# Chapter 11
# The "Rowdy Classroom Problem" in Children with Dyslexia: A Review

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**Abstract** Over the last decades, the role of auditory processing difficulties in dyslexia has been largely debated. Recently, speech perception in noise (SIN) difficulties and their potential link with reading impairment have been investigated. However, noise has typically been considered as a unitary concept, despite the very different sort of interference it induces. Indeed, background noise typically interferes with the signal target at both peripheral and central levels of the auditory pathway. Our purpose is to review the literature to better specify SIN perception difficulties in children with dyslexia, with respect to the type of interference induced by the noise. We will first provide a description of the two main types of auditory masking corresponding to peripheral and central levels of interference. Then, we will review the existing studies that investigated SIN perception in children with dyslexia, with a detailed focus on the nature of interference induced. We hope to provide a guide to speech-language therapists, audiologists, and research scientists. In

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particular, we will specify the nature of the SIN perception difficulties experienced by children with dyslexia and will highlight the need for more precise screening and investigation tools regarding auditory processing difficulties in dyslexia.

**Keywords** Dyslexia · Masking · Speech in noise · Cocktail party problem · Speech intelligibility · Auditory processing

## 11.1 The Cocktail-Party Problem

"How do we recognize what one person is saying when others are speaking at the same time?" This question, initially formalized years ago as the cocktail-party problem (Cherry 1953, pp. 975–976), applies to most situations of human communication. Indeed, from cocktail parties to busy business meetings, understanding a given speaker is often complicated by the presence of interfering sounds, be they simultaneous speakers or environmental noises. Generations of scientists investigated speech in noise (SIN) perception in various populations, ranging from normally hearing to hearing-impaired listeners. Noise was most often considered as a unitary concept, whose presence degrades the representation of the speech target. However, psychoacoustic studies have shown that different background noises affect speech perception differently. In this chapter, we will first specify the different types of interference induced by different noise backgrounds. With this distinction in mind, we will review data of SIN perception difficulties in a specific population of normally hearing listeners who have been shown to experience unexpected difficulties in noise, namely individuals with developmental dyslexia.

### *11.1.1 Peripheral Noise Interference*

Understanding a colleague's idea, for instance, during a crowded meeting is sometimes challenging, as it requires combining efficient sensory perception and cognitive processing of the relevant speech signal while ignoring irrelevant, simultaneous speakers. The presence of background noise induces interference at two distinct levels of the auditory pathway: peripheral and central. At the peripheral level, complex auditory scenes are parsed by an auditory filterbank into their different frequency components. Schematically, the sharper the auditory filter, the better the frequency selectivity.

Because speech is a broadband signal, part of the difficulty encountered in complex auditory scenes stems from an overlap in energy coming from simultaneous auditory objects. Indeed, as long as they share common spectral components, a speech target and a simultaneous masker will interact within a number of auditory filters, hence hampering the perception of the speech target. Masking of a speech target due to spectral overlap with a simultaneous masker at the peripheral level has been called energetic masking (EM, Pollack 1975). Note that in initial studies, the background noise had a spectrum equal to the long-term average spectrum of a speech signal (henceforth, speech-shaped noise, SSN).

Recent studies aiming at specifying the nature of the interference induced by SSN on speech intelligibility revealed that it was anything but a simple picture. Indeed, Stone, Füllgrabe, and Moore (2012) showed that notionally steady maskers (e.g., the stationary SSN used in most studies), once processed by the auditory filterbank, contain random amplitude fluctuations. These amplitude fluctuations are thought to interfere with amplitude modulations of the speech signal, hence inducing modulation masking (MM), which accounts for most of the difficulty induced by notionally steady SSN. In order to isolate pure EM, the authors presented listeners with combinations of sinusoids that were sufficiently sparse to fall within different auditory filters, hence avoiding superimposed modulations at the output of the filterbank. This “ideal” stationary masker (i.e., without random amplitude fluctuations at the output of the auditory filterbank) actually induced very limited amounts of masking.

The presence of background noise thus impedes speech intelligibility at the peripheral level through two distinct masking phenomena: energetic and by modulation, both occurring at the filter output. However, typical cocktail-party situations usually gather an important number of simultaneous speakers. Therefore, the presence of speech, rather than “simple” noise in the background induces additional difficulty in perceiving the signal of interest.

### *11.1.2 Central Noise Interference*

In the 1980s–1990s, the first models of the auditory system were aimed at predicting auditory perception on the basis of anatomo-physiological properties (Dau, Kollmeier, & Kohlrausch 1997; Glasberg & Moore 1990). Comparing humans’ and models’ performance in cocktail-party situations led to a surprising observation: in many natural auditory environments, the listeners’ performance was lower than what would be predicted based on traditional models of the peripheral auditory system (Neff & Green 1987). The first report of this phenomenon is attributed to Pollack (1975) who termed it informational masking (IM), in opposition to the well-known energetic masking. Four decades later, the concept of IM is still ill defined (see Durlach et al. 2003, for a discussion on the definitional issues related to IM).

Canonical experiments investigating IM have focused on situations where a fixed-frequency regularly repeating target tone was embedded in a multitone background sequence whose components fell outside of a silent “protected gap” surrounding the target, a manipulation that minimizes cochlear EM (Neff, Dethlefs, & Jesteadt 1993; Neff & Green 1987). The first parametric study evaluating detection of a target using this design revealed rather staggering results: listeners experienced threshold elevations from 20 to up to 60 dB when presented in noise, compared to quiet (Kidd, Mason, Deliwala, Woods, & Colburn 1994). Threshold elevations thus confirm the presence of masking that cannot be attributed to a spectral overlap between target and maskers. Interestingly, factors typically known to influence auditory scene analysis were shown to improve listeners' performance in IM situations, such as target repetition, relative coherence of the concurrent stream spectral content, as well as spatial and frequency separation between the target and masker (Akram, Englitz, Elhilali, Simon, & Shamma 2014). In addition to these bottom-up (perceptual) factors, top-down (cognitive) factors were shown to influence performance as well. Whereas uncertainty regarding the target to identify, fatigue, or attentional failure in focusing on the relevant target while ignoring the noise likely contribute to increase IM, musical expertise (Oxenham, Fligor, Mason, & Kidd 2003) or auditory training (Neff et al. 1993) tend to reduce IM.

