

Speech-in-noise perception deficit in adults with dyslexia: Effects of background type and listening configuration

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ABSTRACT

Developmental dyslexia is associated with impaired speech-in-noise perception. The goal of the present research was to further characterize this deficit in dyslexic adults. In order to specify the mechanisms and processing strategies used by adults with dyslexia during speech-in-noise perception, we explored the influence of background type, presenting single target-words against backgrounds made of cocktail party sounds, modulated speech-derived noise or stationary noise. We also evaluated the effect of three listening configurations differing in terms of the amount of spatial processing required. In a monaural condition, signal and noise were presented to the same ear while in a dichotic situation, target and concurrent sound were presented to two different ears, finally in a spatialised configuration, target and competing signals were presented as if they originated from slightly differing positions in the auditory scene. Our results confirm the presence of a speech-in-noise perception deficit in dyslexic adults, in particular when the competing signal is also speech, and when both signals are presented to the same ear, an observation potentially relating to phonological accounts of dyslexia. However, adult dyslexics demonstrated better levels of spatial release of masking than normal reading controls when the background was speech, suggesting that they are well able to rely on denoising strategies based on spatial auditory scene analysis strategies.

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1. Introduction

Developmental dyslexia constitutes the most frequent neurodevelopmental disorder in children with about 5–10% of individuals affected in a given age-group, with detrimental effects on language-learning abilities, scholarship and socio-professional integration (Shaywitz, 2003). It is defined as a durable impairment in the development of normal reading-skills despite appropriate education and in the absence of other sensory or cognitive deficits. Children with dyslexia mainly experience difficulties with the acquisition of writing, reading and spelling abilities. However, when questioning the neurocognitive underpinnings of dyslexia, this definition rapidly appears as reflecting only the tip of the iceberg. First of all, there is currently a rather large consensus amongst researchers to say that dyslexia and related literacy problems derive from an underlying phonological information processing impairment. According to this view, dyslexic people suffer from a core deficit in the representation, storage and/or retrieval of phonological information (see for example Ramus, 2001; Ramus & Szenkovits, 2008;

Snowling, 2000). This phonological deficit first appears in oral language production of affected children around 3–4 years when they experience difficulties with tasks requiring explicit manipulation of phonological information, such as rhyme games. During their later acquisition of reading and writing skills, this primary phonological impairment affects the acquisition of robust correspondence rules used to successfully map unique and unambiguous phonemes onto graphemes. This view is supported by observations in dyslexic participants of phonological awareness difficulties (explicitly segmenting speech into rimes, syllables or phonemes, for example) (Bruck & Treiman, 1990; Compton, DeFries, & Olson, 2001; Snowling, Goulandris, Bowlby, & Howell, 1986; Sprenger-Charolles, Cole, Lacert, & Serniclaes, 2000); of short-term verbal memory deficits (encoding and recalling sequences of words or phonemes) (Nelson & Warrington, 1980); of slowed lexical retrieval (rapidly naming pictures, for example); of difficulties in the repetition of complex pseudowords or rare words (Snowling, 1981; Snowling et al., 1986), or of rapid automatized naming of images and objects (Denckla & Rudel, 1976; Wolf et al., 2002; Wolff, Michel, & Ovrut, 1990). Although the origins of this phonological deficit are still a widely debated issue, the observation that an important proportion of dyslexic children experience difficulties manipulating phonological information is amongst most reproducible observations about dyslexia. A second aspect of the dyslexic syndrome sometimes minimized by its clinical definition is that associated

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impairments generally remain at adult age, causing persistent and measurable language processing troubles in adults (Sanchez & Coppel, 2000). Notably, in dyslexic adults as well as in children, the most important and reproducible difficulties are associated with phonological processing (Byring & Pulliainen, 1984; Cornelissen, Hansen, Bradley, & Stein, 1996; Pennington, Van Orden, Smith, Green, & Haith, 1990; Ramus et al., 2003; Reid, Szczerbinski, Iskierka-Kasperek, & Hansen, 2007). It thus appears that the core phonological deficit of dyslexia persists at least partially over the lifespan of dyslexic individuals.

In this context, it can seem somehow paradoxical that dyslexia would be associated with a core, very reproducible phonological deficit but that in the meantime children and adults with dyslexia do not consistently show auditory language processing difficulties. This would suggest that the underlying phonological deficit is largely compensated for in the case of speech perception by the acquisition of robust sound-to-phoneme mapping rules. This could be due to the fact that during oral language acquisition, most often multiple acoustic cues are bound to one single phoneme, whereas during the acquisition of reading in most human languages one phoneme must be bound to multiple, often unrelated orthographic patterns. The absence of impairment for speech processing is even used to dissociate people with dyslexia from people suffering from broader language development impairment affecting oral language skills, named specific language impairment (SLI) (Bishop & Adams, 1990; Bishop & Clarkson, 2003). It could however be that part of the difficulties in finding clear explanations for the neurocognitive origins of dyslexia arise from the fact that precisely one of the most important dimensions of dyslexia, i.e. speech comprehension, is not yet well understood. Recent observations started further evaluating one aspect of the dyslexic syndrome that was up to now relatively left aside, the fact that an important proportion of dyslexics experience difficulties in understanding speech. This difficulty was often ignored because it is hardly observable in favourable listening conditions (speech-in-quiet) where dyslexics usually perform as well as matched normal readers. But it becomes very reproducible as soon as listening conditions become challenging (speech-in-noise). Below we will review studies that have explored aspects of speech and speech-in-noise comprehension in dyslexia.

First studies of speech comprehension involving dyslexic participants have demonstrated the importance of adding background noise to speech-targets in order to characterize speech comprehension difficulties in dyslexic participants. Brady, Shankweiler, and Mann (1983), for example, asked fifteen 8-years old dyslexic children to repeat words presented against a background of amplitude-modulated flat-spectrum noise with modulations derived from speech signals at a 0 dB signal-to-noise ratio (SNR). Results showed a clear speech-in-noise comprehension deficit in dyslexic children, with a decrease of intelligibility scores of about 10% compared to aged-matched normal readers. Bradlow, Kraus, and Hayes (2003), demonstrated that children with learning disabilities performed worse than control children during sentence perception in noise and that they were more adversely affected by the decreasing SNR than controls. Accordingly, Wible, Nicol, and Kraus (2002) reported abnormal and asynchronous neurophysiological responses to speech-in-noise but not to speech-in-quiet in learning disabled children. In a more recent study, Ziegler, Pech-Georgel, George, and Lorenzi (2009) further showed that speech-perception deficits in dyslexics do not only appear when extrinsic noise (e.g. stationary or modulated speech-shaped noise) is added to target-speech but also when the signal is degraded *per se* (e.g. by eliminating temporal fine-structure cues). The authors interpreted their findings as evidence that the addition of background noise is not necessary for the speech-perception deficit to occur in dyslexia but that this deficit may stem from a general lack of speech robustness in the presence of any kind of degradation or

interference affecting clarity of speech signals. A speech-in-noise comprehension deficit could be reproduced in 5-year old preschool children with a familial history of dyslexia (Boets, Ghesquière, van Wieringen, & Wouters, 2007; Boets, Wouters, van Wieringen, & Ghesquière, 2007). These later observations would consider the deficit of speech-in-noise perception to be a very central, maybe causal aspect of dyslexia, eventually related to the origin of phonological impairments. Indeed, it could directly reflect processes involved in either the formation of phonological categories during childhood or acoustical- or speech-processing impairments that are otherwise attributed to impaired phonological processing. For other authors however, the speech-in-noise deficit observed in dyslexics could well be only very indirectly related to the phonological deficit because the addition of noise does not hinder the processing of one particular phonemic contrast (bea/pea), both in adults (Hazan, Messaoud-Galusi, Rosen, Nouwens, & Shakespeare, 2009) and children (Messaoud-Galusi, Hazan, & Rosen, 2011). All these observations raise the crucial question of specifying the limits and implicated processes of the speech-in-noise deficit in dyslexia.

