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RUNNING TITLE: PHONOTACTICS AND SLI

The Sensitivity of Children with SLI to Phonotactic Probabilities During Lexical Access

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Abstract

The procedural deficit hypothesis (Ullman & Pierpont, 2005) has been proposed to account for the combination of linguistic and nonlinguistic deficits observed in specific language impairment (SLI). According to this proposal, SLI results from a deficit in procedural memory that prevents children from developing sensitivity to probabilistic sequences, amongst other deficits. We tested the ability of children with SLI to rely on a specific type of probabilities characterizing sequences that occur in a given language: phonotactic probabilities. Twenty French-speaking children with SLI (*M* = 10;1), 20 typically developing children matched for chronological age (*M* = 10;0) and 20 typically developing children matched for receptive vocabulary (*M* = 7;4) performed an auditory lexical decision task. Pseudoword stimuli were built with combinations of either frequently associated phonemes (high phonotactic probability) or infrequently associated phonemes (low phonotactic probability). Phonotactic probabilities had a significant impact on the accuracy and speed of pseudoword rejection in children with SLI, but not in the two control groups. SLI children's greater reliance on phonotactic probabilities relative to typically developing children appears to contradict the PD hypothesis. Phonotactic probabilities may help them to partially overcome their difficulties in developing and accessing the phonological lexicon during spoken word recognition.

Abstract word count: 199

Learning outcomes. After reading this article, readers will understand the importance of sensitivity to phonotactic probabilities in language processing. They will also learn that such sensitivity is preserved in children with SLI. Finally, readers will understand that children with SLI are more prone to use phonotactic information when accessing their lexicon than typically-developing children.

Keywords: SLI, statistical learning, procedural deficit hypothesis, phonotactic probabilities, phonological representations, auditory lexical decision.

1. Introduction

Specific language impairment (SLI) is characterized by extreme difficulty with language acquisition in the absence of mental retardation, frank neurological damage, hearing deficits, or severe environmental deprivation (Bishop, 1992; Leonard, 2014; Tomblin et al., 1997). Children with SLI have deficits in a range of language domains including phonology (Joanisse & Seidenberg, 1998, 2003; Maillart & Parisse, 2006; Ramus, Marshall, Rosen, & van der Lely, 2013), word learning (Gray, 2003, 2004, 2005; Li & McGregor, 2010), and morpho-syntactic skills (Maillart & Schelstraete, 2005; Redmond & Rice, 2001; Rice, Wexler, & Cleave, 1995). Even though the exclusion criteria mentioned above are determinant in SLI diagnosis, there is increasing evidence that children with SLI also exhibit subtle non-linguistic deficits, such as impairments of working memory (Archibald & Gathercole, 2006; Gathercole & Baddeley, 1990), attention (Oram Cardy, Tannock, Johnson, & Johnson, 2010), or motor skills (Hill, 2001; Zelaznik & Goffman, 2010).

In order to account for the combination of linguistic and non-linguistic deficits observed in SLI, some authors have theorized that this neurodevelopmental disorder results from a non-linguistic processing deficit (e.g., Bishop, 1992; Gathercole & Baddeley, 1990; Joanisse & Seidenberg, 1998, 2003; Leonard, 2014; Tallal & Piercy, 1974), but most have failed to explain the heterogeneity of the co-occurring disorders. A possible exception is the hypothesis proposed by Ullman and Pierpont (2005) to account for the full range of linguistic and non-linguistic deficits observed in SLI: the procedural deficit (PD) hypothesis. The central claim of the PD account is that SLI results from a selective deficit of the procedural memory system, which is involved in the acquisition and retention of procedural knowledge. This hypothesis has received increasing attention in the past decade (e.g., Hsu & Bishop, 2014; Lum, Conti-Ramsden, Morgan, & Ullman, 2014), but few studies have sought to characterize the specific markers of this hypothetical deficit in the context of language acquisition itself. In the present study, we examined whether children with SLI develop sensitivity to a hallmark of the adequate functioning of the procedural memory system when processing oral language: phonotactic probability.

