuli (e.g., Farmer & Klein, 1995; McArthur & Bishop, 2001). One aim of this review is to establish the prevalence rate of auditory deficits in dyslexia. Second, the review attempts to identify whether some auditory features are more difficult than other features to process for individuals with dyslexia. Third, the association between auditory processing abilities and reading and spelling skills is reviewed.

Method

Definition of Dyslexia

Studies selected for the current review met the following selection criteria: participants in each study had either a diagnosis of dyslexia or performance at or below the 16th percentile or below a reading age of 1.5 years on a standardized measure of reading and/or spelling. In addition, the participants had Performance IQs on the *Wechsler Intelligence Scales* in the average or above range (i.e., IQ > 80). Participants were from several different language backgrounds: Chinese, Dutch, English, Finnish, French, German, Hebrew, Norwegian, and Spanish. One study investigating children at risk for dyslexia was also included.

Studies conducted up to and including January 2010 were located through searches of the Google Scholar, Medline, and PsycINFO databases and reviews of reference lists of topic-related articles. Keywords used were (dyslexia or reading disability) and auditory processing and (frequency or frequency modulation or intensity or amplitude modulation or rise time or duration or gap detection). Out of the 74 studies found, 14 study samples were rejected because participants did not meet the above criteria for reading problems, leaving 61 studies to be analyzed. Out of the 61 studies, 17 used brain research methods.

Assessment of Auditory Processing

Measures used to probe auditory processing include (a) behavioral nonadaptive and (b) behavioral-adaptive discrimination or detection tasks and (c) brain event-related potential (ERP) or event-related field (ERF; recorded with magnetoencephalography (MEG)) measures.

In all of the studies, the sound stimuli were presented through headphones, except for one ERP study, in which the stimuli were presented through loudspeakers. A total of 10 studies used monaural stimulation (right ear, best ear, or both ears separately); the rest of the studies used binaural stimulation. In behavioral studies, motor or verbal response was required, whereas the ERP studies were passive in the sense that they did not require any response from the participants. Participants were engaged in a cover task such as watching videos during sound presentation. ERPs thus allow the measurement of sensory processing without effects of task demands, such as active attention, motivation, or understanding of instructions.

Behavioral Measures

In nonadaptive tasks, a preselected set of stimuli are used to test each participant's auditory perception. Usually in these studies two sounds are presented and the participant decides whether the sounds were the same or different. This type of task is called a two-interval, two-alternative, forced-choice task (two stimuli are presented and two response options are given). Adaptive behavioral tasks utilize an algorithm that adapts to the participants' performance, trying to find the discrimination threshold where the difference between stimuli is perceived usually with 75% accuracy. This threshold is called just noticeable difference.

ERP and ERF Measures

ERPs and ERFs are measures of electromagnetic activity driven by changes in cognitive processing that are usually time locked to stimuli. To obtain a clearly visible signal, stimuli of interest are typically presented in 100 or more trials and brain responses are averaged across individual stimuli. The most common measures of ERP activity are peak amplitudes and latencies or mean amplitude over a time window. Peak amplitude refers to the strength of activation or voltage of the electrical signal at its highest period, whereas peak latency refers to the time between the onset of the stimulus and when the amplitude reached its peak value.

In the majority of the reviewed ERP studies (15 of 17 studies; 88%), preattentive auditory discrimination responses, mismatch negativity (MMN; *n* = 15; Näätänen, 1992), and late discriminative negativity (LDN; *n* = 5; Cheour, Korpilahti, Martynova, & Lang, 2001) were examined.

MMN is thought to reflect the detection of change in a sound stream at the level of the sensory memory (Näätänen, 1992; Näätänen & Alho, 1997). MMN is typically investigated using an oddball paradigm, where one standard sound occurs regularly and several deviant sounds differing in some feature or features occur rarely. The neural trace of the deviant sounds does not match the trace generated by the repeated sound. This mismatch elicits a negative response at the fronto-central scalp locations at about 150–250 ms from the deviancy onset. In the same paradigm, LDN with a frontal distribution starting at about 400 ms can be observed. The function of LDN is not clear, but it may reflect ongoing processing of the deviant-standard difference (Cheour et al., 2001). In the present review, we use the terms *MMN* and *LDN* for the change detection responses occurring around 150–250 ms and after 400 ms, respectively.

In some of the reviewed ERP studies, amplitude modulation following response (AMFR) was examined. The waveform structure of AMFR follows the amplitude changes of the modulated sound, showing the phase locking of brain activity to the rate of the AM in a sound (McAnally & Stein, 1997). In addition, some of the studies examined the N1 response that has been proposed to reflect detection of transient changes, for example sound onsets, in the auditory environment. The N1 response peaks about 100 ms from stimulus onset and has the largest amplitude at the fronto-central scalp locations (Näätänen & Picton, 1987).

Analyses

Effect sizes for each study were calculated using Cohen's *d* (mean (dyslexic group) – mean (control group)/square root of (*SD* (dyslexic group)^2 + *SD* (control group)^2/2)). Also, 95% confidence intervals were calculated. Average effect sizes were calculated for each auditory feature using sample-size-weighted effect sizes (Cohen's *d* × (sample size of study/total sample size) summed over all studies).

The variability of the performance in auditory processing tasks was examined by comparing the standard deviations of performance in the auditory tasks between participants with dyslexia and those with typical reading skills. The standard deviation of dyslexic readers was divided by that of the typical readers for each of the auditory tasks in each of the studies. This figure was then averaged over the studies. Thus, a value of 1 indicates similar variability between groups, and a value of 2 indicates 2 times greater variability in those with dyslexia than controls.