Understanding speech in cocktail-party situations (Cherry, 1953), i.e. understanding one person speaking while other voices or noises are also present in the background, is a complex task that we solve by using multiple kinds of acoustic cues and processing strategies (see Bregman, 1994; Bronkhorst, 2000; Divenyi, 2004 for reviews). First of all, the cocktail-party situation requires processing multiple speech signals originating from different positions in the auditory space. This situation could perhaps be simplified as a dichotic listening task, where one must pay more attention to what is said to one ear while someone says something else to its other ear. Numerous studies on dichotic listening already demonstrated that dyslexics have trouble processing two different speech signals presented in two different ears (see Ben-Artzi, Fostick, & Babkoff, 2005; Dermody, Mackie, & Katsch, 1983 or Dickstein & Tallal, 1987 amongst others). Impaired dichotic listening abilities could be one cause of the speech-in-noise deficit observed in dyslexia. But the cocktail party phenomenon relies on other processes that could also well be hindered in dyslexia. One of the main ways to solve the cocktail-party problem is to take advantage of the fact that concurrent speech signals contain amplitude modulations (AM), peaks and valleys of higher or lower masking power. Listeners can benefit from these temporal dips in the background to listen to target-signal. The intelligibility benefit provided by an amplitude modulated background sound, compared to a flat background sound is referred to as the amplitude modulation advantage (Festen & Plomp, 1990; Howard-Jones & Rosen, 1993). Listening into the dips requires efficient processing of medium- to short-sized temporal information from speech present in glimpses of target-signal, in the range of tens to hundreds of milliseconds (Bronkhorst, 2000; Howard-Jones & Rosen, 1993; McDermott, 2009). Menell, McAnally, and Stein (1999), showed impaired behavioural sensitivity and diminished electrophysiological responses to AMs of white noise in dyslexics. Other authors later showed that more than reduced audibility of both slow and fast temporal envelope cues, dyslexics show poor encoding fidelity of these cues (Lorenzi, Dumont, & Füllgrabe, 2000; Rocheron, Lorenzi, Füllgrabe, & Dumont, 2002), in particular for rise times of speech amplitude envelope (Richardson, Thomson, Scott, & Goswami, 2004). Thus, impaired AM processing could be one other cause of the speech-in-noise deficit observed in dyslexia. Another important strategy to successfully understand speech at the cocktail-party is to efficiently parse the auditory scene and perform clear spatial separation of sound sources. If sources are spatially separated, different cues can help one allocate attention to different auditory objects. One potentially implicated mechanism here is auditory stream segregation, the ability to perceive different parts of the acoustic signal as belonging to the same auditory object. This ability

is mostly based on the detection of temporal coherence in different sound streams. Previous work already shows that dyslexic adults perceive a sequence of alternating tones with high (1000 Hz) and low (400 Hz) pitch as being two different streams if they are separated by less than 210 ms. In comparison, normal-reading controls continued to perceive discrete tones down to 130 ms gaps (Helenius, Uutela, & Hari, 1999). This would suggest that auditory objects formation could be hindered in dyslexia, another potential explanation for the speech-in-noise deficit observed in dyslexia. Other potentially affected mechanisms could involve the processing of binaural differences such as interaural level differences (ILDs) or interaural time differences (ITDs) which is also required for good speech-in-noise comprehension (Bronkhorst & Plomp, 1988; Drullman & Bronkhorst, 2000; Freyman, Balakrishnan, & Helfer, 2001; Freyman, Helfer, McCall, & Clifton, 1999; Hawley, Litovsky, & Culling, 2004). ILDs are due to acoustic headshadow, assuming that a target sound originates from the front of a listener and a competing sound source is situated 90° to its right, sound arriving on the left ear will be partially filtered out by the head, causing intensity decreases up to 20 dB thus increasing the SNR on this ear. ITDs depict the difference in incidence-time at both ears for a single acoustic source in space. Typically ITDs range from 0 μ s for a source placed at azimuth 0° (front direction) to a maximum of around 650 μ s for a source present at azimuths + or –90°. Perception or intelligibility increases due to target-background separation due to these spatial cues is referred to as binaural unmasking. In dyslexic participants, Hill, Bailey, Griffiths, and Snowling (1999), measured binaural release of masking in 12 adults for a 200 Hz pure tone presented in concurrent low-pass Gaussian noise with a cut-off frequency of 1000 Hz. This experiment did not yield any significant difference between dyslexics and matched controls, suggesting normal spatial sound-source segregation and binaural integration abilities in adults with dyslexia, at least for the processing of non-speech (tonal) targets. However, other more recent work studying the processing of spatialised speech targets showed that dyslexics recognized centrally presented targets in the presence of a speech masker less well than matched normal readers (Geiger et al., 2008). This latter observation suggests that dyslexics could exhibit spatial-listening impairments more easily identifiable when target and competing sound are both speech. This suggests that dyslexics could exhibit different binaural release of masking amounts depending on the type of concurrent sound considered. This is also well known in normal readers: spatial separation advantage in speech-in-noise perception depends on the type of noise used as masker. Indeed, in cocktail party situations, two types of masking can occur, namely energetic and informational masking (Bronkhorst, 2000; Brungart, 2001). Energetic masking refers to the overlap of a target- and competing sound in time and frequency, at the peripheral level, and appears whenever a target sound is concomitantly encoded at the cochlear level with any broadband noise. Informational masking refers to the type of information contained in competing sound which can be of comparable nature (speech against a background of speech) and can cause informational interferences. Previous studies (Arbogast, Mason, & Kidd, 2002; Brungart, Simpson, Ericson, & Scott, 2001; Freyman et al., 2001; Freyman et al., 1999; Hawley et al., 2004; Kidd Jr, Mason, Rohtla, & Deliwala, 1998) evaluated the advantage of spatial separation for informational and energetic masking in normal readers. These studies all showed that spatial advantage was greater for informational than for energetic masking. Kidd et al. (1998), for instance, showed that with an informational masker, the advantage of spatial separation of target and masker was 20–30 dB, whereas spatial advantage for broadband noise was only 10 dB.

