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RESEARCH ARTICLE

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Speech perception in noise in children with dyslexia: Does speech sound disorder matter?

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The aim of this observational cohort study with a control group is to compare consonant perception skills in quiet and in noise in children with typical language and learning development and in children with dyslexia, with and without Speech Sound Disorder (SSD). Three groups were included: A control group of twenty children with normal reading abilities and typical language development, twelve children with dyslexia and typical language development and thirteen children with dyslexia and SSD. All subjects received a consonant recognition test in three different listening conditions (quiet, + 10 and 0 Signal-to-Noise Ratio). In all test conditions, children with dyslexia and SSD had significantly lower consonant recognition scores than the control group and the children with dyslexia and typical language development ($p < .0001$). The poorer performances observed in children with dyslexia and SSD may be explained by impaired phonological processing underlying both conditions.

KEYWORDS
consonant recognition, dyslexia, language, noise, phoneme, speech sound disorder

1 | INTRODUCTION

Between 4% and 8% of children attending primary school show a developmental disorder in learning to read despite normal intelligence, adequate educational opportunities and in the absence of neurological or sensory deficits (Butterworth & Kovas, 2013).

Practitioner points

- Children with dyslexia may have difficulties with speech understanding in noise because of an associated speech sound disorder.
- Twenty children with typical development and twenty-five children with dyslexia received a consonant recognition test in quiet and in noise.
- Only children with dyslexia and an associated speech sound disorder had poorer speech-in-noise recognition abilities than peers with typical language development.
- The poor speech-in-noise identification abilities in children with dyslexia and speech sound disorder may be due to impaired auditory processing.
- In clinical practice, the diagnostic work-up of children with dyslexia should include tests of phoneme recognition in noise in order to identify those at risk for poor speech-in-noise perception and increased listening effort in classrooms, and in order to improve the acoustic environment.

Referring to DSM-5 (American Psychiatric Association, 2013), dyslexia is a term used to describe a pattern of learning difficulties characterized by problems with accurate or fluent word recognition, poor decoding, and poor spelling abilities.

The phonological theory of dyslexia postulates that it arises from an impairment of phonological awareness (Goswami, 2000; Schülte-Korne & Bruder, 2010), interpreted as the ability to reflect upon and manipulate sounds in spoken words. A deficient phonological awareness is believed to originate from impaired processing of sensory information in speech, specifically for individual acoustic cues (Smith-Spark, Henry, Messer, & Zięcik, 2017; Zuk et al., 2018).

Over the last years, several papers have shown that, compared to controls, children with dyslexia have a higher prevalence of deficient discrimination of frequency/pitch, stimulus duration and auditory stream segregation (Casini, Pech-Georgel, & Ziegler, 2017; Goswami, Fosker, Huss, Mead, & Szucs, 2011; Palladino, Cismondo, Ferrari, Ballagamba, & Cornoldi, 2016).

However, dyslexia is a heterogeneous disorder, where not all cases are characterized by an auditory processing impairment (Stein, 2018): Recently, Stein (2019) has proposed that the core deficit of dyslexia is a magnocellular system dysfunction affecting both auditory and visual processing and that the degree of dysfunction in each subsystem could explain the variability of clinical presentation.

Moreover, 25%–30% of reading disorders are associated with Speech Sound Disorder (SSD) (Gallagher, Frith, & Snowling, 2000; Pennington & Lefly, 2001; Tambyraja, Farquharson, & Justice, 2020). The DSM-5 definition of SSD is "a persistent difficulty with speech sound production that interferes with speech intelligibility or prevents verbal communication of messages, in the absence of a physical, structural, neurological, or hearing impairment" (American Psychiatric Association, 2013). This condition typically manifests in pre-school age and can be considered an important factor of linguistic vulnerability in dyslexia (Adlof & Hogan, 2018; Delage & Durrleman, 2018; Preston, Hull, & Edwards, 2013). In multi-factorial models, SSD is identified as one of the predictors of the subsequent development of dyslexia, together with language impairment and family history (Hayiou-Thomas, Carroll, Leavett, Hulme, & Snowling, 2017; Peterson, Pennington, & Shriberg, 2009). The coexistence of dyslexia and SSD may be explained by an underlying common deficit in phonological awareness (Johnson, Pennington, Lowenstein, & Nittrouer, 2011; Melby-Lervåg, Halaas, & Hulme, 2012), causing a reduced ability to recognize and separately manipulate phonemes in SSD, and a difficulty in matching phonological representations to graphemes in dyslexia.