Auditory Processing and Dyslexia

Processing of Sound Frequencies

Altogether 30 studies compared discrimination of sounds at different frequencies between groups of dyslexic and nondyslexic readers (see Table 1). Of the 14 (71%) studies that used adaptive tasks to measure frequency discrimination, 10 showed group differences that were statistically detectible across conditions. A minority of studies (4 out of a total 14 studies; 29%) report significant group differences on adaptive frequency measures on some, but not all, experimental conditions (Ahissar, Lubin, Putter-Katz, & Banai, 2006; Amitay, Ahissar, & Nelken, 2002; Banai & Ahissar, 2006; Walker, Shinn, Cranford, Givens, & Holbert, 2002). For instance, Ahissar et al. (2006) found that differences in group performance on the frequency discrimination task reached statistical significance when the reference sound remained constant. However, when the reference sound changed in frequency from trial to trial, group performance differences were no longer statistically detectible. Poorer average performance of children with dyslexia relative to nondyslexics on this type of an auditory discrimination task may reflect the inability of those with dyslexia to use the repeated reference sound as an anchor for comparing sounds.

Nonadaptive behavioral studies have not found group differences as often as the adaptive studies (see Table 1). In

Table 1. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Frequency Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Studies with small frequency changes					
Goswami et al., 2010 (English)	10.5 y	27/44	**2.2**	1.70–2.67	Frequency discrimination threshold (***)
Renvall & Hari, 2003	30 y	11/8	**2.0**	1.02–2.96	MMF amplitude, left (*), right (*ns*) hemisphere
Ahissar et al., 2006	13.1 y	12/16	**1.6**[a]	0.80–2.30	Frequency discrimination threshold, constant reference tone (**)
Walker et al., 2002	20.6 y	9/9	**1.6**	0.59–2.55	Frequency discrimination threshold (*ns*)
Baldeweg et al., 1999	33.4 y	10/10	**1.3**	0.36–2.20	Frequency detection, MMN amplitude, latency (**)
McAnally & Stein, 1996	28.0 y	26/23	**1.0**	0.43–1.58	Frequency discrimination threshold (***)
McArthur et al., 2008	10.3 y	37/68	**1.0**[a]	0.63–1.44	Frequency discrimination threshold (**)
Gibson et al., 2006	9.8 y	44/44	**0.8**	0.35–1.19	Frequency discrimination threshold (**)
Halliday & Bishop, 2006a	10.7 y	28/28	**0.8**	0.30–1.37	Frequency discrimination threshold (**)
Banai & Ahissar, 2004	17–30 y	59/48	**0.7**[a]	0.32–1.09	Frequency discrimination threshold (**)
Banai & Ahissar, 2006	13.1 y	12/22	**0.7**[a]	–0.02–1.44	Frequency discrimination threshold, 1 (*ns*) & 2 (**) reference sounds
Heath et al., 2006	36.3 y	41/49	**0.7**	0.26–1.10	Frequency discrimination threshold (*)
Thomson & Goswami, 2008	10.8 y	23/25	**0.7**	0.07–1.22	Frequency discrimination threshold (*)
Amitay, Ben-Yehudah, et al., 2002	21.5 y	30/30	**0.6**	0.11–1.15	Frequency discrimination threshold, 50 & 250 ms tones (*)
Lachmann et al., 2005	9.8 y	12/16	**0.6**	–0.23–1.33	MMN amplitude (** in one subgroup)
Amitay, Ahissar, et al., 2002	22 y	27/23	**0.5**	0.01–1.04	Frequency discrimination threshold (*ns*)
Watson & Miller, 1993	24 y	54/24	**0.5**	0.05–1.02	Frequency discrimination (*ns*)
Adlard & Hazan, 1998	10.8 y	12/13	**0.3**	–0.51–1.12	Formant & F0 frequency discrimination (*ns*)
Maurer et al., 2003	6.6 y	29/31	**0.2**[a]	–0.32–0.71	Frequency detection (*ns*), eMMR (*ns*), MMR & LDN (**) amplitudes
Schulte-Körne et al., 1998a	12.5 y	15/19	**–0.1**	–0.77–0.63	MMN & LDN amplitude (*ns*)
Kujala et al., 2006	33 y	11/9	**–0.3**	–1.26–0.60	MMN amplitude, optimal (*), oddball (*ns*)
Watson, 1992	Adults	25/20	**–0.6b**	–1.17–0.04	Frequency discrimination (*ns*)
Total, frequency	—	**554/582**	**0.7**	—	—
Studies with large frequency changes					
Schulte-Körne et al., 2001	30.5 y	13/12	0.5	–0.36–1.28	MMN & LDN amplitude (*ns*)
Hämäläinen et al., 2008	9.3 y	25/21	0.2	–0.44–0.74	MMN, LDN amplitude in pair with long interval (*ns*)
Sharma et al., 2006	10.3 y	19/15	0.2[a]	–0.58–0.87	Frequency detection, MMN amplitude (*** only for 1.1 kHz missing harmonic task)
No effect size calculated because of small sample size or lack of data					
Corbera et al., 2006	11.6 y	11/13	NA	NA	MMN amplitude (*ns*), latency (***)
France et al., 2002	Adults	20/16	NA	NA	Frequency discrimination threshold, 1 ref tone (*), 6 ref tones, 10 & 200 ms ISI (*ns*), 400 & 1000 ms (***)
Hugdahl et al., 1998	11.8 y	25/25	NA	NA	MMN amplitude (*), latency (*)
Kujala et al., 2003	28 y	8/8	NA	NA	MMN amplitude, group × electrode interaction (*)
Meng et al., 2005	11.1 y	7/11	NA	NA	MMN amplitude (*ns*)

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: MMF = mismatch field; MMN = mismatch negativity; MMR = mismatch response; LDN = late discriminative negativity) and significance level of the group difference are also shown. *ns* = not significant; ISI = inter-stimulus interval.

[a] Mean and *SD* provided by the authors of the study.

[b] Effect size estimated from a figure.

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

two out of six studies, performance of the participants with dyslexia was poorer compared to that of typical readers (Baldeweg et al., 1999; Sharma et al., 2006). This difference in results found using adaptive versus nonadaptive tasks could be the result of the lesser sensitivity of the latter tasks.