All these observations suggest that the origin of the speech-in-noise deficit reproducibly observed in participants with dyslexia is not identified and could be attributed to different sources because

different processes interact in the complex cocktail-party situation. Most notably, spatial (listening configuration employed) and informational (speech or non-speech nature of the target and competing signals) characteristics of the stimulation used in different experiments seem to be a source of potential discrepancies in reported results. The goal of the present study was to compare the ability of normal-reading adults and adults with a history of dyslexia to understand speech under different listening configurations, namely configurations that do implicate spatial separation of sound sources or not and under different background conditions, with backgrounds containing various amount of linguistic information. This experiment was designed to address two main questions: (i) are adult dyslexics sensitive to spatial unmasking effects in speech comprehension tasks? In other words, do they benefit from binaural cues in order to alleviate masking of target speech in noisy situations and (ii) are dyslexics sensitive to the linguistic nature of the target or concurrent sound in spatialised speech-in-noise comprehension situations?

2. Materials and methods

2.1. Participants

Sixteen adult participants with a documented history of dyslexia (7 males, 9 females; mean age: 24.94 years, S.D.: 6.28) and 16 control participants (1 male, 15 females; mean age: 24.37 years, S.D.: 6.11), IQ and handedness took part in this experiment. Participants were all recruited at the local university and were all engaged in higher-education programs. All dyslexic participants were formally diagnosed by a psychologist or neuropsychologist prior to inclusion. All participants gave informed consent and were paid for their participation, the protocol used in this experiment obtained a favourable advice from the local ethics committee (ID RCB: 2008-A00708-47). All were right handed native French speakers, aged 18–43 years, and had no other documented hearing or language disorders. All participants were screened for audiometric pure-tone thresholds and no one exceeded 20 dB HL at any frequency in a 250–8000 Hz range. Amongst our 32 participants, pure-tone thresholds were significantly better in the right ear. Observed thresholds were on average up to 3 dB higher in the left ear (average difference = 1.63 dB, S.D. = 7 dB), however this right-ear advantage was evenly distributed across experimental groups. This was confirmed by a repeated-measures ANOVA ran on the audiometric thresholds as dependant variable and including factors Group (2: dyslexics vs. normal readers), Ears (2: left-ear vs. right-ear) and Frequency (11: tested frequencies). This analysis revealed a significant main effect of Ears [$F(1,29) = 5.38, p < .05$] and frequency [$F(10,290) = 9.07, p < .05$] but no main effect of Group [$F(1,29) = 0.26, p = .62$], or Group $\times$ Ear interaction [$F(1,29) = 0.62, p = .44$] suggesting that this pure-tone threshold asymmetry was the same in both groups.

Both groups also underwent a battery of psychometric tests, including the Edinburgh Handedness Inventory (Oldfield, 1971), non-verbal intellectual abilities (Raven's Standard Progressive Matrices; Raven, 1941), the French reading test 'L'Alouette' (Lefavrais, 1967) and neuropsychological battery 'Odédys' (Jacquier-Roux, Valdois, Zorman, Lequette, & Pouget, 2005). This battery includes word reading and spelling tests, and phonological, verbal working memory and visual attention assessment. Table 1 summarizes the characteristics of each group.

Briefly, independent *t*-tests showed that both groups did not differ on non-verbal IQ, age or handedness (all p s $> .05$). Reading abilities were clearly impaired in the dyslexic group: lexical age was markedly lower in dyslexics ($M = 130.94$ months, S.D. = 20.55) in comparison with normal readers ($M = 166.12$ months, S.D. = 7.64, $p < .001$). Word reading was also affected in dyslexics, with lower scores for pseudowords ($p < .05$) and lower speed for words ($p < .05$) and pseudowords ($p < .001$). Phonological abilities were clearly impaired, dyslexics performing lower in phoneme deletion ($p < .05$) and acronyms ($p < .05$) and being slower to achieve both tests (phoneme deletion: $p < .001$; acronyms: $p < .01$). Dyslexics also showed a deficit in sentence dictation (grammar: $p < .05$; orthography: $p < .05$), as well as words spelling ($p < .05$). Verbal working memory was also affected, ascending ($p < .01$) span being poorer for dyslexics than normal readers. No differences between the two groups emerged for oral skills, namely words and non-words repetition (both $p > .05$). Finally no visuo-spatial deficit was observable.

2.2. Procedure

Participants sat in a quiet sound-protected room in front of a computer-screen. Audio stimuli composed of 126 single words embedded in acoustic background were delivered via headphones (Beyerdynamic DT48, 200 Ω). Participants were asked to carefully listen to audio stimuli and repeat the word they heard to an experimenter. We tested three different backgrounds and three different listening configurations, leading to 9 conditions, and using 14 target-words per condition. Nine lists of stimuli

Table 1
Descriptive statistics and group differences for Normal readers and Dyslexics.

	Normal readers			Dyslexics			Statistics			
	<i>n</i>	<i>M</i>	S.D.	<i>n</i>	<i>M</i>	S.D.	<i>df</i>	<i>t</i> -Value	Significance	Group difference
Age (months)	16	292.5	73.305	16	299.250	75.319	30	−0.257	n.s.	–
Handedness (Edinburgh Inventory)	16	86.875	14.930	16	89.375	14.818	30	0.475	n.s.	–
IQ (Raven's Progressive Matrices)										
Score (/60)	16	50.687	7.245	16	45.750	8.805	30	−1.732	n.s.	–
Visuo-spatial attention (Bell's test)										
Accuracy (/35)	16	34.312	1.014	16	34.062	1.124	30	−0.661	n.s.	–
Verbal short-term memory										
Ascending span	16	7.937	1.652	16	6.312	1.621	30	−2.808	<0.01	−1.63
Descending span	16	6.062	1.731	16	5.000	1.713	30	−1.745	n.s.	–
Reading aloud (L'alouette)										
Lexical age (months)	16	166.125	7.641	16	130.937	20.554	30	−6.419	<0.001	−35.19
Reading aloud (words)										
Words – score (/20)	16	19.812	0.359	16	19.094	1.655	30	−1.697	n.s.	–
Words – time (s)	16	12.219	4.644	16	16.531	6.876	30	2.079	<0.05	4.31
Pseudowords – score (/20)	16	19.312	0.602	16	17.062	3.336	30	−2.655	<0.05	−2.25
Pseudowords – time (s)	16	17.312	4.557	16	29.625	11.848	30	3.880	<0.001	12.31
Phonological awareness										
Phoneme deletion – score (/10)	16	9.812	0.544	16	8.125	2.705	30	−2.446	<0.05	−1.69
Phoneme deletion – time (s)	16	24.500	4.733	11	39.909	15.339	25	3.793	<0.001	15.41
Acronyms – score (/10)	16	9.562	0.892	16	7.562	3.265	30	−2.363	<0.05	−2.00
Acronyms – time (s)	16	43.500	8.892	11	71.909	39.132	25	2.823	<0.01	28.41
Dictation (sentences)										
Orthography (/10)	16	9.812	0.544	16	8.562	2.097	30	−2.308	<0.05	−1.25
Grammar (/10)	16	9.937	0.250	16	7.875	3.423	30	−2.404	<0.05	−2.06
Dictation (words)										
Words (/10)	16	9.719	0.256	16	9.219	0.795	30	−2.394	<0.05	−0.50
Pseudowords (/10)	16	9.812	0.403	16	9.437	1.504	30	−0.963	n.s.	–
Repetition										
Words (score/16)	16	15.937	0.250	16	15.812	0.403	30	−1.054	n.s.	–
Logatomes (score/20)	16	19.187	0.911	16	18.812	1.559	30	−0.831	n.s.	–

were created, randomizing noises and listening configurations, so that across lists each word was presented in every listening configuration and noise. Within lists, frequency of target-words was counterbalanced. Each participant heard two blocks of 63 target words. In one block target words were presented to the right ear and in the other block target words were presented to the left ear. Order of presentation of blocks was randomized. Each target word was presented only once to the participants. Before the experimental phase, six practice-items, different from the target words, were given to participants to familiarize themselves to stimulus presentation mode and target-voice. The experiment lasted on average 30 minutes.