Because it cannot be attributed to spectral overlap between target and maskers and is sensitive to high level, cognitive factors (experience, attention, fatigue, etc.), IM is thought to originate at a central level. Gutschalk, Micheyl, & Oxenham (2008) confirmed this distinction between peripheral and central level of background noise interference using magnetoencephalography (MEG). Their results showed that detected targets elicited a long-latency response at the level of the associative auditory areas, which was not the case for undetected targets that only elicited short-latency signals at the level of the primary auditory cortex. This result suggests that, when embedded in a background noise that maximizes IM, auditory target awareness arises between early and late stages of processing within the auditory cortex.

Nevertheless, cocktail parties are usually full of chatty human beings, rather than highly controlled robots that would only communicate with pure tone sequences. The presence of speakers of mixed gender certainly makes cocktail parties worth attending, but they also render it almost impossible to isolate the contribution of IM to listeners' perception difficulties to hear a given interlocutor. Indeed, simultaneous speech streams are broadband signals that are likely to interfere with each other at the peripheral level. Therefore, researchers aiming at evaluating IM of speech typically resorted to a very different line of reasoning than when they worked with tones.

Pioneering the investigation of IM effect on the perception of simultaneous talkers, Brungart (2001) assumed that the total masking could be split into two components, IM and EM. Only the total masking could be directly measured. Listeners' perception of a set of keywords constituting a meaningful sentence was thus evaluated when presented together with a competing speech masker. In order to evaluate the deleterious effect of IM to the listeners' performance, the author estimated the specific contribution of EM by means of a SSN with the same long-term average spectrum as the speech masker, then subtracting it from the total masking. The results of this seminal experiment have drawn general principles governing theories of speech-on-speech perception. First and foremost, IM was suggested to dominate performance in the speech-on-speech condition, as clearly evidenced by a lower intelligibility when the target sentence was presented with another simultaneous sentence than with either SSN or modulated SSN. In addition, a large proportion of the listeners' errors were intrusive words from the competing speech masker, rather than random words. Taken together, these observations suggest that in the presence of a simultaneous talker, most of the listeners' difficulty does not stem from spectral overlap between the streams, but from the linguistic content of the speech masker.

These findings were later replicated using laboratory babble (or “cafeteria”) noise (Brungart, Simpson, Ericson, & Scott 2001). Similarly to the results observed with IM of tones, both perceptual and cognitive factors were found to influence listeners’ perception of speech-on-speech. Perceptual, bottom-up cues reducing similarity (e.g., different-sex vs. same-sex speakers, Brungart 2001; Brungart et al. 2001) or increasing spatial separation between the target and babble noise (Best, Thompson, Mason, & Kidd 2013; Kidd, Arbogast, Mason, & Gallun 2005) improve listeners’ perception of the spoken target. Central, top-down factors such as prior knowledge of the target voice (Freyman, Balakrishnan, & Helfer 2004; Yang et al. 2007), syntactic coherence of the target sentence (Kidd, Best, & Mason 2008), and more generally, selective attention to the target (Zhang, Lu, Wu, & Li 2014) also contribute to improve its perception.

Whereas resorting to a “subtraction strategy” initially provided valuable insights regarding the major contribution of IM to ecological cocktail-party situations, this strategy was recently proven to have an important limitation. Indeed, most of the difficulty induced by stationary noise (such as the SSN used as an index of EM in most studies cited above) actually stems from MM, “whereby the amplitude fluctuations in the masker make it harder to detect and process amplitude fluctuations in the target” (Stone et al. 2012, p. 318). Schematically, SSN thus induces both EM and MM, whereas babble noise induces an important amount of IM in addition to EM and MM. However, because babble and SSN have very different spectral characteristics, speech being mostly periodic (for a review, see Rosen 1992) and noise being intrinsically aperiodic, it is unlikely that the amount of MM induced by a babble noise would be equal to that induced by SSN. Therefore, subtracting the amount of masking due to notionally SSN provides a rather inaccurate estimation of IM in speech-on-speech situations.

Several manipulations have been proposed to isolate the contribution of IM to complex auditory scenes. A classic solution to minimize peripheral masking is to present target and masker speech streams dichotically: as they are presented to opposite ears, target and maskers cannot interact at the cochlear level. Yet, dichotic listening provides listeners with important lateralization cues that allow them to experience spatial masking release (Freyman, Balakrishnan, & Helfer 2001; Freyman, Helfer, McCall, & Clifton 1999). Therefore, another technique was developed in order to minimize peripheral, but maximize central masking. Using speech resynthesis, spectral overlap can be removed by processing target and maskers in order to present them simultaneously but in different frequency bands, subsequently reducing EM/MM. Arbogast, Mason, and Kidd (2002) decomposed speech signals into 15 frequency bands, allocating eight frequency bands to the target speech, and the remaining seven to the masker, which was either composed of a broadband noise or of another speech signal. They observed that signal intelligibility was reduced when the processed masker was composed of broadband noise, and further decreased when it was composed of another speech signal. However, filtering speech signals drastically reduces the ecological validity of the paradigm, as it disrupts speech features (e.g., harmonicity) that are known to improve speech segregation

(Darwin 1997). Further studies are warranted to develop paradigms allowing isolating IM in ecological acoustic scenes (i.e., avoiding signal degradation).

To sum up, noisy backgrounds encountered in most typical cocktail party situations simultaneously induce peripheral and central interference with the relevant speech target. Many healthy listeners experience difficulties perceiving speech in noisy backgrounds despite normal auditory thresholds (Ruggles, Bharadwaj, & Shinn-Cunningham 2011). Crucially, the respective contribution of peripheral and central interference might vary from one listener to another, poor SIN perception hence reflecting limitations at very different levels of the auditory pathway. Therefore, there is a dire need to scrutinize the respective influence of both peripheral and central interference when investigating SIN perception in clinical populations.

The present chapter focuses on a specific population of normally hearing listeners who experience difficulties in noisy backgrounds, namely children with developmental dyslexia. Yet, so far, most studies of SIN perception in dyslexic children have considered noise as a unitary concept, acting like a "corrosive" degrading the representation of the target speech, irrespective of the nature of the interference it induces. This over-simplification likely stems from the lack of paradigms allowing clear distinction between EM, MM and IM of speech. Therefore, the following section will provide an extensive literature review on SIN perception in children with dyslexia, with a specific focus on the respective influence of all three types of masking on SIN perception.