Although not extensively investigated in the literature, poor speech-in-noise recognition appears to be another characterizing feature of children with dyslexia, even though with a high degree of variability (Nittrouer, Krieg, & Lowenstein, 2018; Van Hirtum, Moncada-Torres, Ghesquière, & Wouters, 2019; Ziegler, Pech-Georgel, George, & Lorenzi, 2009). Literature data demonstrate that these difficulties are especially pronounced with consonant identification (Ziegler et al., 2009), and that errors mostly concern the place of articulation (Frey, François, Chobert, Besson, & Ziegler, 2019; Ziegler et al., 2009). Nonetheless, no study has so far investigated the role of an associated SSD in this variability.

This topic is of potential interest for two main reasons: First, it could have practical implications for intervention, and secondly, it could help better understand the relationship between SSD and dyslexia.

Here, we hypothesize that, even if compensated after effective speech therapy, an associated SSD may play an important role in explaining the variability of speech-in-noise perception abilities of children with dyslexia.

Therefore, the aim of the present study is to assess the effect of an associated SSD on consonant recognition skills in children with dyslexia and to compare performances with those of a control group of children with typical learning and language development.

2 | METHODS

This study was approved by the Ethics Committee of our institution and was in accordance with the principles expressed by the Helsinki declaration.

2.1 | Study groups

We enrolled 45 native Italian speakers, divided into three groups: Twelve children with dyslexia and no SSD (no-SSD group, 3 females, 9 males, mean age: 107 ± 11.19 months, age range: 96–127 months); thirteen children with dyslexia and SSD (SSD group, 3 females, 10 males, mean age: 106 ± 8.81 months, age range: 96–109 months); a control group of twenty children with typical development of language and learning abilities (12 females, 8 males, mean age: 106.2 ± 10.2 months, age range: 96–125 months).

Children with dyslexia were included after receiving a thorough assessment by means of a standardized battery for the evaluation of academic skills. As indicated by Italian guidelines (Lorusso et al., 2011), the diagnosis was made when performances in speed and accuracy of reading were below the fifth percentile in three tests: reading passage (MT test by Cornoldi & Colpo, 1998), word and nonword reading (DDE-2 by Sartori, Job, & Tressoldi, 2007).

All children attended grade III to V of primary school with no support teacher and had been attending speech therapy for at least 6 months. None of the children had visual impairment, neurological deficits, cognitive impairment (IQ score ≥ 85) or hearing loss, interpreted as a hearing threshold worse than 20 dB HL for frequencies from 0.5 to 4 kHz.

Children of the control group were enrolled among patients coming for otorhinolaryngology visits to our clinic. This group received the same tests as administered to the children with dyslexia in order to exclude speech and learning disorders, cognitive impairment and hearing loss. Other conditions potentially interfering with speech-in-noise recognition abilities were ruled out through accurate history.

In the group with SSD, the diagnosis had been made in pre-school age as follows:

- performance below 2 SD in the articulation test and within 1 SD in the sentence repetition and in the sentence comprehension test of the Italian standardized battery for the assessment of language in children from 4 to 12 years ("Batteria per la Valutazione del Linguaggio" BVL 4–12, Marini, Marotta, Bulgheroni, & Fabbro, 2015);
- performance within 1 SD at the Peabody Picture Vocabulary Test (Dunn & Dunn, 1981) in its Italian language version (Stella, Pizzoli, & Tressoldi, 2000).

All children in the SSD group attended 1 year of speech therapy at the Phoniatric Unit of Fondazione Policlinico Gemelli IRCCS. Then, as in standard clinical practice, they were re-assessed on a yearly basis by means of the same battery and finally at the time of enrolment in the present study in order to verify that they met inclusion criteria.