2.3. Stimuli

Stimuli were composed by embedding one target-word in a randomly selected 4-s burst of background; target words were always inserted 2.5 s after background onset.

2.3.1. Target-words

Hundred and twenty-six disyllabic words were selected in a middle range of frequency of occurrence (0.13–338.19 occurrence per million (opm), average: 16.82 opm, S.D.: 43.74) according to the French database Lexique2 (New, Pallier, Brysbaert, & Ferrand, 2004). They were pronounced by a 24-year-old female native-French speaker, recorded in a sound-proof room, with a sampling rate of 44.1 kHz.

2.3.2. Backgrounds: speech, modulated and stationary

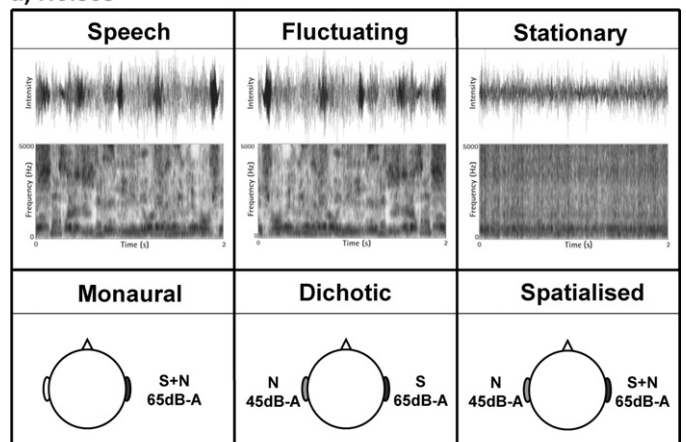
Three different maskers were used as backgrounds: a cocktail-party sound (Speech), a modulated speech-derived sound (Modulated) and a stationary broadband sound (Stationary), the latter being directly derived from the first speech sound (see Fig. 1a); all sounds were originally described in Hoen et al. (2007).

The cocktail-party sound was a mixture of 4 different voices (2 males; 2 females). Every single talker was first recorded in a sound-proof room, reading extracts of French press. Individual recordings were modified according to the following protocol: (i) removal of silences and pauses of more than 1 s; (ii) suppression of sentences containing pronunciation errors, exaggerated prosody or proper nouns; (iii) removal of low-amplitude background noise using noise-reduction optimized for speech signals (CoolEdit Pro© 1.1 – Dynamic Range Processing – preset Vocal limiter); (iv)

intensity calibration in dB-A and normalization of each source at 80 dB-A; (v) final mixing of individual sources into cocktail party sound tracks.

The modulated background was derived from the latter using custom-made Matlab© scripts. Procedure first included extraction of envelope information under 60 Hz using low-pass filtering. Second, using long-term fast Fourier transformation (FFT), the power spectrum and phase distribution of the original signal were computed and original phase information discarded by randomizing phase distribution. An inverse FFT was used to generate a new signal with equivalent power spectrum but randomized phases that was then multiplied with the temporal envelope

a) Noises



b) Listening configurations

Fig. 1. Backgrounds and listening configurations tested: (a) waveform and spectrogram of the three different backgrounds used as maskers and (b) listening configurations (ipsilateral side being arbitrarily represented as the right ear).

of the original cocktail background. Finally, the root mean square (rms) powers of the original and new signals were matched. By doing so, we obtained a modulated background that exhibits equivalent spectral characteristics and containing equivalent amplitude modulations below 60 Hz as the original cocktail-party sound, but without any linguistic details (e.g. phonological or lexical).

The stationary background was also derived from the original cocktail-party sound, by applying the same procedure as for the modulated sound, without multiplying envelope information with the new sound, we thus obtained a background having equivalent spectral characteristics as the original cocktail-party sound, but without any linguistic detail or deterministic amplitude modulations below 60 Hz.

2.3.3. Listening configurations: monaural, dichotic and spatialised

We tested three different listening configurations: monaural, dichotic and spatialised, these listening configurations were explicitly designed to reflect different levels of spatial separation of target-speech and background (see Fig. 1b, for a summary of listening configurations). In the monaural configuration (monaural), the target-word and competing background were both presented into the same ear (65 dB-A; SNR: 0 dB). Thus, in this configuration, the two sources appear as co-located. In the dichotic configuration (dichotic), target-words were presented at 65 dB-A to one ear and background to the contralateral ear at 45 dB-A. This configuration was intended to represent a case of full spatial separation, sources appearing as if they were virtually separated one from each other by 180° and at a very favourable SNR. Finally, in the spatialised configuration (spatialised) we presented the target-word in one ear (65 dB-A), ipsilateral and the background in both ears, but with an interaural level difference of 20 dB between ipsilateral and contralateral ear (65 dB-A ipsilateral and 45 dB contralateral). This results in a situation where spatial-release of masking should occur but necessitates the correct processing of ILD to lateralize the background source at a different position as the target-word source. In all three configurations, ears where target-speech was presented was counterbalanced, participants starting with half of the stimulations in one ear (either left or right, counterbalanced across participants) and finishing the experiment with the remaining half of stimulations in the contralateral ear (either left or right, counterbalanced across participants).

2.4. Data collection and analyses

Participants' responses were analysed by calculating the proportion of target-words correctly identified. These identification rates were then converted to rationalized arcsine transform units (RAU, *Studebaker, 1985*). This transformation places the scores on a linear and additive scale, thus facilitating meaningful statistical comparisons across the entire range of the scale. Performance expressed in RAU was determined for each of the nine experimental conditions and used as dependant variable in statistical analyses. Post hoc comparisons were assessed using the least significant difference (L.S.D.) test with a threshold of $\alpha = .05$. For representation purposes we always used in the graphics raw intelligibility scores, expressed as percentages of correctly repeated words.

3. Results

The ear where target-words were presented (left/right balanced across participants) never produced any significant main effect or any significant interaction in any analyses performed on this dataset, we therefore discarded this factor from any following analyses. A 3-way repeated-measures analysis of variance (ANOVA) was ran, with group (Group: 2: Dyslexics, Controls) as between-subject factor, and background (Background: 3: Speech, Modulated, Stationary) and listening-configuration (Configuration: 3: Monaural, Dichotic, Spatialised) as within-subject factors. This analysis revealed significant main effects for all three factors: Group [$F(1,30) = 5.64$, $p < .05$], Background [$F(2,60) = 7.19$, $p < .01$] and Configuration [$F(2,60) = 202.26$, $p < .001$], one significant first-order interaction Background $\times$ Configuration [$F(4,120) = 6.82$, $p < .001$] and the second-order interaction Group $\times$ Background $\times$ Configuration were also significant [$F(4,120) = 2.88$, $p < .05$]. Given these first results and in order to optimize the presentation of results we decided to run three different analyses along the factor Background. For each background type, we ran a separate analysis using RAU scores as dependent variables in 2-way repeated-measures ANOVA with group (Group: 2: Dyslexics, Controls) as between-subject factor and listening-configuration (Configuration: 3: Monaural, Dichotic, Spatialised) as within-subject factor.