## 11.2 Dyslexia and the Rowdy Classroom Problem

If they rarely attend cocktail parties, most of the children's social life nevertheless takes place amongst noisy backgrounds: lively playgrounds, busy refectories, etc. With average noise levels largely above the World Health Organization guidelines regarding basic acoustical requirements for community noise (General Accounting Office, 1995; cited by Jamieson, Kranjc, Yu, & Hodgetts 2004), most elementary schools are the scene of what could be called a "rowdy classroom problem". Recent studies showed that the amount of background noise in classrooms impacts typically developing children's academic performance (e.g., Bradley & Sato 2008; Shield & Dockrell 2003, 2008). The rowdy classroom problem seems particularly challenging for a specific clinical population: children with developmental dyslexia.

### *11.2.1 Underlying Causes of Developmental Dyslexia*

Learning to read requires accessing meaning from printed symbols, a process that, for alphabetic systems, relies on the ability to map distinct visual symbols onto phonemes (for a review see Morais 2018). If most children achieve fluent and effortless reading in their early school years, a significant proportion of the school age population suffers from developmental dyslexia, namely persistent reading difficulties despite normal intelligence, adequate educational opportunities and in the absence of any neurological or sensory deficiencies (World Health Organization 2008). In their guidelines for teaching to children with learning difficulties, the Belgian minister for Education claimed a ratio of one dyslexic child per classroom of about 20 pupils in elementary school, which is consistent with the 5% prevalence of dyslexia usually reported around the world (Lindgren, Renzi, & Richman 1985, but see Fluss et al., 2009 for a discussion of the socio-economic status influence on this figure).

Because its hallmarks are extremely slow and error-prone reading, poor nonword decoding and weak spelling, dyslexia was initially described as a form of visual word blindness. Surprisingly, first experimental works on the causes of dyslexia soon unveiled another picture: even though they were perfectly able to identify visual letters, poor readers were unable to map them into their corresponding phonemes (Liberman 1973; Shankweiler & Liberman 1972). This process is known as phonological coding (Share 1995), and is defined as the ability to use speech codes to represent information in the form of words and parts of words. Over the last decades, the vast majority of studies confirmed this observation, and the phonological processing deficit is now widely acknowledged as the most prominent hypothesis accounting for dyslexics difficulties learning to read (for a review of the various causes of reading difficulties, see Vellutino, Fletcher, Snowling, & Scanlon 2004). Evidence of poor phonological awareness, poor verbal short-term memory and slow lexical retrieval, three abilities that contribute to phonological processing, pile up to account for the reading difficulties experienced by dyslexic children (Wagner & Torgesen 1987), and are thought to persist well into adulthood (e.g., Law, Vandermosten, Ghesquière, & Wouters 2014). Reduced neural integration between letters and sounds (as indexed by neural activation in temporal auditory cortices when letters and sounds mismatch) further support the hypothesis of a phonological deficit in dyslexic individuals (Blau et al. 2010; Blau, van Atteveldt, Ekkebus, Goebel, & Blomert 2009). Nevertheless, theories regarding the causes underlying reading difficulties are still hotly debated, and can be broadly classified as to whether the phonological deficit is directly or indirectly assumed to lead to reading difficulties.

Several authors claimed that the phonological processing deficit was the side effect of a broader deficit. Abnormal visual processing in dyslexic individuals (Stein 2001, 2018, but see Amitay, Ben-Yehudah, Banai, & Ahissar, 2002, for a discussion of this hypothesis) and atypical learning abilities (Ahissar 2007; Ahissar, Lubin, Putter-Katz, & Banai 2006; Jaffe-Dax, Daikhin, & Ahissar 2018, but see Ziegler, 2008, for a discussion of this theory) have been proposed as broader deficits underlying the reading difficulties associated with dyslexia. While these two hypotheses are still debated, the present review focuses on a third hypothesis, according to which dyslexics’ phonological difficulties are linked to a broader auditory processing impairment.

### *11.2.2 Nonspeech Auditory Perception*

The hypothesis of a broad auditory impairment that would account for phonological processing deficits, hence leading to reading difficulties, was initially proposed by Tallal (1980). Even though this claim was largely debated for both methodological and theoretical reasons (for discussions, see Landerl & Willburger 2010; Rosen 2003), it has stimulated an unprecedented amount of research on auditory processing in dyslexic individuals.

Various auditory processing abilities have been suggested to be impaired in dyslexic individuals, ranging from frequency discrimination (Ahissar, Protopapas, Reid, & Merzenich 2000; Baldeweg, Richardson, Watkins, Foale, & Gruzelier 1999; Hari & Kiesilä 1996; McAnally & Stein 1996) to perception of amplitude modulation (Hämäläinen, Rupp, Soltész, Szücs, & Goswami 2012; McAnally & Stein 1997; Menell, McAnally, & Stein 1999), stream segregation (Helenius, Uutela, & Hari 1999; Lallier et al. 2011; Sutter, Petkov, Baynes, & O'Connor 2000) and spatial processing (Smith & Griffiths 1987). Interestingly, dyslexic children revealed poorer detection of a complex tone target presented in sequences inducing pure IM compared to both chronological age (CA) and reading level (RL) matched controls (Calcus, Colin, Deltenre, & Kolinsky 2015a). The analysis of variations in response time throughout the experiment did not reveal significant fatigue or attentional effects on dyslexic children's performance.

An important question arises from these consistent observations of dyslexics' poorer performance on elementary auditory tasks: how does it relate to reading difficulties? Rosen and Manganari (2001) hypothesized that impaired performance in backward masking might lead to poorer perception of a /ba/-/da/ contrast, as the crucial second formant transition is followed by a vowel (that has more power than the initial consonant), whereas preserved performance in forward masking would not affect the perception of an /ab/-/ad/ contrast. Yet, they failed to report specific impairment for the /ba/-/da/ contrast: dyslexics' speech perception performance was overall poorer than their controls'. Surprisingly, Sebastian and Yasin (2008) showed impaired neural discrimination of pure tones, but not of speech syllables in dyslexic adults. However, the very different nature of the stimuli used as speech and non-speech material somewhat limits the interpretation of their results. On the contrary, Serniclaes, Sprenger-Charolles, Carre, and Demonet (2001) compared dyslexic children' discrimination of sinewave analogues of speech (Remez, Rubin, Pisoni, & Carrell 1981) that are perceived either as simple non-speech whistles or as speech sounds, depending on the instructions. Taking advantage of this ambiguous material, the authors showed that dyslexic children's auditory deficit was specific to speech.