As shown in Table 1, there is considerable variation in findings from ERP and ERF studies. However, in studies where the difference in sound frequency between standard and deviant stimuli is small (< 10%), the ERPs or ERFs of those with dyslexia have smaller amplitudes and/or later MMN latencies than typical readers (Baldeweg et al., 1999; Corbera, Escera, & Artigas, 2006; Hugdahl et al., 1998; Kujala, Lovio, Lepistö, Laasonen, & Näätänen, 2006; Lachmann, Berti, Kujala, & Schröger, 2005; Renvall & Hari, 2003). Maurer, Bucher, Brem, and Brandeis (2003) is the only study in which a smaller LDN response was found. In contrast, in studies in which the difference in sound frequency of stimuli is large (> 10%), group differences are not statistically detectable (Hämäläinen Leppänen, Guttorm, & Lyytinen, 2008; Meng et al., 2005; Schulte-Körne, Deimel, Bartling, & Remschmidt, 2001; Sharma et al., 2006). Bishop (2007), in her review of findings of ERP studies of frequency processing in individuals with language impairment and dyslexia, arrived at a similar conclusion regarding the processing of small and large differences in sound frequency among those with dyslexia.

There are two exceptions to this pattern of results. Schulte-Körne, Deimel, Bartling, and Remschmidt (1998a) did not find any differences in ERPs to a small 5% frequency change in children with spelling problems compared to nonimpaired controls. On the other hand, one study using a large frequency change (50%) revealed a group interaction with electrode position (Kujala, Belitz, Tervaniemi, & Näätänen, 2003).

Factors in addition to differences in frequency processing may contribute to differences in MMN amplitude and latency. For example, when a more complex stimulus presentation paradigm was used, a significant group difference in MMN amplitude was found in contrast to the traditional oddball experiment (Kujala et al., 2006). In addition, one study found that only those children with dyslexia who had problems in the reading of frequent real words showed diminished MMN, whereas children with dyslexia who had problems in nonword reading showed MMN comparable to that of control children (Lachmann et al., 2005).

Five studies report associations between auditory processing (MMN latency: Baldeweg et al., 1999; discrimination thresholds: Goswami et al., 2011; Heath, Bishop, Hogben, & Roach, 2006; McAnally & Stein, 1996; Thomson & Goswami, 2008) and different literacy measures; the correlations range from .35 to .71 ($p < .05$) across dyslexic and typical readers. Four studies report correlations ($r = .38–.80$, $p < .05$) between auditory discrimination thresholds and different reading measures (word identification, nonword reading, word reading) in the control or dyslexia group only (France et al., 2002; Gibson, Hogben, & Fletcher, 2006; Halliday & Bishop, 2006a; Walker et al., 2002).

In summary, it appears that discriminating a small difference (< 10%) in frequency is problematic for both adults and children with dyslexia. The few studies reporting correlations between the varied frequency discrimination measures and different reading measures show somewhat contradictory findings with the correlation showing up within either the control or dyslexia group or across combined groups.

Processing of FM

Of the reviewed studies, 14 investigated FM detection in individuals with dyslexia. As shown in Table 2, group performance differs at slow FM rates (2–40 Hz) in 10 out of the 11 studies. With fast modulation rates (≥ 60 Hz), group differences are not statistically detectable (Adlard & Hazan, 1998; Ramus et al., 2003; Witton et al., 1998; Witton et al., 2002). However, there are also studies deviating from this pattern of findings. One study with school-aged children reported statistically significant group differences at only a 40 Hz FM rate but not at 2 or 240 Hz rates (Dawes et al., 2009). Another study testing FM detection at 2 and 240 Hz rates found children with dyslexia to perform more poorly at both rates compared to controls (C. M. Wright & Conlon, 2009). The latter finding of group difference at the 240 Hz rate could be the result of the increased statistical power given a very large sample size ($N = 122$).

Only one study examined FM processing with both behavioral and ERP measures (Stoodley, Hill, Stein, & Bishop, 2006). Group differences between adults with and without dyslexia were found only in MMN amplitude. The lack of any group difference at slow FM rates when behavioral measures were used differs from the majority of the other studies, but it should be noted that the participants were university students reading at a normal level but below that expected based on their other cognitive skills.

Eight studies report correlations between FM detection thresholds and reading and/or spelling skills. Three studies found that associations with either reading or spelling skills were statistically not significant (Dawes et al., 2009; Heath et al., 2006; Van Ingelghem et al., 2005). One study found a significant, moderate correlation between MMN amplitude to a deviant sound using 20 Hz FM rate and word identification but not between behavioral measures of FM detection and word identification (Stoodley et al., 2006). Associations between FM detection thresholds and reading skills (word and nonword reading; $r = .21–.73$, $p < .05$) were reported in four studies (Gibson et al., 2006; Witton et al., 1998; Witton et al., 2002; C. M. Wright & Conlon, 2009). It seems that even though group differences in auditory processing emerge systematically for slow FM rate thresholds, the evidence on correlations with word and nonword reading is conflicting.