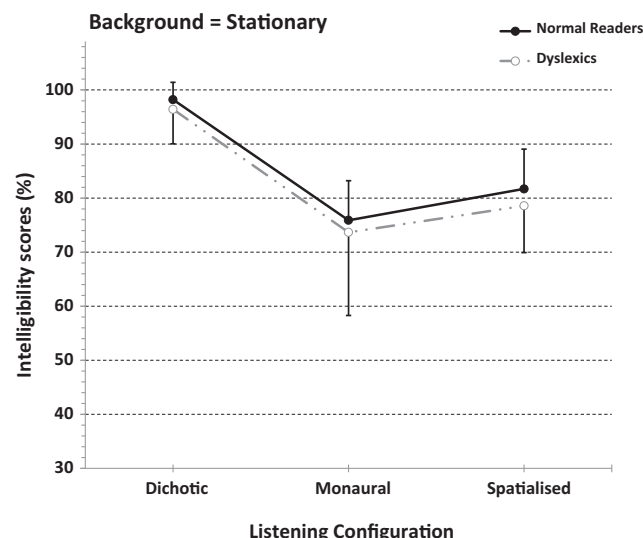


Fig. 2. Speech in stationary background perception. Intelligibility scores observed in the speech in stationary background condition and plotted as a function of listening configuration for adult dyslexics (dashed line) and matched normal readers (black line). Error bars report S.D. values.

3.1. Speech in stationary background

When the background was made of a stationary broadband noise with spectral properties equivalent to 4-talkers babble, dyslexics and normal-readers showed the same pattern of performance. In the dichotic configuration, when concurrent sounds were presented to opposite ears, dyslexics and normal-readers reached comparably high levels of intelligibility (dyslexics: 96.43%, S.D. = 6.39; normal-readers: 98.21%, S.D. = 3.19). Scores dropped in the monaural configuration where both signals are mixed in the same ear (dyslexics: 73.66%, S.D. = 15.37; normal-readers: 75.89%, S.D. = 7.32) and a small spatial-release of masking effect was observed for both groups, scores rising again in the spatialised configuration (dyslexics: 78.57%, S.D. = 8.65; normal-readers: 81.70%, S.D. = 7.36). This pattern was well reflected in the absence of significant main effect of group [$F(1,30) = 1.49$, $p = .23$], but significant main effect of listening configuration [$F(2,60) = 61.78$, $p < .001$], all specific comparisons on this main effect being significant, in particular the small spatial-release of masking was significant on average over all participants (Monaural vs. Spatialised, $p < .05$). The first-order interaction remained non-significant [$F(2,60) = 0.05$, $p = .95$], indicating that for stationary background, only the listening configuration had a significant effect, and that groups did not differ in any considered configuration. When the background was made of stationary speech-derived broadband noise, dyslexics and normal-readers performed comparably, dyslexic adults in particular did not show any speech-in-noise deficit with this type of background (Fig. 2).

3.2. Speech in modulated background

In order to determine if amplitude modulations present in the concurrent sound background are used as efficiently by dyslexics as by normal-readers, we conducted a second analysis on data obtained with speech-derived modulated background. In this situation (Fig. 3), dyslexics reached on average slightly lower intelligibility scores (81.84%, S.D. = 14.43) than normal-readers (84.97%, S.D. = 12.61), even if this effect failed to reach statistical significance [$F(1,30) = 2.89$, $p = .10$]. Again, levels of intelligibility were highly depending on listening-configuration which had a significant main effect [$F(2,60) = 60.51$, $p < .001$] but the first-order interaction did

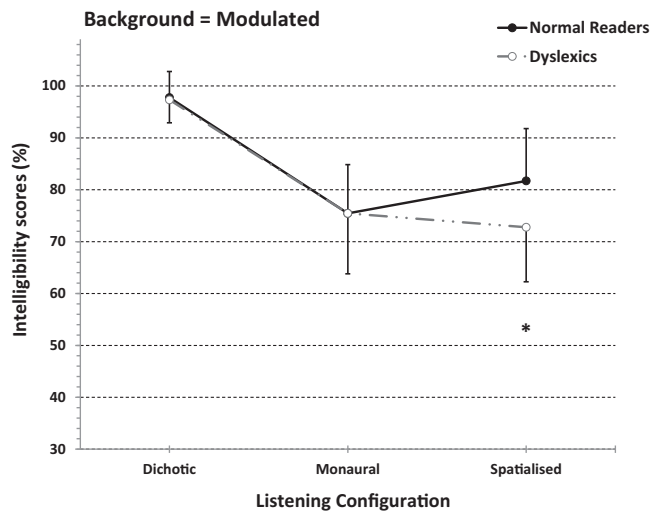


Fig. 3. Speech in modulated background perception. Intelligibility scores observed in the speech in modulated background condition and plotted as a function of listening configuration for adult dyslexics (dashed line) and matched normal readers (black line). Error bars report S.D. values. Asterisks indicate statistically significant differences between the two groups.

not reach significance [$F(2,60) = 2.54, p = .09$]. Dyslexics and normal-readers respectively reached scores of 97.32% (S.D. = 4.49) and 97.77% (S.D. = 5.03) in dichotic configuration [$p = .89$]. In the monaural configuration, both groups experienced equivalent difficulties, respectively 75.45% (S.D. = 11.65) and 75.45% (S.D. = 9.39), post hoc [$p = 1$]. Finally, in the spatialised condition, dyslexics performed at an even lower level as in the monaural configuration 72.77% (S.D. = 10.50), whereas normal-readers slightly improved compared to the monaural configuration, hence experiencing spatial release of masking, reaching a score of 81.70% (S.D. = 10.09), leading to a significant difference between groups in spatialised listening configuration [$p < .01$].

When the masker was a modulated background, normal-readers could still show spatial-release of masking, target-words being more intelligible in the spatialised condition than in the monaural condition, while dyslexics did not.

3.3. Speech-in-speech

When the sound used as masker was a cocktail of speech-sounds (Fig. 4), dyslexics globally achieved lower intelligibility scores (76.34%, S.D. = 20.53) than normal-readers (82.59%, S.D. = 16.00), as reflected in the main significant effect of factor Group [$F(1,30) = 4.95, p < .05$]. However, intelligibility scores depended very much on the listening configuration as indicated by the significant main effect of this latter factor [$F(2,60) = 87.81, p < .001$] and significant first-order interaction [$F(2,60) = 3.61, p < .05$]. In the dichotic configuration all participants could hear target-words very well reaching intelligibility levels of 95.54% (S.D. = 5.76) for dyslexics and 98.21% (S.D. = 3.19) for normal-readers. Post hoc tests revealed that the difference between groups here was non-significant [$p = .52$]. In the monaural configuration, both groups experienced the greatest difficulties, with dyslexics showing on average the lowest scores 55.36% (S.D. = 13.17) compared to normal-readers 69.64% (S.D. = 9.22), this difference being statistically significant [$p < .001$]. Finally, both groups of participants experienced an important spatial release of masking in the spatialised configuration, intelligibility scores rising again to 78.12% (S.D. = 15.75) for dyslexics and 79.91% (S.D. = 16.12) for normal-readers. Post hoc tests revealed that binaural release of masking was significant for both normal readers and dyslexics [both