It is also noteworthy that, at the individual level, only a subgroup of dyslexic individuals (about 30%; for a review see Ramus, Pidgeon, & Frith 2003) show non-speech auditory processing impairments. Importantly, speech intelligibility requires listeners to not only perceive simultaneous acoustic cues, but also integrate them over multiple temporal scales (e.g., Hickok & Poeppel 2007). Taken together, these observations have led researchers to consider the possibility of a specific difficulty related to linguistic material in dyslexic individuals.

### *11.2.3 Speech Perception*

Progress in signal analysis allowed investigation of speech perception by evaluating listeners’ categorical perception (CP). Speech perception is categorical as long as discrimination between two tokens depends on their labelling, rather than their acoustical differences (Liberman, Harris, Hoffman, & Griffith 1957). Inefficient categorization of speech sounds would likely affect the processing of speech sounds, consequently impeding acquisition of the phoneme to grapheme conversion code. Various studies have thus evaluated CP in individuals with dyslexia, as poor CP might be causally related to reading difficulties. If these studies provided one consistent finding, it is that dyslexics’ perception of speech is anything but a clear picture.

Many studies have reported poor CP in dyslexic individuals (Brandt & Rosen 1980; Godfrey, Syrdal-Lasky, Millay, & Knox 1981; Mody, Studdert-Kennedy, & Brady 1997). Yet, this deficit was either limited to few phonological contrasts (Cornelissen, Hansen, Bradley, & Stein 1996), to synthetic but not natural speech (Blomert & Mitterer 2004), or again, to only a subgroup of dyslexics (Adlard & Hazan 1998; Manis et al. 1997). Altogether, the CP deficit associated with dyslexia was thus proposed to be “fragile” (Blomert & Mitterer 2004).

In addition, not all researchers agree on the idea that phonological representations are merely underspecified in dylexia. In fact, recent studies support the hypothesis that phonological representations might in fact be overspecified in dyslexic individuals. Indeed, Serniclaes et al. revealed that dyslexic children were actually better at discriminating intra-category variants of the same phoneme (e.g., two acoustically different /ba/) than typical readers. This surprising finding suggests that dyslexics might experience allophonic speech perception (Serniclaes et al. 2001; Serniclaes, van Heghe, Mousty, Carre, & Sprenger-Charolles 2004; Varnet, Meunier, Trolle, & Hoen 2016). However, other studies failed to provide clear support for either underspecified (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare 2009; Robertson, Joanisse, Desroches, & Ng 2009) or overspecified (Messaoud-Galusi, Hazan, & Rosen 2011; van Beinum, Schwippert, Been, van Leeuwen, & Kuijpers 2005) phoneme representations in dyslexic individuals.

Recently, another explanation has emerged regarding the possible cause for the fragile and inconsistent speech perception difficulties observed in dyslexic individuals. Indeed, all the studies reported above focused on optimal, quiet listening situations. Yet, everyday communication usually happens in deleterious noisy backgrounds that reduce the redundancy of acoustic cues available in the target speech (e.g., Zeng et al. 2005). Therefore, recent researches have explored SIN perception as a new potential source for the cascading difficulties encountered by dyslexic individuals.

### *11.2.4 Speech Perception in Noisy Backgrounds*

Pioneering investigation of SIN perception and its potential influence on reading, Brady, Shankweiler, and Mann (1983) revealed that 8 year-old poor readers identified monosyllabic words presented in quiet similarly to CA controls, but performed significantly lower when words were presented in SSN. Over the last decades, speech perception deficits in noise, but not in quiet have been largely replicated in various studies (e.g., Messaoud-Galusi et al. 2011; Rüsseler, Gerth, Heldmann, & Münte 2015; Ziegler, Pech-Georgel, George, & Lorenzi 2009), hence confirming the hypothesis of a subtle, but consistent impairment in speech perception, which reveals itself in adverse listening conditions. It has been noted that studies investigating dyslexics' speech perception often led to ceiling scores in the quiet condition (e.g., Brady et al. 1983; Rüsseler et al. 2015; Ziegler et al. 2009). To circumvent this limitation, recent studies provided measures of speech perception thresholds in more demanding tasks (i.e., discrimination and identification of a voicing contrast). Varying the method used to measure listeners' thresholds, the results confirmed preserved performance in quiet that significantly worsened in noise when dyslexics were compared to typical readers (Hazan et al. 2009; Messaoud-Galusi et al. 2011).

In the vast majority of studies, group comparisons consistently showed poorer performance in dyslexics' than CA controls (e.g., Bradlow, Kraus, & Hayes 2003; Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus 2009; Dole, Hoen, & Meunier 2012; Poelmans et al. 2011). To our knowledge, only three studies failed to report poorer SIN perception in dyslexic individuals. The first one was conducted on 6 year-old children at risk for dyslexia with no later confirmation of the diagnostic outcome (Elbro, Borstrøm, & Petersen 1998). The second was an extensive study showing that, unlike children with specific language impairment, dyslexic children were not impaired in a SIN perception task when compared to both CA and RL controls (Robertson et al. 2009). The third study was performed on adults who were selected from a university population. Some of them performed within the normal range on reading and spelling, which the authors acknowledged might reflect successful compensation mechanisms (Law et al. 2014). Thus, on the whole, the available data confirm the claim of a subtle speech perception deficit associated with dyslexia, which would only reveal its true prevalence in adverse listening conditions.