Furthermore, to be sure that they could reliably receive the consonant recognition test, we verified that none of them had deficits of phoneme discrimination, as assessed by the nonword discrimination task of a standardized Italian battery (BVN 5–11 by Bisiacchi, Cendron, Gugliotta, Tressoldi, & Vio, 2005).

Demographic data of children with dyslexia and controls, together with their grades and the results in the MT and DDE-2 tests, are detailed in Tables 1 and 2, respectively.

2.2 | Consonant recognition test

For the assessment of consonant recognition, an open-set task was used (Amigoni et al., 1997) in which stimuli consist of sixteen Italian consonants in an /a/- C- /a/ context (/aba/, /aka/, /atʃa/, /ada/, /afa/, /aga/, /adʒa/, /ala/,

TABLE 1 Demographic data, grade and the results in the MT and DDE-2 tests in the children with dyslexia

Patient	Group	Age (mo)	Sex	Grade	sMT	aMT	cMT	WRs	WRa	NWRs	NWRa
1	SSD	96	M	III	IIR	SP	SP	<5	10	<5	10
2	SSD	103	M	III	IIR	IIR	AR	<5	10	<5	10
3	SSD	102	M	III	IIR	AR	AR	<5	10	10	<5
4	SSD	105	F	III	IIR	AR	AR	10	<5	<5	25
5	SSD	100	F	III	AR	IIR	AR	10	<5	<5	10
6	SSD	106	F	III	IIR	AR	SP	<5	5	10	<5
7	SSD	102	M	III	IIR	SP	AR	25	<5	10	<5
8	SSD	109	M	IV	IIR	AR	SP	<5	5	5	<5
9	SSD	112	M	IV	AR	AR	AR	25	<5	10	<5
10	SSD	120	M	V	IIR	AR	AR	<5	10	<5	<5
11	SSD	126	M	V	IIR	AR	IIR	5	<5	<5	5
12	SSD	98	M	III	IIR	SP	AR	<5	10	<5	10
13	SSD	99	M	III	IIR	AR	IIR	<5	10	10	<5
14	No-SSD	100	M	III	IIR	AR	IIR	10	<5	<5	10
15	No-SSD	114	M	IV	AR	AR	IIR	<5	10	10	<5
16	No-SSD	117	M	IV	IIR	AR	SP	<5	10	<5	10
17	No-SSD	127	F	V	IIR	AR	SP	10	<5	10	<5
18	No-SSD	112	F	IV	IIR	AR	SP	<5	10	<5	<5
19	No-SSD	97	M	III	IIR	IIR	SP	5	<5	10	<5
20	No-SSD	126	M	V	AR	IIR	AR	10	<5	<5	10
21	No-SSD	100	M	III	IIR	AR	SP	<5	10	<5	10
22	No-SSD	106	F	III	AR	SP	AR	25	<5	5	<5
23	No-SSD	96	M	III	IIR	AR	AR	<5	10	<5	<5
24	No-SSD	100	M	III	AR	IIR	AR	10	<5	<5	5
25	No-SSD	98	M	III	IIR	SP	AR	<5	10	<5	10

Abbreviations: aMT, MT test accuracy; AR, attention request (performance is borderline, that is, between 5th and 10th percentile, and follow-up is indicated); IIR, immediate intervention request (performance is below fifth percentile, so that dyslexia is diagnosed and intervention by a speech therapist is indicated); NWRa, non-word reading accuracy percentile (DDE-2 test); NWRs, non-word reading speed percentile (DDE-2 test); sMT, MT test speed; SP, sufficient performance (performance is between 25th and 50th percentile, so neither intervention nor follow-up are indicated); WRa, word reading accuracy percentile (DDE-2 test); WRs, word reading speed percentile (DDE-2 test).