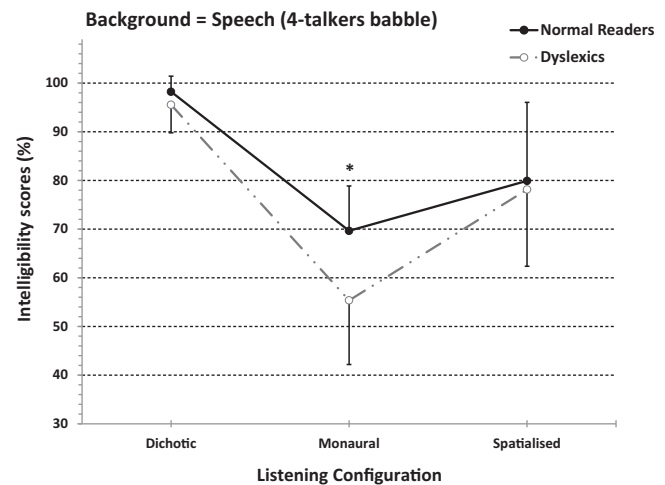


Fig. 4. Speech-in-speech perception. Intelligibility scores observed in the speech-in-speech condition and plotted as a function of listening configuration for adult dyslexics (dashed line) and matched normal readers (continuous line). Error bars report S.D. values. Asterisks indicate statistically significant differences between the two groups.

$p < .001$]. Same tests also revealed that normal readers and dyslexics performed equally well in the spatialised configuration [$p = .66$].

3.4. Unmasking effects – spatial release vs. modulation release

In order to better quantify and characterize different release of masking phenomena occurring in different conditions in both groups, we defined two indexes, one quantifying benefit of binaural cues and the second benefit of modulations in background. We defined the “spatial release of masking index” (SRI) for every type of background as the difference between intelligibility scores obtained in the spatialised minus monaural listening configuration ($SRI = \text{spatialised} - \text{monaural}$). The “modulation release of masking” index (MRI) was defined as the difference between intelligibility scores in the modulated background condition minus scores in the stationary background condition ($MRI = \text{modulated} - \text{stationary}$). Both indexes were calculated for each of the 32 participants. Again inferential statistics were based on RAU scores, while figures used indexes calculated on average intelligibility percentages for readability. Two repeated-measures ANOVA were run with group (Group: 2: Dyslexics, Controls) as between-subject factor and -for SRI-, type of background (Background: 3: Speech, Modulated, Stationary) or -for MRI-, listening-configuration (Configuration: 3: Dichotic, Monaural, Spatialised) as within-subject factor.

The spatial-release of masking index (Fig. 5a) was maximal when the background was speech for both dyslexics and normal-readers. Dyslexics even showed a larger SRI ($M = 22.77\%$, S.D. = 19.03) than normal-readers ($M = 10.27\%$, S.D. = 13.55). Although the main effect for group remained non-significant [$F(1,30) = 0.09, p = .77$], the ANOVA revealed a significant main effect of Background [$F(2,60) = 8.10, p < .001$], and a significant first-order interaction [$F(2,60) = 4.02, p < .05$]. Post hoc comparisons performed on this interaction revealed a significant Group difference for the SRI in speech [$p < .05$], a tendency to a significant Group difference in modulated background [$p = .09$] (dyslexics: -2.68% , S.D. = 16.47; normal-readers: 6.25% , S.D. = 13.01) and a non-significant difference between dyslexics and controls in stationary noise [$p = .87$] (dyslexics: 4.91% , S.D. = 17.83; normal-readers: 5.80% , S.D. = 7.92). In order to evaluate if individual indexes had significant absolute values we ran a one sample t -test against value 0 (see Table 2). This analysis revealed that the SRI

Table 2

Between-group differences for the spatial release of masking index (SRI) and the modulation release of masking index (MRI).

	Normal readers						Dyslexics					
	M	S.D.	dl	t-Value	p	Significance	M	S.D.	dl	t-Value	p	Significance
Spatial release												
Stationary	4.237	5.781	15	2.931	0.010	*	3.585	13.014	15	1.102	0.288	–
Modulated	4.563	9.496	15	1.922	0.074	–	–1.955	12.023	15	–0.651	0.525	–
Speech	7.496	9.888	15	3.032	0.008	*	16.621	13.890	15	4.786	0.000	*
Modulation release												
Dichotic	–0.326	4.843	15	–0.269	0.791	–	0.652	5.672	15	0.460	0.652	–
Monaural	–0.326	7.488	15	–0.174	0.864	–	1.304	13.260	15	0.393	0.700	–
Spatialised	0.000	6.596	15	0.000	1.000	–	–4.237	9.561	15	–1.772	0.097	–

Asterisks indicate statistically significant differences between the two groups.

was significantly different from 0 for the normal readers group in stationary ($M=4.24$, $S.D.=5.78$, $t(15)=2.93$, $p<.05$) and speech backgrounds ($M=7.50$, $S.D.=9.89$, $t(15)=3.03$, $p<.01$) and showed a tendency to be significant in modulated background ($M=4.56$, $S.D.=9.50$, $t(15)=1.92$, $p=.07$). In dyslexics however, the SRI was significant only when the background was speech ($M=16.62$, $S.D.=13.89$, $t(15)=4.79$, $p<.001$). Dyslexics however did not benefit from spatial unmasking when the background was not speech, SRI remaining non-different from 0 when the background was stationary ($M=3.59$, $S.D.=13.01$, $t(15)=1.10$, $p=.29$) or modulated ($M=-1.96$, $S.D.=12.02$, $t(15)=-0.65$, $p=.53$). These results clearly showed that the spatial-release of masking was maximal when

the masker was speech and that dyslexics actually showed larger spatial release of masking in this condition.

The modulation-release of masking index (Fig. 5b) was small in general compared to the SRI: almost absent in the dichotic listening configuration (dyslexics: 0.89%, $S.D.=7.77$; normal-readers: -0.45% , $S.D.=6.63$), it increased slightly for the dyslexic group only in the monaural condition (dyslexics: 1.79%, $S.D.=18.16$; normal-readers: -0.45% , $S.D.=10.26$), both differences between groups remaining non-significant respectively [$p=.74$] and [$p=.58$] with no significant main effects for Group [$F(1,30)=0.12$, $p=.73$] or Configuration [$F(2,60)=0.84$, $p=.44$], and no significant interaction [$F(2,60)=1.08$, $p=.35$]. In the spatialised listening configuration, normal readers showed no modulation advantage 0.00% ($S.D.=9.03$), whereas dyslexics showed a quantifiable but not significant modulation disadvantage: -5.80% ($S.D.=13.10$), non-significant post hoc [$p=.15$]. One-sample t -tests against the value 0 remained all non-significant suggesting that we did not observe any significant modulation release effect in this experiment, either for normal readers or for participants of the dyslexic group.