In an extensive study of the nature of the SIN perception deficit, (Ziegler et al. 2009) evaluated dyslexic childrens consonant identification. The consonant was selected from the following set: /p,t,k,b,d,g,f,s,ʃ,m,n,r,l,v,z,j/, and presented within /vCv/ logatomes (v being always /a/), together with both fluctuating and stationary background noises. Indeed, the presence of "dips" in a fluctuating background noise is known to favour masking release in adult listeners, a phenomenon that relies on rapid spectro-temporal analysis of the information available when the "local" signal-to-noise ratio (SNR) exceeds a certain threshold (Gnansia, Jourdes, & Lorenzi 2008). The authors thus presented dyslexic children with both fluctuating and stationary background noises. The results confirmed previous evidence of SIN perception impairment when dyslexics were presented with both stationary and fluctuating noises. Crucially, dyslexics’ performed significantly worse than both CA and RL control children, which allowed the authors to conclude that the impairment in SIN perception reflects a core difficulty inherent to dyslexia rather than a maturational delay or a feedback of reading acquisition on speech perception (Goswami 2003). Moreover, SIN perception predicted significant unique variance in reading, even after controlling for sensory and cognitive factors. Yet, the dyslexics’ SIN deficits were not due to poor spectro-temporal, low-level auditory resolution, as the magnitude of their masking release was similar to the controls’. Similar SIN perception deficits were observed when presenting dyslexics with internal noise (i.e., speech was degraded in order to preserve only its slow envelope modulations). Calcus, Deltenre, Colin, and Kolinsky (2017) confirmed impaired SIN perception in dyslexics compared to CA, but not RL controls along with preserved masking release abilities, even at SNR of −12 dB. Other studies replicated and extended observation of a SIN perception deficit in 5 year-old pre-schoolers who later developed dyslexia, with SIN perception uniquely contributing to reading level observed at the age of eight (Boets et al. 2011). Significant correlations between reading and SIN perception were also reported in 11 year-old children with dyslexia (Poelmans et al. 2011). Taken together, these results suggest that SIN is a core deficit associated with dyslexia, due to a lack of robustness of speech representation in the presence of both internal and external noise.

However, so far, most studies examining SIN perception in dyslexics have considered noise as a unitary concept, overlooking the importance of the nature of the interference induced by the noise background. Yet, preserved ability to analyze the spectro-temporal content of the auditory scene, as indexed by preserved masking release in dyslexic children, rules out a purely sensory explanation to their SIN perception difficulties. Therefore, there is a dire need to specify the nature of the interference induced by a specific background noise, as each noise type may reflect a different processing mechanism.

Table 11.1 provides a brief description of the most prominent experiments that investigated SIN perception in dyslexics. Most of them used SSN as a masker, which, as we commented on, induces interference at the peripheral level of the auditory system through a combination of MM and EM. Only one study aimed at specifying the respective influence of pure MM and EM on dyslexic children’s difficulties perceiving SIN. The results confirmed poorer SIN perception in dyslexic than CA, but not RL controls in both noise conditions (Calcus, Lorenzi, Collet, Colin, & Kolinsky 2016). With respect to IM, some studies resorted to babble noise, composed of 4- (Dole et al. 2012), 12- (Elbro et al. 1998) or 20- interfering speakers (Hazan et al. 2009; Hazan, Romeo, & Pettinato 2013; Messaoud-Galusi et al. 2011). Even though the presence of an interfering speaker induces mainly IM of a speech target (Brungart 2001; Brungart et al. 2001), the amount of masking induced by an N-talker babble noise greatly varies with N (Simpson & Cooke 2005). If a 4-talkers babble maximizes IM, the presence of 20 simultaneous speakers drastically reduces the informational nature of the masker, which mostly induces EM/MM.

**Table 11.1** Experiments that have investigated SIN perception in dyslexic children (in chronological order)

| Study | Participants | Target and task | Masker | Dyslexics' performance |
|---|---|---|---|---|
| Brady et al. (1983) | Poor reader children (n = 15) vs. CA controls | Monosyllabic words identification | Quiet and Modulated SSN (0 dB SNR) | Preserved in quiet, but affected by the presence of noise when compared to CA |
| Snowling et al. (1986) | Dyslexic children (n = 19) vs. CA and RL controls | High and low frequency words; pseudo-words identification | Quiet and SSN (0 and −3 dB SNR). | Deficit in all listening conditions (including quiet): lower than CA when repeating low frequency words; lower than both CA and RL for pseudo-words |
| Cornelissen et al. (1996) | Dyslexic adults (n = 10) vs. CA controls | CV identification | White noise (+19, 0, −2, −3 dB SNR) | Poorer for some CV contrasts (/ta/ with /a/ and /pa/ with /fa/) |
| Elbro et al. (1998) | Children at risk for dyslexia (n = 23) vs. CA controls | Phoneme discrimination (minimal pairs) | 12-talkers babble noise (+15 dB SNR) | No deficit |
| Bradlow et al. (2003) | Children with learning disabilities (n = 63) vs. CA controls | Keyword identification in simple sentences | White noise (−4 and −8 dB SNR) | Poorer than CA, especially when SNR decreases |
| Chandrasekaran et al. (2009) | Poor reader children (n = 15) vs. CA controls | Keyword identification in simple sentences | SSN (adaptive threshold measure) | Poorer than CA |

| | | | | |
|---|---|---|---|---|
| Ziegler et al. (2009) | Dyslexic children (n = 19) vs. CA and RL controls | Consonant identification /vCv/ | Quiet, stationary and modulated SSN (0 dB SNR) | Preserved in quiet. Poorer than both CA and RL in stationary noise. Preserved masking release |
| Hazan et al. (2009) | Dyslexic adults (n = 17) vs. CA controls | Phoneme discrimination and identification (CP) /pea/-/bee/ contrast | Quiet and 20-talkers babble (adaptive threshold measure) | Preserved in quiet. Overall preserved in noise, but poorer than CA with fixed-step threshold measure of discrimination abilities |
| Robertson et al. (2009) | Dyslexic children (n = 14) vs. CA and RL controls | Phoneme discrimination and identification (CP) /ball/-/doll/ continuum | Quiet and white noise (+12 dB SNR) | No deficit |
| Boets et al. (2011) | 5 year-old children at risk who were subsequently found to be dyslexics (n = 16) vs. CA controls | Monosyllable identification | SSN (−1, −4, −7 dB SNR) | SIN performance in kindergarten uniquely contributed to reading in Grade 1 |
| Poelmans et al. (2011) | 11 year-old dyslexic children (n = 13) vs. CA controls | /vCv/ logatomes and sentences repetition | SSN (−4, −7, −10 dB SNR) | SIN deficit persists until 11 year-old, and correlates with reading |