Table 2. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Frequency Modulation Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Studies with slow modulation rates (< 60 Hz)					
Witton et al., 2002	25.4 y	21/17	**1.2**	0.55–1.87	FM detection threshold, 2 Hz (**)
Boets et al., 2007	7.3 y	28/9	**0.9**	0.07–1.65	FM detection threshold, 2 Hz (*)
Van Ingelghem et al., 2005	11.3 y	10/10	**0.9**	0.00–1.85	FM detection threshold, 2 Hz (*)
Gibson et al., 2006	9.8 y	44/44	**0.8**[a]	0.39–1.23	FM detection threshold, 2 Hz (**)
Ramus et al., 2003	21.1 y	17/17	**0.7**	0.04–1.42	FM detection threshold, 2 Hz (*)
Witton et al., 1998	30.4 y	23/21	**0.7**[b]	0.07–1.28	FM detection threshold, 2 Hz (***) & 40 Hz (*)
Dawes et al., 2009	9.8 y	20/19	**0.6**[a]	−0.04–1.25	FM detection threshold, 2 Hz (*ns*) & 40 Hz (***)
Heath et al., 2006	36.3 y	41/49	**0.6**	0.14–0.98	FM detection threshold, 2 Hz (*)
Halliday & Bishop, 2006b	11.8 y	16/16	**0.5**[a]	−0.24–1.19	FM detection threshold, 2 Hz & 20 Hz (*ns*)
C. M. Wright & Conlon, 2009	8.6 y	52/70	**0.5**	0.12–0.85	FM detection threshold, 2 Hz (**)
Stoodley et al., 2006	25.6 y	9/10	**0.4**	−0.55–1.36	FM detection threshold, 2 Hz & 20 Hz (*ns*), MMN/LDN amplitude, 5Hz (*ns*), 20 Hz (*)
White et al., 2006	10.5 y	22/23	**0.3**	−0.34–0.86	FM detection threshold, 2 Hz (*ns*)
Total, FM	—	**303/305**	**0.6**	—	—
Studies with fast modulation rates (≥ 60 Hz)					
Ramus et al., 2003	21.1 y	17/17	0.6	−0.11–1.28	FM detection threshold, 240 Hz (*ns*)
C. M. Wright & Conlon, 2009	8.6 y	52/70	0.6	0.27–0.99	FM detection threshold, 240 Hz (**)
Dawes et al., 2009	9.8 y	20/19	0.5	−0.12–1.25	FM detection threshold, 240 Hz (*)
Witton et al., 2002	25.4 y	21/17	0.5	−0.16–1.16	FM detection threshold, 240 Hz (*ns*)
Adlard & Hazan, 1998	10.3 y	12/13	0.2	−0.67–0.96	Formant FM detection, 60–300 Hz (*ns*)
Stoodley et al., 2006	25.6 y	9/10	−0.1	−1.33–0.57	FM detection threshold, MMN, LDN, 240 Hz (*ns*)
Witton et al., 1998	30. 4 y	23/21	−0.3	−0.86–0.35	FM detection threshold, 240 Hz (*ns*)
No effect size calculated because of lack of data					
Talcott et al., 2003	11.4 y	22/17	NA	NA	FM detection threshold, 2 Hz (*)

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: MMN = mismatch negativity; LDN = late discriminative negativity) and significance level of the group difference are also shown.
ns = not significant.
[a] Mean and *SD* provided by the authors of the study.
[b] Effect size estimated from a figure.
*$p < .05$. **$p < .01$. ***$p < .001$.

Processing of Sound Intensity

As shown in Table 3, only 2 of the 16 samples of studies that investigated intensity processing in dyslexia reported a significant group difference (Goswami et al., 2011; Thomson, Fryer, Maltby, & Goswami, 2006). The sole ERP study that examined MMN for a change in sound amplitude (Kujala et al., 2006) did not find any statistically detectable differences, which suggests that individuals with dyslexia process sound intensity in the same way as their nondyslexic peers.

Three of the four studies that calculated correlations between intensity discrimination and literacy skills found no statistically significant associations with word reading or spelling (Pasquini et al., 2007; Richardson et al., 2004; Thomson et al., 2006). One study found statistically significant associations between intensity discrimination threshold and reading skills in English-speaking ($r = .28$) and Spanish-speaking ($r = .45$) schoolchildren (Goswami et al., 2011).

Processing of AM

As reported in Table 4, 6 out of 8 studies that investigated AM detection show that individuals with dyslexia have higher discrimination thresholds, indicating poorer performance, at least at some AM rates (typically at 10–160 Hz). In addition, in ERP studies participants with dyslexia have smaller AMFR, showing corroborating evidence (McAnally & Stein, 1997; Menell, McAnally, & Stein, 1999). However, even though group differences were found on measures of AM perception, when examining the confidence intervals in Table 4, it can be seen that they encompass zero, which suggests that there is variation across the different conditions used in the individual studies.

There are also some contradictory findings. For example, Witton et al. (2002) found detection of AM at the 2 Hz rate to be intact but impaired at the 20 Hz modulation rate in adults with dyslexia. This is in line with results of most other studies. In contrast, Stuart, McAnally, McKay, Johnston, and

Table 3. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Intensity Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Goswami et al., 2011 (English)	10.5 y	27/44	**0.9**	0.43–1.41	Intensity discrimination threshold (*)
Goswami et al., 2011 (Spanish)	11.4 y	18/21	**0.9**	0.20–1.49	Intensity discrimination threshold (*ns*)
Nicolson et al., 1995	14.0 y	10/10	**0.9**[a]	–0.03–1.82	Intensity discrimination threshold (*ns*)
Thomson et al., 2006	22.3 y	20/19	**0.7**	0.02–1.31	Intensity discrimination threshold (*)
Fraser et al., 2010	10.2 y	11/11	**0.6**	–0.28–1.47	Intensity discrimination threshold (*ns*)
Watson & Miller, 1993	24 y	54/24	**0.5**	–0.01–0.97	Intensity discrimination threshold (*ns*)
Pasquini et al., 2007	21.8 y	18/18	**0.4**	–0.25–1.10	Intensity discrimination threshold (*ns*)
Amitay, Ben-Yehudah, et al., 2002	21.5 y	30/30	**0.3**	–0.23–0.80	Intensity discrimination threshold (*ns*)
Banai & Ahissar, 2004	17–30 y	59/48	**0.3**[a]	–0.08–0.68	Intensity discrimination threshold (*ns*)
Nicolson et al., 1995	18.2 y	12/12	**0.3**[a]	–0.68–1.28	Intensity discrimination threshold (*ns*)
Richardson et al., 2004	8.8 y	24/24	**0.3**	–0.26–0.90	Intensity discrimination threshold (*ns*)
Kujala et al., 2006	33 y	11/9	**0.2**	–0.76–1.10	MMN amplitude, latency (*ns*)
Nicolson et al., 1995	9.3 y	9/9	**0.2**[a]	–0.60–1.07	Intensity discrimination threshold (*ns*)
Thomson & Goswami, 2008	10.7 y	23/25	**–0.1**	–0.72–0.44	Intensity discrimination threshold (*ns*)
Watson, 1992	Adults	25/20	**–0.2**[b]	–0.84–0.36	Intensity discrimination threshold (*ns*)
Rocheron et al., 2002	12.7 y	5/10	**–0.5**[a]	–1.65–0.71	Intensity discrimination threshold (*ns*)
Total, intensity	—	**356/334**	**0.5**	—	—

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: MMN = mismatch negativity) and significance level of the group difference are also shown. *ns* = not significant.