4. Discussion

The goal of the present research was to further explore the speech-in-noise perception deficit observed in dyslexia and study its susceptibility to the nature of background and listening configuration. In particular, we were interested in testing if the characterized deficit would be sensitive to the spatial distribution of target- and masker-sound. We therefore ran a speech-in-noise perception study using isolated words presented in three types of background: a stationary background (stationary), a speech-derived modulated background (modulated) and a 4-talkers babble (speech) in three different listening configurations: target-sound presented to one ear and the masker to the contralateral ear with an interaural level difference of 20 dB (Dichotic); both target-sound and masker presented to the same ear (Monaural); and target-sound in one ear but background in both ears with an interaural level difference of 20 dB (Spatialised).

Results from this experiment first add to the existing literature on the existence of a speech-in-noise comprehension impairment in dyslexia (Boets, Ghesquière, et al., 2007; Boets, Wouters, et al., 2007; Ziegler, Pech-Georgel, George, Alario, & Lorenzi, 2005; Ziegler et al., 2009). On average, adult dyslexics performed less well than matched normal-readers on intelligibility measures of isolated words presented against backgrounds of different acoustical nature. However, our observations also demonstrate a strong modulation of the dyslexics' speech-in-noise perception impairment by two factors: (i) the listening configuration and spatial separation of target- and masker-sounds and (ii) the nature of the background, in particular regarding its phonological content. This contextual modulation of the speech-in-noise comprehension deficit is rather large as in some conditions dyslexics did not show any

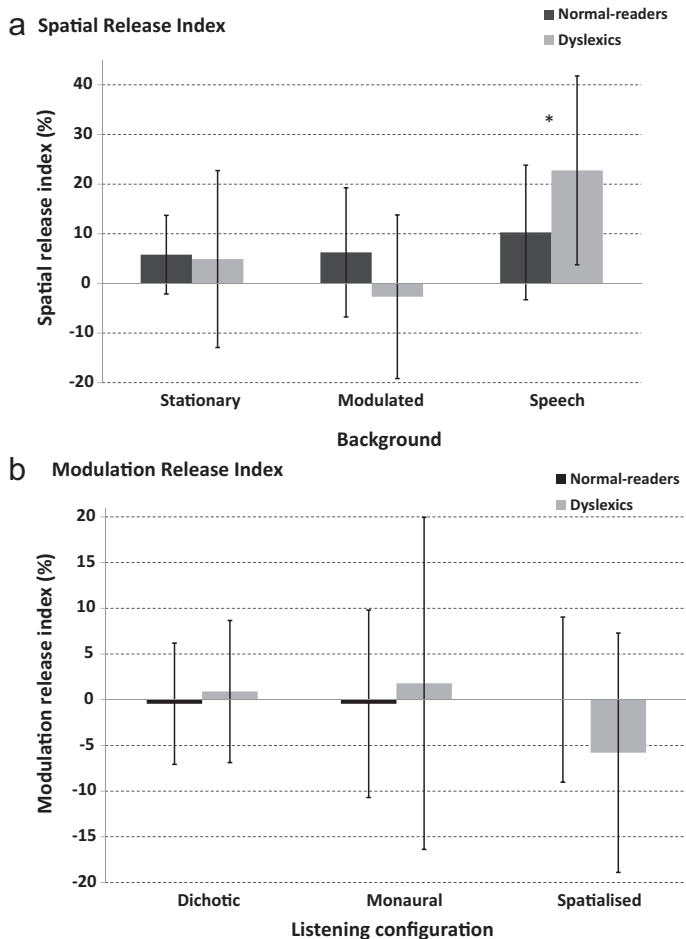


Fig. 5. Masking release indexes. Spatial (a) and Modulation (b) release indexes calculated for dyslexics (grey) and matched normal readers (black). Error bars show S.D. Asterisks indicate statistically significant differences between the two groups.

speech-comprehension difficulties and behaved exactly as normal readers and in some conditions their impairment compared to normal-readers could reach 9–14% drop in intelligibility scores, a significant impairment. In the following we will discuss these observations in turn before relating them to the general discussion of current models of dyslexia.

4.1. Effect of listening configuration

Our results suggest a clear effect of the listening configuration on the abilities of dyslexic participants to understand speech in noisy conditions.

In a condition where the target-words and concurrent background were presented in opposite ears (Dichotic), dyslexics and normal readers did not differ significantly. Interestingly, this listening configuration was associated to very high levels of intelligibility and low levels of variability on average across backgrounds and groups ($M = 97.25$, $S.D. = 1.07$). This suggests two things: first the fact that the 4-talkers babble sound that we used as a masker is not creating very important amounts of informational masking. This is in agreement with what we already observed in a former experiment on speech intelligibility (Hoen et al., 2007), where we could show that this kind of mixture of 4 different voices creates a rather information-saturated sound, causing less informational masking effect than babbles composed with 2 or 3-talkers. We also know from this experiment that this masker causes informational masking both at the phonological and at the lexical level but in a very small proportion (few words remain accessible from the background). Second, this observation suggests that dyslexic adults do not experience difficulties for speech and noise separation if both signals are presented in a dichotic fashion, meaning in a situation minimizing energetic masking. This observation is in line with past work having evidenced speech comprehension or speech perception deficits in children with dyslexia limited to difficult situations, either when the task (Banai & Ahissar, 2006) or the presence of noise in the background made speech processing more difficult (Brady et al., 1983; Breier, Gray, Fletcher, Foorman, & Klaas, 2002). When the listening situation is easy to handle (no energetic masking and limited informational masking) adult dyslexics do not experience speech-in-noise perception difficulties.

In the monaural configuration, dyslexics and normal-readers experienced more difficulties than in any other listening-configuration. Of course the monaural configuration maximizes energetic masking as both signals must be encoded on the same ear and introduces the largest uncertainty about concurrent voices, in particular when the background is made up of speech (Brungart, 2001; Brungart, Chang, Simpson, & Wang, 2006; Brungart et al., 2001; Hoen et al., 2007). This is also the background causing the most important difference between adult dyslexics and normal-readers, the group difference in this condition equating 14.29%. In a situation where the target-sound and background sources were not separable in space, dyslexics and normal-readers experienced the larger masking effects (i.e. lower intelligibility scores) and dyslexic participants showed a clear impairment compared to normal-readers. Interestingly, dyslexics performed comparably to normal-readers in the monaural configuration when the background were made of non-speech sounds (stationary or modulated), but when the concurrent signal was also speech, then dyslexics showed a marked speech-in-noise comprehension deficit. This confirms the specificity of the speech-in-noise deficit showed by dyslexic participants to concurrent speech-sounds (e.g. speech-in-speech conditions) compared to speech-in-noise conditions (Brady et al., 1983; Breier et al., 2002). Phonological uncertainty increased and worsened by the maximized energetic masking and concurrent encoding of different phonemes at the

same time on the same ear is making speech perception significantly more difficult for adult dyslexics than for matched controls.