(continued)

**Table 11.1** (continued)

| Study | Participants | Target and task | Masker | Dyslexics' performance |
|---|---|---|---|---|
| Inoue, Higashibara, Okazaki, & Maekawa (2011) | Dyslexic children (n = 10) vs. CA controls | Phoneme identification /ba/ vs. /da/ | Quiet and multi-talker babble (0 dB SNR) | Preserved in quiet, but poorer than CA in noise (especially when the target appears with a high probability) |
| Messaoud-Galusi et al. (2011) | Dyslexic children (n = 62) vs. CA controls | CP (cf. Hazan et al. 2009) | Quiet and 20-talkers babble (adaptive threshold measure) | Similar to Hazan et al. (2009): preserved in noise, but poorer than CA with fixed-step threshold measure of discrimination abilities |
| Hazan et al. (2013) | Dyslexic children (n = 34) vs. CA controls | /CV/ identification | 20-talkers babble (0 dB SNR) | Poorer than CA when intonation of the target varies |
| Dole et al. (2012) | Dyslexic adults (n = 16) vs. CA controls | Disyllabic word identification | SSN<br>modulated SSN<br>4-talkers babble | → preserved<br>→ impaired when spatialized<br>→ impaired when monotic |
| Law et al. (2014) | Dyslexic adults (n = 36) vs. CA controls | Keyword sentences & /CVC/ words | → SSN (−5, −10, −13 dB SNR)<br>→ SSN (adaptive threshold measure) | No deficit |

| | | | | |
|---|---|---|---|---|
| Rüsseler et al. (2015) | Dyslexic adults (n = 12) vs. CA controls | Disyllabic words (congruent or incongruent with visual information) | Quiet and white noise (+30 dB SNR) | Preserved in quiet, but poorer than CA when congruent AV information in noise |
| Calcus et al. (2015b) | Dyslexic children (n = 10) vs. CA and RL controls | /CV/ identification | Quiet SSN; modulated SSN; 4-talkers babble (dichotic listening; SNR = −30 dB) | Preserved in quiet, but poorer than CA (but not RL) in all noise conditions |
| Varnet et al. (2016) | Dyslexic adults (n = 20) vs. CA controls (n = 18) | Phoneme categorisation /da/-/ga/ contrast | White noise (adaptive thresholds) | Poorer than CA |
| Calcus et al. (2016) | Dyslexic children (n = 16) vs. CA and RL controls | /vCvCv/ identification | Quiet; SSN; modulated SSN (SNR: 0 to −12 dB) | Preserved in quiet, but poorer than CA (but not RL) in all noise conditions. Preserved masking release |
| Calcus et al. (2017) | Dyslexic children (n = 14) vs. CA and RL controls | /vCv/ and /vCvCv/ identification | Quiet combination of sinusoids; SSN; modulated SSN; 1−, 4−, and 8-talkers babble (SNR = 0 dB) | Preserved in quiet, but poorer than CA (but not RL) in all noise conditions |

Very few studies specifically investigated pure IM on dyslexic individuals' speech perception difficulties. However, the available data suggest that central interference contributes to their difficulties. In a disyllabic word identification task, Dole et al. (2012) presented target and maskers in various spatial settings, including dichotic presentation. Presenting target and masker dichotically prevents spectral overlap at the peripheral level, hence minimizing EM/MM. Adults with dyslexia had a lower performance than typical readers in this condition, indicating masking at a more central level of the auditory pathway. Investigating /CV/ identification in various background noises presented dichotically, Calcus, Colin, Deltenre, and Kolinsky (2015b) showed an overall lower performance in dyslexic than CA, but not RL, control children. These studies converge to point toward a central contribution to dyslexics difficulties perceiving SIN.

## 11.3 Discussion in the Rowdy Classroom

A consistent finding emerges from the various studies reviewed in this chapter: dyslexic children are affected by the presence of background noise, or at least more so than CA controls. If evidence regarding the specific contribution of peripheral and central interference of noise on dyslexics' SIN perception remains scarce, the existing data suggest that they both contribute to the difficulties encountered by dyslexic children. The following section will be dedicated to highlight similarities and divergences in results regarding SIN perception in dyslexic children.

First, the vast majority of studies reported lower SIN perception performance in dyslexic children compared to typical readers when a SSN background induced mostly peripheral interference. Interestingly, preserved masking release has been consistently reported in dyslexic children, as their identification performance improves to the same extend as in typical readers when presented with fluctuating background maskers (Calcus et al. 2016; Ziegler et al. 2009). Dip listening is known to require high spectro-temporal resolution at the level of the cochlea (Festen 1990). As stated by Ziegler et al. (2009, pp. 733), "normal masking release [in dyslexics] therefore suggests that low-level auditory or peripheral processes are intact". Accordingly, Zettler, Sevcik, Morris, and Clarkson (2008) showed that on average, dyslexic children performed similarly to typical readers in a task that required them to integrate amplitude fluctuations across multiple frequency bands to segregate signals from noise. According to the authors, this suggests that dyslexic children adequately use temporal and spectral information in noise to identify a signal. Altogether, these observations are at odds with a purely sensory explanation of dyslexic children's SIN perception deficit. Hence, they rule out theories of poor temporal auditory processing (Tallal 1980). In sum, dyslexic children are impaired in noisy situations inducing peripheral interference with an auditory target, but this difficulty is not attributable to poorer peripheral auditory processing. This apparent paradox has led us to further examine the role of central mechanisms contributing to the SIN perception difficulties in dyslexics.

Dyslexics’ consonant identification performance has been reported to be lower than CA controls’ with babble noise, be it presented monotically (Dole et al. 2012), dichotically (Calcus et al. 2015b) or diotically (with target and maskers presented simultaneously to both ears; Calcus et al. 2016; Inoue, Higashibara, Okazaki, & Maekawa 2011). Because the presence of babble in the background is thought to induce mainly IM (Brungart 2001), which takes place at a central level of the auditory pathway (Durlach et al. 2003; Gutschalk et al. 2008), this observation points to a central contribution to the SIN perception difficulties experienced by dyslexic children.