TABLE 2 Demographic data, grade and the results in the MT and DDE-2 tests in the control group

Subject	Age (mo)	Sex	Grade	sMT	aMT	cMT	WRs	WRa	NWRs	NWRa
1	97	F	III	SP	SP	SP	25	50	50	50
2	96	M	III	O	O	O	50	50	50	25
3	102	F	III	SP	O	SP	25	25	25	50
4	111	M	IV	SP	SP	O	50	25	50	50
5	121	M	V	SP	SP	SP	50	25	50	50
6	97	F	III	SP	O	SP	25	50	25	50
7	98	F	III	O	SP	O	25	50	50	50
8	116	F	IV	SP	SP	SP	50	50	25	25
9	112	F	IV	O	SP	SP	50	25	25	25
10	99	F	III	SP	SP	SP	25	50	50	50
11	125	M	V	SP	SP	O	50	25	50	25
12	96	F	III	O	O	SP	25	50	25	50
13	118	F	V	SP	SP	SP	50	25	25	25
14	114	M	IV	SP	SP	O	25	50	50	25
15	98	F	III	SP	SP	SP	50	25	50	50
16	120	F	V	O	O	SP	25	50	25	25
17	99	F	III	SP	SP	SP	25	25	25	25
18	96	M	III	O	O	SP	50	25	50	50
19	112	M	IV	O	SP	SP	25	25	25	25
20	97	M	III	SP	SP	O	50	25	25	50

Abbreviations: aMT, MT test accuracy; cMT, MT test comprehension; NWRa, non-word reading accuracy percentile (DDE-2 test); NWRs, non-word reading speed percentile (DDE-2 test); O, optimal performance (performance above 50th percentile); sMT, MT test speed; SP, sufficient performance (performance is between 25th and 50th percentile, so neither intervention nor follow-up are indicated); WRa, word reading accuracy percentile (DDE-2 test); WRs, word reading speed percentile (DDE-2 test).

/ama/, /ana/, /apa/, /ara/, /asa/, /ata/, /ava/, /aza/), where "C" varies from one stimulus to the next and covers a frequency distribution dropping at 6 dB/octave above 500 Hz. Each list is composed of 32 stimuli, so that each /a/-C- /a/ is played twice. Lists were presented in a random order in three listening conditions: quiet (signal equivalent to 65 dB HL, no noise); + 10 Signal-to-Noise Ratio (SNR, signal equivalent to 65 dB HL; noise equivalent to 55 dB HL); 0 SNR (signal equivalent to 65 dB HL; noise equivalent to 65 dB HL). Stimuli were delivered free-field by a digitally recorded female voice (PSM04 system audiometer Interacoustics AD229e; amplifier Interacoustics AP12), in a double-wall sound-treated audiometric suite and in an auditory-only modality. Background noise consisted of a continuous speech-shaped white noise. Subjects were instructed to repeat each stimulus, and the recognition score was calculated as percentage of correct answers.

2.3 | Statistical analysis

We used the statistical package MedCalc (version 12, Marienkerke, Belgium). The Kolmogorov–Smirnov test was used to assess the distribution of the continuous variables examined in the study. Parametric and nonparametric tests were applied depending on data distribution. Significance was accepted for p values <.05.

3 | RESULTS

One-way ANOVA showed that the three groups were age-matched, in that their mean age did not differ significantly ($F [2, 18] = 1.97$; $p = .178$). A Mann–Whitney test did not reveal any statistically significant differences between the SSD and the no-SSD group in the DDE-2 tests (word speed: $U = 48$, $p = .870$; word accuracy: $U = 50$, $p = 1$; non-word speed: $U = 45$, $p = .675$, non-word accuracy: $U = 45.5$, $p = .716$). The distribution of reading performance categories in the two groups with dyslexia was found to be the same on Fisher's exact test ($p = 1$ for the MT subtests "speed" and "accuracy", $p = .650$ for the MT subtest "comprehension").

3.1 | Consonant recognition

The Kolmogorov–Smirnov test showed that the outcome variable "consonant recognition" did not have a normal distribution. Therefore, a Friedman and a Kruskal-Wallis test were applied in order to investigate, respectively, the effect of the within-subjects variable ("noise level") and of the between-subjects variable ("group") on consonant recognition. Post-hoc analysis was performed according to Conover (1999).