Finally, in the Spatialised configuration we observed an effect of spatial release of masking, intelligibility scores being on average higher than in corresponding monaural conditions as reflected in the SRI. However, this effect of spatial unmasking was strongly modulated in dyslexics by the type of background (Speech: $SRI = 22.77\%$ /Modulated: $SRI = -2.68\%$ /Stationary: $SRI = 4.9\%$). This was also the trend observed in normal-readers, however with a slightly different pattern: (Speech: $SRI = 10.27\%$ /Modulated: $SRI = 6.25\%$ /Stationary: $SRI = 5.8\%$). First these results confirm that spatial release of masking depends on the kind of concurrent sound involved. In particular it seems to be maximized when informational masking is maximized (background = speech) and this is true for normal-readers as well as dyslexics, both groups minimize the effects of informational masking by relying on spatial strategies (Arbogast et al., 2002; Brungart & Simpson, 2002; Freyman et al., 2001; Freyman et al., 1999; Hawley et al., 2004; Kidd et al., 1998). The SRI was significantly larger when the background was speech for dyslexics than for normal-readers. This can be explained by the fact that when the competing background is also speech, target and masker phonological information have to be encoded on the same ear in the Monaural configuration thus maximizing masking effects compared to all other listening configurations, in particular for dyslexic participants. Intelligibility then increases thanks to spatial release in the spatialised configuration, reaching comparable levels across background types and across groups, thereby maximizing the SRI when the background is speech for dyslexics. Although the speech-in-speech condition is the one where dyslexics show the greatest difficulties, it is also the condition where they show the largest improvements thanks to spatial separation of target and background sources. This observation could reflect a particular compensation strategy used by adult dyslexics. They would maximize spatial segregation of sound streams, based on spatial cues as interaural level difference or the fundamental frequency signature of voices, all long-term variations of the speech signal. This result is in agreement with former works having demonstrated that although dyslexics show deficits in integrating short-temporal binaural cues (deficits in detecting movements or precise positions of tones in the auditory space), they can still efficiently process interaural temporal cues that last over longer time-frames like interaural phase differences, resulting in normal binaural masking levels (Amitay, Ahissar, & Nelken, 2002).

4.2. Effect of background-type

When manipulating the nature of the noise used as background, Speech was the masker creating the largest masking effects in normal-readers as well as in dyslexics. This is in agreement with former work suggesting additive masking effects of energy and levels of information present in the background (Brungart, 2001; Brungart et al., 2001). Certain authors even suggested that in a speech-in-speech situation, informational masking was the source of largest masking effects (Brungart et al., 2006). Using the same type of background we have already demonstrated that in the 4-talkers situation, masking effect are maximized because participants process the background cocktail sound up to the lexical level (i.e. words), leading to supplementary phonological and lexical information competing with the target-information in this situation (Boulinger, Hoen, Ferragne, Pellegrino, & Meunier, 2010; Hoen et al., 2007). This is again the case in our study where globally, intelligibility scores were lowest when the background was speech. However, looking in more detail into the effect of intensity modulations on intelligibility scores, we could evidence a clear difference between normal-readers and dyslexics calculating the modulation release index. The MRI was significantly lower for

dyslexics than for normal-readers in particular in the spatialised listening configuration (Group difference = 7.86%). This result suggests that although dyslexics seem to be able to parse the auditory scene based on long-lasting auditory cues (differences in intensity, amplitude or fundamental frequency) they do not benefit from amplitude modulations in the concurrent background as normal-readers do. The MRI obtained in our study is not quantitatively in agreement with previous studies, yielding greater improvements (Amitay et al., 2002; Ziegler et al., 2009). An explanation could be provided here by the size of the modulations contained in our modulated background. Recall that dips in the signal emerge as intensity modulations of relatively short durations (10s to 100s of ms). In our case in particular, using a mixture of 4-talkers typically reduces the size of the dips available, which is typically diminishing the release of masking caused by the dips (Howard-Jones & Rosen, 1993). As a matter of fact, the MRI was rather low in our experiment; even normal-readers had no major benefit from the small modulations offered by our modulated background. However, normal-readers did show positive MRIs in all three listening configurations; dyslexics did only in the monaural configuration and showed no benefit in the dichotic configuration and even showed a decrease of performances due to amplitude modulations in the spatialised configuration. This observation could be explained by different hypotheses. The first one would be that dyslexics do not get the dips in the background, i.e. they do not identify regions of lower noise-amplitude as being regions of the signal where they can get relevant information, in agreement with former studies having demonstrated difficulties in dyslexic children to process envelope information in speech signals (Lorenzi et al., 2000). However, if this observation may explain part of the picture it is in the end rather unlikely as dyslexic participants still showed small effects of modulation unmasking in the monaural condition, similar to normal-readers. The second hypothesis would be that dyslexics actually get the dips, but they do not perceive relevant information inside the dips, and even worse, the information they get from the dips may in the end be causing additional masking effects. This hypothesis would be in agreement with recent work by Hopkins and Moore (2009), who have shown a crucial role of the temporal fine structure (TFS) of sound in listening into the dips. According to their work, crucial information for benefiting from dips in modulated background is contained in the TFS of sounds, the processing of which requires good spectro-temporal definition as it diminishes in hearing loss for example (Ardoint, Sheft, Fleuriot, Garnier, & Lorenzi, 2010). Therefore participants with dyslexia may get the dips but are unable to efficiently process TFS of sounds present in the dips. Another hypothesis could be that they do get the dips and efficiently process the TFS of sounds inside the dips but that this partial phonological information is just not sufficient to create reliable phonological information activations and lead to successful word recognition. This could be related to the effect of internal noise in the speech signal observed by Ziegler et al. (2009). The determination of why participants with dyslexia experience no modulation advantage in noisy situation deserves more investigation as it is a clear disadvantage when having to understand speech in noise and could well explain part of the dyslexia speech-in-noise deficit.

4.3. Speech-in-noise perception deficit and dyslexia

Clearly, our results are in congruence with the observation of sub-optimal speech sound encoding and processing in noisy situations in the context of dyslexia. The fact that speech constitutes the worst background for dyslexics could be interpreted in the context of the phonological deficit hypothesis as it would suggest that the deficit may be specific to speech-sounds used as maskers (Brady et al., 1983; Breier et al., 2002). However, we have shown that under certain listening conditions speech-modulated

background could also reveal impairments in dyslexics. And contrary to what has been observed so far speech sounds also contain cues that can be well exploited by dyslexics to perform spatial unmasking, whereas physical modulated background made this process inefficient. This observation does not completely rule out the phonological explanation because our task was always speech perception and it may be that noisy conditions just impose increased processing demands on dyslexic participants, preventing them to successfully use phonological information present in target speech signals. But the fact that dyslexics show very important spatial release of masking for speech together with a deficient processing of dips in the signal may also well be interpreted in a “processing time-window” view. In agreement with the temporal-order model (Stein & Talcott, 1999; Tallal, 1980, 2004; Tallal, Miller, & Fitch, 1993), it seems that dyslexics experience difficulties processing acoustical cues that are in the time-range of the dips (10–100 ms) or in the temporal resolution of the TFS whereas they seem rather good at using acoustical cues that unfold on longer time-scales (F0 modulations, ILD). Our results even suggest that adult dyslexics might be compensating their difficulties to process short acoustic cues by relying more or more efficiently on longer cues, such as F0 modulations and ILD, than do normal-readers who can benefit from both types of cues. This would explain why we have found an SRI that was better for dyslexics than for normal-readers in the speech condition. This latter observation should be detailed and future research will be dedicated to this issue. Do dyslexics rely more on longer temporal cues than on shorter and do they do it more efficiently than normal readers?

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