As an interim conclusion, we can note that dyslexic children perform poorer than CA controls in auditory environments that respectively induce purely peripheral and purely central interference. Yet it is worth noting that their performance does not significantly worsen as compared to CA controls’ in conditions inducing peripheral and central interference simultaneously (e.g., Calcus et al. 2017). Taken together, the data thus suggest that both peripheral and central interference respectively contribute to the dyslexics’ SIN perception difficulties, but do not seem to interact. Crucially, as stated before, peripheral auditory processing seems to be preserved in dyslexic children. Therefore, difficulties in both peripheral and central masking likely stem from non-sensory (i.e., cognitive) processes. Whereas this was expected in the case of central masking, it is somewhat more surprising regarding peripheral masking, which is typically thought to reflect the limits of the cochlear frequency selectivity. This apparent paradox is likely explained by the fact that peripheral auditory processing operates under central control. Indeed, an extensive efferent auditory pathway provides anatomical substrate to top-down modulation of auditory perception, especially in noise (for a review, see Winer 2006). Whether dyslexics’ difficulties in noise stem from a purely central deficit or from a disruption of the efferent auditory pathway remains an open question. Exploration of the top-down modulation of speech encoding in noisy backgrounds might break new ground in this respect.

Remarkably, dyslexic children seem to consistently benefit from various types of acoustic cues to improve their perception. The perceptual cues that were considered in the literature include spatial lateralization, repetition of the target, fluctuations in the background noise, or variation in the number of interfering talkers (Calcus et al. 2015b, 2016; Dole et al. 2012). Other factors such as the lexical frequency of the target words (Snowling, Goulandris, Bowlby, & Howell 1986) or the consistency in the speakers’ intonation (Hazan et al. 2013) also help them improve SIN perception. Note however that, if their performance improves thanks to perceptual cues (as compared to performance without such cues), it does not normalize (as compared to CA controls’ performance).

Last, studies generally report only weak support for a link between auditory processing and reading abilities. Indeed, most studies failed to reveal significant correlations between reading abilities and all of the auditory tasks that were evaluated in dyslexic children (e.g., Robertson et al. 2009). Scrutinizing individual profiles unveiled a similar picture, with only a subgroup of dyslexic children consistently impaired in a majority of the noise conditions tested within each study (31% of the dyslexic children in Calcus et al. (2016); 28% in Calcus et al. (2017)). Among this subgroup, not all individuals were also impaired in phonological processing (21% of the dyslexic children tested in Calcus et al. (2016)) or categorical perception (12.5% of the dyslexic children tested in Calcus et al. (2016)). This figure is consistent with previous data suggesting that the vast majority of children perform within the norms on auditory tasks, with only about 30% of them being impaired in auditory processing (Adlard & Hazan 1998; Amitay et al. 2002; Ramus et al. 2003; Rosen, Windzio, & Galaburda 2001). The fact that only a minority of dyslexic children are consistently impaired in auditory tasks might explain the small to medium size effects reported in most studies (e.g., Calcus et al. 2015a, 2016). Further research is required to determine whether dyslexic children exhibiting consistently poor auditory performance share other commonalities and hence would form a specific subgroup.

Almost as informative as the convergence between studies are discrepancies found across experiments. Two major inconsistencies are observed. The first one concerns the comparison of dyslexics' to typical readers' performance. Indeed, whereas two studies reported that dyslexics' performance was lower than both RL and CA controls' (Snowling et al. 1986; Ziegler et al. 2009), recent SIN perception data are mixed on that matter. If dyslexic children perform consistently lower than CA controls, this is not the case when compared to RL controls. Dyslexic children were reported to perform similarly (Calcus et al. 2015a, 2016) or even better in some conditions (Calcus et al. 2017) than RL controls.

Two (not necessarily incompatible) explanations might account for the absence of a significant difference when comparing dyslexics to RL controls. The first one is that dyslexic children might experience a mere developmental delay in speech perception abilities, which would bring them to the same level as younger children (i.e., RL controls). Indeed, SIN intelligibility improves with age in typically developing children, especially in situations inducing mainly IM (Lutfi, Kistler, Oh, Wightman, & Callahan 2003; Wightman, Kistler, & O'Bryan 2010). However, this developmental delay remains to be explained. In addition, this explanation might hold for speech perception but does not account for more general impairments, namely for the fact that dyslexic children were found to be impaired when compared to both CA and RL controls in a nonspeech detection task inducing pure IM (Calcus et al. 2015b).

Another explanation might be that reading acquisition itself impacts the quality of and/or access to phonological representations, hence favoring SIN perception. Goswami (2015, p. 44) recently discussed more generally the idea that the "reduction in reading experience that is inherent in being dyslexic can itself cause differences in sensory processing between participants with dyslexia and controls". In agreement with this view, when listening to speech, adults who remained illiterate for strictly socio-economic reasons show reduced activation (compared to literates) of the planum temporale (Dehaene et al. 2010), a region known to host phonological representations (e.g., Chang et al. 2010; Jacquemot, Pallier, Le Bihan, Dehaene, & Dupoux 2003). Similar reduced activation has been observed in dyslexics (Blau et al. 2010, 2009; Monzalvo, Fluss, Billard, Dehaene, & Dehaene-Lambertz 2012).

Reading acquisition may in fact help in finely tuning phonemic boundaries and hence in increasing the precision of phoneme identification in literates compared to illiterates (Serniclaes, Ventura, Morais, & Kolinsky 2005), which would be most helpful in suboptimal listening conditions (for a review, see Kolinsky 2015). Experiments using word identification in dichotic listening suggest that in suboptimal conditions, literate people also use an attentional mechanism focusing on the phonemic structure of speech (Morais, Castro, Scliar-Cabral, Kolinsky, & Content 1987), which seems to be strategic as it is modulated by instructions to pay attention to phonemes (Morais, Castro, & Kolinsky 1991). Such a strategy might help in reconstructing poorly perceived SIN sequences and is obviously less available to dyslexics and illiterates, who are very poor at phoneme awareness (e.g., Morais, Cary, Alegria, & Bertelson 1979; Morais, Cluytens, & Alegria 1984). In addition, in typical readers, auditory words activate brain regions associated with orthographic processing, an effect that is not observed in illiterate adults (Dehaene et al. 2010) and that is strongly reduced in children with reading difficulties (Desroches et al. 2010; Monzalvo et al. 2012). Behaviorally, in literates, orthographic representations have been shown to influence spoken word recognition (e.g., Ziegler & Ferrand 1998), an effect that is particularly strong in noisy backgrounds (Pattamadilok, Morais, & Kolinsky 2011) and that is also reduced in dyslexic adults (Pattamadilok, Nelis, & Kolinsky 2014). Altogether, these studies concur to support the idea that at least some sensory deficits observed in dyslexic children might result from the effects of reduced reading experience on their brain.