[a] Mean and *SD* provided by the authors of the study.

[b] Effect size estimated from a figure.

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

Table 4. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Amplitude Modulation Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Rocheron et al., 2002	12.7 y	5/10	**1.1**[a]	–0.09–2.26	AM detection threshold, 4 Hz & 128 Hz (*)
McAnally & Stein, 1997	27.7 y	15/15	**0.6**[a]	–0.15–1.33	AMFR amplitude, 20–80 Hz (*)
Menell et al., 1999	27.6 y	20/20	**0.6**[a]	–0.04–1.23	AM detection threshold, 10–160 Hz (**), AMFR amplitude, 10–160 Hz (*)
Witton et al., 1998	25.4 y	21/17	**0.5**	–0.14–1.17	AM detection threshold, 2 Hz (*ns*), 20 Hz (*)
Hämäläinen et al., 2009	9.0 y	30/30	**0.4**	–0.15–0.87	AM detection threshold, 20 Hz (*ns*)
Total, AM	—	**91/92**	**0.5**	—	—
No effect size calculated because of small sample size or lack of data					
Amitay, Ahissar, et al., 2002	22 y	27/23	NA	NA	AM detection threshold, 4–500 Hz (*ns*)
Lorenzi et al., 2000	10.5 y	6/6	NA	NA	AM detection threshold, 4 Hz (***), 1024 Hz (*), 16–256 Hz (*ns*)
Stuart et al., 2006	35.5 y	18/13	NA	NA	AM detection threshold, 1 Hz (**) & 100 Hz (*ns*)

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: AMFR = amplitude modulation following response) and significance level of the group difference are also shown. *ns* = not significant.

[a] Mean and *SD* provided by the authors of the study.

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

Castles (2006) found that detection at the 1 Hz AM rate was impaired and at the 100 Hz AM rate intact in adults with dyslexia. The latter finding appears contradictory but may be the result of different methods used for measuring AM perception. In the Witton et al. study, the participants indicated which of the two separate sounds was amplitude modulated. In the Stuart et al. study, the participants listened to a single 4 s tone and had to decide when they heard AM in the tone, during either the 2nd or 3rd second of the tone. Also, Hämäläinen et al. (2009) found no group differences in schoolchildren with and without dyslexia for 20 Hz AM detection scores.

Only four of the studies examined associations between AM detection and different reading measures (including word and nonword reading and a composite of different reading measures). In three studies, a moderate correlation ($r = .39–.48, p < .05$) was reported across the groups (Menell et al., 1999; Stuart et al., 2006; Witton et al., 2002). In one study no statistically significant associations were found (Hämäläinen et al., 2009). Overall, it appears that group differences are rather consistently found with AM detection tasks, particularly with moderate or fast modulation rates (at or above 4 Hz). Variation in AM processing also seems to be associated with differences in a diverse set of reading skills.

Processing of Sound Rise Time

As reported in Table 5, group differences were found in sound rise time processing in the 11 samples studied. ERP studies also show group differences in N1/MMN and LDN responses. N1 has been found to be less sensitive to different rise times in children with dyslexia compared to controls (Hämäläinen, Leppänen, Guttorm, & Lyytinen, 2007). In one study, MMN was larger in children with dyslexia to rise time change compared to control children (Hämäläinen et al., 2008). In contrast, LDN was smaller in response to a change in sound rise time in the same study in children with dyslexia. It is interesting that in one study, despite the group difference found in ERPs, the same children did not show behavioral group differences in rise time discrimination (Hämäläinen et al., 2009).

In the 10 samples studied, significant correlations between rise time perception and word and nonword reading, spelling, and masked word recognition and nonword or word choice performance across the reading groups were found ($r = .28–.60$; Fraser, Goswami, & Conti-Ramsden, 2010; Goswami et al., 2002; Goswami et al., 2011; Hämäläinen, Leppänen, Torppa, Muller, & Lyytinen, 2005; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Pasquini et al., 2007; Richardson et al., 2004; Thomson et al., 2006; Thomson & Goswami, 2008). One study that did not find group differences in rise time perception reported a statistically significant correlation between rise time discrimination and spelling ($r = .39$), but only in the children with reading problems (Hämäläinen et al., 2009).

Processing of Sound Duration

As shown in Table 6, statistically detectable differences in the performance of individuals with and without dyslexia were found in 8 of 12 study samples. Two MMN studies found significant differences (Corbera et al., 2006; Huttunen, Halonen, Kaartinen, & Lyytinen, 2007), whereas two MMN studies found no statistically detectable differences between those with dyslexia and controls (Baldeweg et al., 1999; Kujala et al., 2006). The only stimulation parameter explaining the difference between study findings could be faster stimulation rate (onset-to-onset interval of 100–300 ms vs. 500–700 ms) in the studies that found group differences.

Only four studies examined correlations between literacy skills and duration processing. Two behavioral studies found a significant association between duration discrimination threshold and word reading ($r = .36–.42, p < .05$; Thomson et al., 2006; Thomson & Goswami, 2008). In addition, one study found no statistically significant association between word reading and duration discrimination thresholds in English speakers but did find an association in Spanish speakers (Goswami et al., 2011). In contrast, the association between MMN amplitude or latency and word and nonword reading skills was not statistically detectable (Baldeweg et al., 1999).