As expected, subjects of each group obtained significantly lower consonant recognition scores as noise level became more challenging from quiet to SNR = 0. In the control group, a significant median score decrease (Friedman's $F [2, 38] = 555$, $p < .0001$) was observed both from Quiet to SNR = +10 (Cohen's d = 22) and from SNR = +10 to SNR = 0 (Cohen's d = 32). In the no-SSD group, the median score showed again a significant decrement (Friedman's $F [2, 18] = 114$, $p < .0001$) from Quiet to SNR = +10 (Cohen's d = 1.52) and from SNR = +10 to SNR = 0 (Cohen's d = 1.76). Likewise, in the SSD group a significant progressive decrement (Friedman's $F [2, 18] = 381$, $p < .0001$) was observed from the easiest to the most difficult listening condition (Cohen's d = 2).

Between-group comparisons showed a significant effect of the factor "group" on consonant recognition with all test conditions (Quiet: $\chi (2) = 21.72$, $p < .0001$; SNR +10: $\chi (2) = 18$, $p = .0001$; SNR 0: $\chi (2) = 22.58$, $p < .0001$). As far as the "Quiet" condition is concerned, post-hoc analysis for pairwise comparison revealed a significantly lower consonant recognition score in the SSD group than in the other two (control and no-SSD) groups (Cohen's d = 16 for the control vs SSD comparison, "d" = 1.86 for the no-SSD vs SSD comparison). Similarly, with the "SNR = +10" noise level, the consonant recognition score was significantly worse for the SSD group than in the control and no-SSD groups, whose scores did not differ significantly (Cohen's d = 2 for the control vs SSD comparison and "d" = 2.23 for the no-SSD vs SSD comparison).

In the most challenging condition ("SNR = 0"), post-hoc analysis showed significant differences in all pairwise comparisons: The children with dyslexia in the no-SSD group performed significantly better than those in the control and in the SSD group; the controls had significantly lower scores than the children with dyslexia and no SSD and significantly better scores than the children with dyslexia and SSD (Cohen's d = 6.95 for the control vs SSD comparison and "d" = 2.82 for the no-SSD vs SSD comparison).

In order to investigate a possible interaction between factors, consonant recognition data for the two noisy listening conditions were also analysed by means of a two-way ANOVA, which confirmed the significant effect of "group" ($F [2, 74] = 37.67$, $p < .001$) and "condition" ($F [1, 74] = 62.14$, $p < .001$) on the outcome, and yielded a near-significant Group × Condition interaction ($F [2, 74] = 2.96$, $p = .057$).

A comprehensive representation of within- and between-group results is provided in Figure 1.

4 | DISCUSSION

Our results support the study hypothesis that only children with dyslexia and an associated SSD have an impairment of consonant recognition in noise. Moreover, the performance decrease in this group in the more challenging SNR

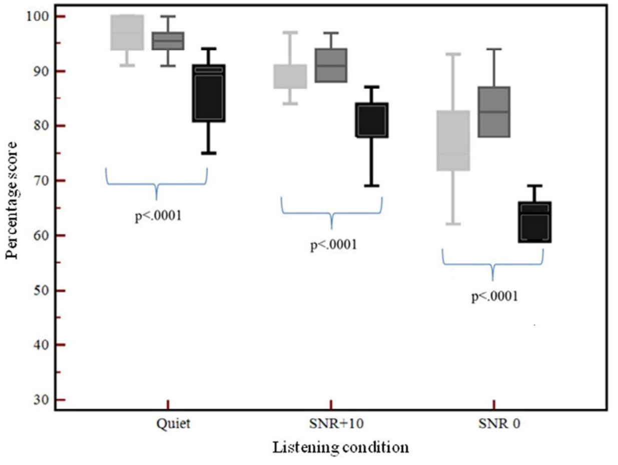

FIGURE 1 Consonant recognition scores in the three groups for all noise levels. Box plots represent median (central horizontal line), 25th and 75th percentile (upper and lower limits) and range (whiskers' ends). Pale grey box plots: control group; dark grey box plots: no-SSD group; black box plots: SSD group

condition was greater than in the other groups, as if both phonological difficulties and difficult listening conditions added up to determine lower scores in children with dyslexia and SSD.