In any case, further studies are warranted to disentangle the respective contribution of maturation and reading acquisition on SIN perception. As commented on by Goswami (2015), only a few research designs can to some extent control for the effects of reading experience, and if similar outcomes are found using combinations of these designs, causality is likely to be present. These designs involve not only reading level-matched studies, but also research with illiterate adults, studies on pre-readers who go on to be diagnosed with dyslexia, and, most critically, longitudinal studies that follow the same children over the whole learning process as well as well-controlled training studies.

The second finding that is inconsistent across studies concerns the potential cause(s) underlying dyslexics’ auditory processing deficit in noise. Preserved masking release rules out the hypothesis of a strictly sensory deficit in dyslexics’ auditory processing. Accordingly, several studies claimed that peripheral auditory processing is preserved in dyslexic children (e.g., Zettler et al. 2008; Ziegler et al. 2009), whose difficulties would thus stem from and/or be exacerbated by non-sensory factors (Hazan et al. 2013; Messaoud-Galusi et al. 2011). As discussed above, high inconsistency in dyslexics’ impairment across various noise conditions of the same study is in line with this interpretation. Notably, up to 40% of children diagnosed with reading difficulties also exhibit attention-deficit/hyperactivity disorder (see Eden & Vaidya 2008, for a discussion on comorbidity between dyslexia and attention-deficit/hyperactivity disorder). Altogether, this suggests that dyslexics’ difficulties perceiving SIN might in fact stem from an attention deficit. However, recent studies reporting high intra-individual inconsistencies within the dyslexic population focused on children who were free of a formal diagnosis of attention-deficit/hyperactivity disorder. Yet, dyslexic children might experience subtle attentional lapses that might only reveal in the more complex auditory tasks. Therefore, there is a need for methodological tools allowing investigation of auditory attention in complex acoustic environments.

Overall, the nature of the relationship between auditory processing and reading abilities in dyslexic children remains an open question. One possibility is that because most everyday listening situations are noisy, a difficulty in SIN perception would hamper the acquisition of precise phoneme representations, ultimately hampering the acquisition of phoneme-to-grapheme conversion. Another possibility is that poor SIN perception reflects imprecise phoneme representations (or difficulties in accessing this information, e.g., Boets et al. 2013), whose detrimental consequences remain unnoticed in favourable listening conditions, i.e., in quiet, revealing themselves only in more adverse, noisy, conditions. Support for a causal relationship comes from correlations observed between auditory processing and reading abilities (Poelmans et al. 2011; Tallal 1980), from observations that dyslexic children are impaired in SIN perception tasks even when compared to RL controls (Ziegler et al. 2009), and from the fact that basic auditory processing difficulties have been reported in newborns at risk of dyslexia (Leppänen et al. 2010) which, together with SIN perception deficits (e.g., Boets et al. 2011), are thought to predict later reading abilities.

Yet, not all individuals with dyslexia show an auditory deficit and, conversely, not all individuals with such a deficit have dyslexia (for a review, see Hämäläinen, Salminen, & Leppänen 2013), and although many at-risk preliterate children show impaired basic auditory processing when compared to controls, it is impossible to discriminate on that basis between those who, later on, will become typical or atypical readers (e.g., Plakas, van Zuijen, van Leeuwen, Thomson, & van der Leij 2013). Other results provide only weak support for a direct link between poor speech processing and poor reading skills. Indeed, correlations between these abilities were not consistently reported (Calcus et al. 2015b, 2016; Robertson et al. 2009). Accordingly, only a subgroup of dyslexic children seems consistently affected by the presence of background noise, but not all of them are also impaired in literacy-related tasks. Lastly, comparing dyslexic to RL control children led to contradictory results (Calcus et al. 2017; Ziegler et al. 2009). Taken together, these findings do not support the hypothesis of a causal relation between SIN perception and reading abilities (Hazan et al. 2009; Messaoud-Galusi et al. 2011; Robertson et al. 2009). As stated by Rosen (2003, pp. 524), “This [. . .] is at the heart of what appears to be the uselessness of the auditory measure as a gauge of the language/literacy deficit”. If we cannot rule out the possibility of a relationship between auditory processing and reading abilities, most studies support the idea that both difficulties tend to co-occur in dyslexia, but are not causally related. The available evidence is rather in line with a risk factor model (e.g., Bishop 2006; Pennington 2006; van Bergen, van der Leij, & Jong 2014), which proposes that no single deficit is either necessary or sufficient to lead to dyslexia, but that a number of factors may interact to lead (or not) to reading difficulties. Studies investigating the relationship between

SIN perception and reading abilities in other populations (e.g., children with mild to moderate sensorineural hearing loss, illiterate adults) might pave to way to a better understanding of the complex link between auditory processing and reading difficulties.

## 11.4 Conclusion

Developmental dyslexia is a multidimensional disorder that affects a significant proportion of the school age population. The most prominent hypothesis regarding dyslexia postulates a phonological impairment as the core deficit leading to reading difficulties. This chapter intended at evaluating SIN perception difficulties in children with dyslexia, with a special focus on the respective contribution of peripheral and central processes to these difficulties. Taken together, the findings reviewed here suggest that dyslexic children are impaired in noisy environments inducing both types of interference, as evidenced by studies inducing mainly peripheral (EM/MM) and central (IM) masking. Interestingly, recent results concur to support the hypothesis of preserved sensory (i.e., peripheral) processes. However, they consistently point to a deficit in nonsensory factors that might contribute to the SIN perception difficulties, although the role of auditory attention factors to SIN perception in dyslexic children remains unclear. Further studies are needed to investigate whether SIN difficulties stem from a purely cognitive deficit or from an impairment of the efferent auditory pathway in dyslexic children.

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