Processing of Gap Duration

As shown in Table 7, 9 articles with 10 different samples investigated processing of gap detection among individuals with dyslexia. Of these study samples, 7 showed no group differences between those with dyslexia and controls. However, gap detection thresholds may vary as children grow older and mature. In a cross-sectional study using small sample sizes, Hautus, Setchell, Waldie, and Kirk (2003) found gap detection thresholds to be elevated in 6- and 8-year-olds but not in 10-, 12-, or 25-year-olds with dyslexia. Two studies found group differences also in 10- and 11-year-olds (Sharma et al., 2006; Van Ingelghem et al., 2001). In contrast, findings from a longitudinal study conducted by Boets, Wouters, van Wieringen, and Ghesquiere (2007) showed no group differences in gap detection at 5 years in children who were classified as either poor or typical readers based on a composite of their word, pseudoword, and nonword reading and word spelling skills at 7 years. In addition, two other studies with 10- to 12-year-old children found no statistically detectable group differences (Adlard & Hazan, 1998; Schulte-Körne, Deimel, Bartling, & Remschmidt, 1998b); similarly, three studies with adults found no statistically detectable group differences in gap detection performance (King, Lombardino, Crandell, & Leonard, 2003; McAnally & Stein, 1996; Schulte-Körne et al., 1998b). In the only ERP study, group differences were found to be not statistically detectable for MMN to a gap deviancy in adults with and without dyslexia (Kujala et al., 2006).

Of the four studies that examined correlation between gap detection thresholds and literacy measures, two studies did not find any associations with word reading or spelling (King et al., 2003; Schulte-Körne et al., 1998b). Two studies that also showed group differences showed a significant correlation between gap detection and word and pseudoword reading skills (words: $r = .60$, nonwords: $r = .57, p < .05$; Van Ingelghem et al., 2001) and gap detection and nonword reading skills ($r = .38, p < .05$; Sharma et al., 2006). Overall, the majority of the studies did not find gap

Table 5. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Rise Time Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Goswami et al., 2002	9.0 y	25/24	**1.4**	0.85–1.99	5-ramp rise time discrimination threshold (***)
Hämäläinen et al., 2005	37 y	13/19	**1.2**	0.48–1.94	Rise time detection in paired tones (**)
Fraser et al., 2010	10.4 y	11/11	**1.1**	0.23–1.98	2-ramp (**) and 1-ramp (*ns*) rise time discrimination threshold
Muneaux et al., 2004	11.4 y	20/18	**1.1**	0.45–1.76	5-ramp rise time discrimination threshold (***)
Thomson et al., 2006	22.3 y	20/19	**1.0**	0.36–1.65	2-ramp (**) and 1-ramp (*) rise time discrimination threshold
Goswami et al., 2011 (English)	10.5 y	27/44	**0.8**	0.35–1.33	2-ramp (**) and 1-ramp (***) rise time discrimination threshold
Hämäläinen et al., 2008	9.3 y	25/21	**0.7**	0.14–1.33	LDN to rise time change in paired tones (*)
Richardson et al., 2004	8.8 y	24/24	**0.7**	0.16–1.31	2-ramp (**) & 1-ramp (*) rise time discrimination threshold
Thomson & Goswami, 2008	10.8 y	23/25	**0.7**	0.15–1.31	Multiple-ramp (*) and 1-ramp (**) rise time discrimination threshold
Goswami et al., 2011 (Spanish)	11.4 y	18/21	**0.5**	–0.15–1.14	2-ramp (*ns*) and 1-ramp (*) rise time discrimination threshold
Pasquini et al., 2007	21.8 y	18/18	**0.5**	–0.15–1.19	5-ramp (*), 2-ramp (*ns*) and 1-ramp (*ns*) rise time discrimination threshold
Hämäläinen et al., 2009	9.0 y	21/26	**0.2**	–0.18–0.58	2-ramp and 1-ramp rise time discrimination threshold (*ns*); same sample of children as in Hämäläinen et al., 2008
Total, rise time	—	**234/244**	**0.8**	—	—

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: LDN = late discriminative negativity) and significance level of the group difference are also shown. *ns* = not significant.
*$p < .05$. **$p < .01$. ***$p < .001$.

Table 6. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Duration Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Thomson & Goswami, 2008	10.8 y	23/25	**1.4**	0.81–1.97	Duration discrimination threshold (*)
Goswami et al., 2011 (Spanish)	11.4 y	18/21	**1.1**	0.46–1.75	Duration discrimination threshold (**)
Thomson et al., 2006	22.4 y	20/19	**1.0**	0.39–1.68	Duration discrimination threshold (**)
Banai & Ahissar, 2004	17–30 y	59/48	**0.9**[a]	0.48–1.25	Duration discrimination threshold for 100 ms (***) and 1,000 ms (***) sounds
Banai & Ahissar, 2006	13.1 y	12/22	**0.9**[a]	0.13–1.59	Duration discrimination threshold for 100 ms (*) and 400 ms (**) sounds
Watson & Miller, 1993	24 y	54/24	**0.8**	0.27–1.25	Duration discrimination (ns at $\alpha = .004$)
Goswami et al., 2011 (English)	10.5 y	27/44	**0.6**	0.15–1.12	Duration discrimination threshold (*)
Kujala et al., 2006	33 y	11/9	**0.5**	−0.43–1.43	MMN amplitude, latency (*ns*)
Baldeweg et al., 1999	33.4 y	10/10	**0.3**	−0.59–1.26	MMN amplitude, latency and behavioral accuracy (*ns*)
Total, duration	—	**234/222**	**0.9**	—	—
No effect size calculated because of small sample size or lack of data					
Corbera et al., 2006	11.6 y	11/13	NA	NA	MMN amplitude (*), latency (***)
Huttunen et al., 2007	11.8 y	21/21	NA	NA	MMN amplitude, hemisphere × group interaction (*)
Watson, 1992	Adults	25/20	3.5[b]	NA	Duration discrimination (*), excluded as an outlier value

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: MMN = mismatch negativity) and significance level of the group difference are also shown. *ns* = not significant.
[a] Mean and *SD* provided by the authors of the study.
[b] Effect size estimated from a figure.
*$p < .05$. ** $p < .01$. *** $p < .001$.