In our study, the SSD group also scored lower than normal in quiet listening conditions, while the no-SSD group showed a performance comparable to that of typical readers.

The few studies in the literature investigating the speech-in-noise abilities of children with dyslexia have found lower performances than those of typical readers. Ziegler et al. (2009) reported that children with learning difficulties perform similarly to age-matched good readers when tested with speech-in-quiet perception tasks, and concluded that only noisy listening conditions cause a performance decrease. Frey et al. (2019) showed that the abnormal speech sound processing (in terms of voicing, place and manners of articulation) of children with dyslexia is not restricted to noisy listening conditions, but also occurs in quiet conditions, consistent with our results.

To our knowledge, this is the first study to investigate the possibility that a co-occurring SSD may contribute to determining the speech-in-noise recognition abilities of children with dyslexia. Children with dyslexia and SSD may have impaired discrimination of basic auditory components of speech sounds, consistent with the phonological theory of dyslexia (Goswami, 2000; Schülte-Korne & Bruder, 2010; Stein, 2019; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Therefore, it is possible that this subgroup has a poor phonological representation and awareness, lacking the ability to map the acoustic signal to the matching phonological category (Lauterbach, Park, & Lombardino, 2017; Loucas, Baird, Simonoff, & Slonims, 2016; Ramus & Szenkovits, 2008; Vandewalle, Boets, Ghesquière, & Zink, 2011). Such difficulties become more evident with stationary noise (as used in our study), which makes it even more difficult to extract spectral and temporal cues.

The auditory processing of subjects with dyslexia during speech-in-noise listening has also been the object of electrophysiological studies that have demonstrated a processing dysfunction in the central auditory pathways, at both brainstem (Chandrasekaran, Hornickel, Skoe, Nicol, & Kraus, 2009; Wible, Nicol, & Kraus, 2002) and cortical level (Frey et al., 2019; Hamalainen, Rupp, Soltesz, Szucs, & Goswami, 2012; Lovio, Naatanen, & Kujala, 2010; Nagarajan et al., 1999). In recent work with cortical evoked auditory potentials, Frey et al. (2019) have shown that in children with dyslexia the N1 component is delayed in stationary noise, thus suggesting a temporal de-organization in adverse listening conditions. In Goswami's (Goswami et al., 2011) “temporal sampling framework” theory, dyslexia originates at the level of oscillatory networks in the auditory cortex, where a primary neural deficit determines impaired processing of temporal features of phonemes, such as amplitude modulation and onset time.

Another important finding of our study was that children with dyslexia and no associated SSD have normal speech recognition abilities, both in noise and in quiet. This supports the hypothesis that the phonological theory cannot entirely explain the pathophysiology of dyslexia, and suggests that other mechanisms could be involved, such as an impairment of visual processing (Schülte-Korne & Bruder, 2010). Consistently, Nittrouer et al. (2018) have found that in children with dyslexia the reading difficulties and the poor speech recognition in noise are independent and cannot be attributed to a single underlying factor. The above-mentioned comprehensive theory by Stein (2019) could explain such heterogeneity of performances: If a magnocellular system dysfunction is common to dyslexia, the variability of clinical presentation and of speech-in-noise recognition abilities may depend on how extensively each subsystem (auditory or visual) is affected.

In conclusion, the speech-in-noise perception difficulties observed in the subset of children with dyslexia with a co-occurring SSD may be caused by the same phonological impairment underlying the two conditions.

The limitations of the study include sample number and a lack of error analysis concerning voicing, place and manner of articulation. Moreover, further studies on this subject should consider a child group with SSD and without dyslexia to help understand the role of SSD in determining consonant recognition abilities.

Finally, our results may allow considerations for both diagnosis and intervention. It would be worthwhile routinely assessing children with dyslexia for a concurrent persistent SSD and for consonant perception skills both in quiet and in noise. The children with the poorest performance are expected to experience speech perception difficulties and a need for increased listening effort in the typically noisy classroom environment. Therefore, they may be candidates to receive specific training to improve discrimination, identification, and categorization of auditory inputs, or to obtain specific support in the classroom, such as phono-isolation or frequency modulation systems to improve SNR.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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