Table 7. Effect Sizes and 95% Confidence Intervals (CIs) for the Differences Between Individuals With Typical Reading Skills (C; controls) and With Reading Problems (RD) for Gap Perception.

Study	Age	*N* (C/RD)	Effect Size	95% CI	Method and Significance Level
Van Ingelghem et al., 2001	11.3 y	10/10	**1.5**	0.53–2.38	Gap detection threshold (**)
Sharma et al., 2006	10.3 y	19/15	**0.9**[a]	0.17–1.57	Threshold when two sound heard as one (**)
Adlard & Hazan, 1998	10.3 y	12/13	**0.6**	–0.18–1.45	Gap detection (*ns*)
Boets et al., 2007	7.3 y	28/9	**0.6**	–0.22–1.36	Gap detection threshold (*ns*)
King et al., 2003	24.4 y	14/11	**0.6**	–0.23–1.42	Gap detection threshold (*ns*)
McAnally & Stein, 1997	28.0 y	26/23	**0.4**[a]	–0.15–0.89	Gap detection threshold (*ns*)
Schulte-Körne et al., 1998b	12.5 y	14/15	**0.4**	–0.41–1.10	Gap detection threshold (*ns*)
Kujala et al., 2006	33 y	11/9	**0.2**	–0.77–1.09	MMN amplitude, latency (*ns*)
Schulte-Körne et al., 1998b	27.5 y	22/9	**0.2**	–0.61–1.02	Gap detection threshold (*ns*)
Total, gap	—	**156/114**	**0.6**	—	—
No effect size calculated because of small sample size					
Hautus et al., 2003	6.1–25.4 y	6–11/4–6	NA	NA	Gap detection threshold for 6–8 y (*), 10–25 y (*ns*)

Note: The total effect size is weighted by sample size. Studies have been arranged according to effect size (in bold). Testing method (for event-related potential studies: MMN = mismatch negativity) and significance level of the group difference are also shown. *ns* = not significant.
[a] Mean and *SD* provided by the authors of the study.
*$p < .05$. ** $p < .01$. *** $p < .001$.

detection differences that were statistically significant between dyslexic and typical readers, and the reported correlations were found only in studies also showing group differences.

Effect Size Summary and Variability Across Different Auditory Features

A funnel plot was drawn using the effect sizes from all studies. Funnel plots are used to examine the possibility of publication bias: It is possible that only those studies using small sample sizes but demonstrating large effects are published. However, as can be seen from Figure 1, the plot showed a triangle-like distribution of the effect sizes; that is, the smaller studies had both smaller and larger effect sizes compared to those of the studies with larger sample sizes. This indicates that there is no evidence for publication bias in the reviewed studies.

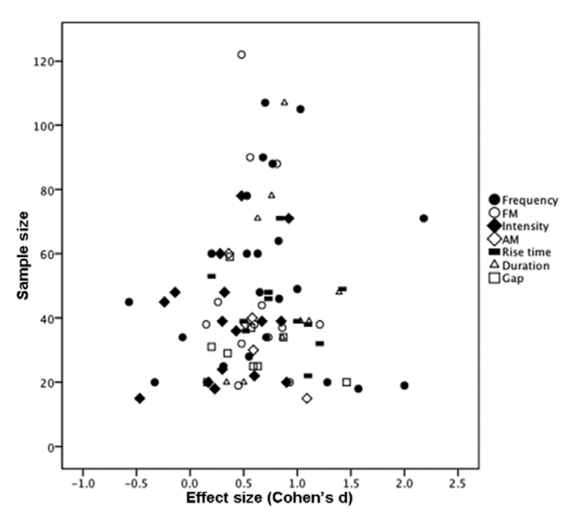

Figure 1. Funnel plot showing the effect size and sample size of all reviewed studies.
Filled circles are studies examining frequency perception, open circles frequency modulation, filled diamonds intensity, open diamonds amplitude modulation, filled rectangles rise time, open triangles duration, and open squares gap detection.

To answer the question of the prevalence of auditory deficits in dyslexia, an average of the sample-size-weighted effect sizes was calculated across the different sound features and study samples. This average effect size indicates that approximately 38% to 43% of the distributions for control and dyslexia groups do not overlap (i.e., effect size of 0.65 on average, calculated across individual studies). This is close to a previous estimation, according to which 39% of individuals with dyslexia show auditory processing deficits (Ramus, 2003). However, for some sound features the mean sample-size-weighted effect sizes are larger. Table 8 shows that for duration perception, the effect size is 0.9 (52% nonoverlap), for rise time perception 0.8 (47% nonoverlap), for frequency perception 0.7 (43% nonoverlap), for FM perception 0.6 (38% nonoverlap), and for intensity, AM, and gap perception 0.5 (33% nonoverlap).

It is often the case that the task performance in the dyslexia samples has more variation than that of typical readers, indicating possible existence of subgroups or other confounding factors such as attention problems. As Table 8

Table 8. Numbers of Study Samples in Which Auditory Processing in Individuals With Dyslexia Was Investigated and the Number (and percentage) of Study Samples That Showed Group Differences Between Individuals With Dyslexia and Typical Reading Skills.

	Frequency[a]	FM[b]	Intensity	AM	Rise Time	Duration	Gap
Number of studies	25	13	16	8	11	12	10
Group difference found (*n*/%)	19/76%	12/92%	2/13%	6/75%	11/100%	9/75%	3/30%
Weighted mean effect size	0.7 (43%)	0.6 (38%)	0.5 (33%)	0.5 (33%)	0.8 (47%)	0.9 (52%)[c]	0.5 (33%)
SD of RD/*SD* of C	1.8	2.1	1.5	2.5	1.4	1.8	1.4

Note: Weighted (by sample size) mean effect size (Cohen's *d*) (in parentheses is the percentage of nonoverlap between the two groups' distributions) and the standard deviation of dyslexia samples divided by that of control samples. C = controls; RD = participants with reading disability.

[a] Five studies using large frequency differences between standard and deviant sound excluded (Hämäläinen et al., 2008; Kujala et al., 2003; Meng et al., 2005; Schulte-Körne et al., 2001; Sharma et al., 2006); see Table 1.

[b] Studies and conditions using FM rates faster than or equal to 60 Hz excluded; see Table 2.

[c] Outlying value (3.5) of Watson (1992) removed.

shows, the variability in performance of participants with dyslexia is 1.4 to 2.5 times greater compared to that of controls (variability in the dyslexic groups divided by that of controls). It seems that the same auditory features showing the largest effect sizes (frequency, FM, duration) also show the largest variability between groups (1.8, 2.1, 1.8, respectively). An exception to this seems to be rise time perception, where the variability in individuals with dyslexia compared to controls was only 1.4 times greater. The larger variability in general could indicate that a subpopulation of individuals with dyslexia have problems in processing AM and FM as well as duration and frequency. However, perception of gaps and intensity show less variability between groups (1.5 and 1.4, respectively). Although the performance of individuals with dyslexia does demonstrate more variability in these tasks as well, the variability is greater in those tasks showing group differences. This suggests that the increased variability is the result of dyslexia subgroups instead of, for example, general attention problems that would affect all tasks equally.

Discussion

The present review examined the nature of auditory processing deficits in children and adults with dyslexia. Overall, statistically detectable differences in auditory processing between groups of dyslexic and typical readers were reported on measures of duration, rise time, and slow FM rates. On average, children and adults with dyslexia also appear to have more difficulty processing small differences in sound frequency and the AM perception. In most of the reviewed studies, perceiving a gap between sounds as well as the intensity of sounds was found to be typical in individuals with dyslexia.

For FM and frequency perception, a pattern seems to emerge: Group differences are found at slower FM rates (less than 60 Hz) and for smaller frequency differences (10% or smaller). This is in line with the observation made by Bishop (2007) that in MMN studies group differences between language-learning-impaired individuals and controls are found only when small frequency differences need to be detected. For AM perception, group differences are observed, interestingly, at high modulation rates (10–320 Hz; except for one study), whereas at slow modulation rates (1–4 Hz) the results are less consistent.

One explanation for the different findings at fast and slow AM and FM rates could be related to the perception of frequencies and intensity in general. It has been suggested that FM perception at slow modulation rates relies on frequency perception (Moore, 2003). This would explain why reader group differences are seen at the slow FM rates. On the other hand, in the present review perception of intensity was found to be intact in individuals with dyslexia in most studies, and thus AM detection at slow rates, possibly related to the perception of intensity (Moore, 2003), does not show consistent group differences.

Of the reviewed studies, 17 used ERP or ERF measures. Results obtained with ERP or ERF measures were mainly in line with those obtained from behavioral studies. However, with ERPs it is possible to examine the time course of auditory processing and to try to find which auditory processing stages are different in individuals with dyslexia. Response to oscillations of AM stimuli (AMFR) showed diminished amplitudes in participants with dyslexia relative to controls (McAnally & Stein, 1997; Menell et al., 1999), which suggests that basic auditory processing problems can exist at the thalamic or early cortical level. Participants with dyslexia also have atypical processing of changes in sound streams, indicating poorer discrimination at preattentive levels in ERP or ERF studies. This is manifested in differences in MMN amplitude and latency (e.g., Baldeweg et al., 1999; Corbera et al., 2006; Hugdahl et al., 1998; Kujala et al., 2003; Kujala et al., 2006; Lachmann et al., 2005). In addition to the atypical change detection response, LDN, reflecting further processing of stimulus difference, has also been reported to be smaller in individuals at risk for and with dyslexia (Hämäläinen et al., 2008; Maurer et al., 2003).

However, there are inconsistencies in findings on group differences also when brain responses are examined. The seemingly contradictory findings could be related to several confounding factors such as variation in the severity of the reading problems and heterogeneity of the neural origins of dyslexia. These include the question of whether a specific subpopulation of individuals with dyslexia is more likely to have auditory processing deficits, as hinted by the increased variability in auditory task performance.

Most of the reviewed studies were carried out with adults or school-aged children. In these samples, auditory deficits did not seem to diminish as a function of age (see Tables 1–7) as predicted by the hypothesis of a maturational lag in children with LLI (McArthur & Bishop, 2004; B. A. Wright & Zecker, 2004). However, the development of auditory skills in younger children at risk for dyslexia is mainly uncharted territory. It has been suggested that auditory processing deficits present at birth are ameliorated in later infancy and childhood, possibly obscuring the effects of these early processing anomalies on the development of neural networks that lead to reading impairment (Galaburda et al., 2006). For instance, infants at risk for familial dyslexia have been shown to differ in their brain responses to speech sounds, and variation in these responses is related to differences in later reading related language skills (Guttorm et al., 2005; Guttorm, Leppänen, Richardson, & Lyytinen, 2001; Leppänen et al., 2002; Leppänen, Pihko, Eklund, & Lyytinen, 1999; Pihko et al., 1999). Further longitudinal studies are needed to investigate the effect of brain development on basic auditory and speech processing skills over extended periods of time.

The studies in this review showed that at least a subgroup of individuals with dyslexia have auditory processing problems in dynamic and speech prosody-related sound features (FM, AM, rise time, duration) as well as in perception of sound frequency. However, the anomalous processing of these and other sound features by individuals with dyslexia does not necessarily indicate causal connections, and the significance of these deficits in the development of dyslexia remains an open question.

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