1.1. The Procedural Deficit (PD) Hypothesis

The PD hypothesis (Ullman & Pierpont, 2005) is based on the assumption that long-term memory can be divided into two distinct memory systems: declarative and procedural (Squire & Zola, 1996). This distinction is supported by research indicating that the two systems are responsible for different types of learning and have a distinct neurobiological basis. Declarative memory is involved in the explicit learning and storage of past events and facts, and relies on the hippocampus. In contrast, procedural memory is involved in the acquisition and use of implicit motor and cognitive skills, and relies on the striatum of the basal ganglia. The two systems are also differentially involved in language development and processing. The declarative system is thought to be responsible for the development of the mental lexicon, which stores word-specific knowledge. The procedural system, on the other hand, is thought to be involved in the acquisition of various aspects of grammar, including morphology and syntax, but also phonology.

According to the PD hypothesis, SLI is the consequence of structural and functional abnormalities of the brain structures that control the procedural memory system. Support for this hypothesis comes from neuroimaging studies which have found functional abnormalities of the basal ganglia, inferior frontal cortex, and superior temporal cortex in children with SLI compared to normal controls when performing a linguistic task (Liegeois et al., 2003; Neville, Coffey, Holcomb, & Tallal, 1993;Vargha-Khadem et al., 1998).

A number of behavioral studies have given evidence of a deficit in procedural learning in children with SLI, but Ullman and Pierpont (2005)'s PD hypothesis has mainly been tested using non-verbal designs. In serial reaction time tasks – where reduced reaction times to stimuli are taken to indicate learning of sequences – children with SLI generally perform less well than typically developing children (Hsu & Bishop, 2014; Lum, Gelgic, & Conti-Ramsden, 2010; Tomblin, Mainela-Arnold, & Zhang, 2007), but such deficits have not been observed systematically (Gabriel, Maillart, Guillaume, Stefaniak, & Meulemans, 2011; Gabriel, Meulemans, Parisse, & Maillart, 2015; Gabriel, Stefaniak, Maillart, Schmitz, & Meulemans, 2012; Lum & Bleses, 2012). In a recent meta-analysis that focused on SRT tasks only, Lum et al. (2014) showed that the likelihood that children with SLI will learn probabilistic sequences depends on a number of factors, such as the number of exposures to the sequence and the children's age.

Procedural learning in children with SLI has also been tested using non-sequential tasks. Preserved non-verbal procedural learning was found in a pursuit rotor task (Hsu & Bishop, 2014), in a spatial contextual cueing task (Gabriel, Schmitz, Maillart & Meulemans, 2009), and in a mirror-tracing task (Desmottes, Maillart, & Meulemans, 2015). These results were taken to suggest that poor procedural learning in children with SLI might result from a specific difficulty learning sequence-specific information.

1.2. The Importance of Sensitivity to Phonotactics in Language Development

Only a few studies have investigated the possible interference of an implicit sequence learning deficit with the processing of verbal materials in SLI. Language acquisition partly relies on statistical learning of phonological, lexical, and morphosyntactic regularities (see for example Shukla, Gervain, Mehler, & Nespor, 2012), an ability that is thought to be supported by the procedural system (Ullman et al., 1997). Regarding phonology in particular, languages are characterized by regularities in associations between their phonological constituents. In a given language, the rules that determine the sound combinations that may or may not occur in a language are referred to as 'phonotactic constraints', and the likelihood that a given phonological sequence will occur in syllables and words has been termed 'phonotactic probability'.

Sensitivity to phonotactic constraints and probabilities develops during infancy. Nine-month-olds are sensitive to the phonotactic patterns of their native language (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993), and prefer to listen to pseudowords containing legal or high-probability phonotactic sequences over those containing illegal or low-probability sequences (Friederici & Wessels, 1993; Jusczyk, Luce, & Charles-Luce, 1994).

Sensitivity to phonotactic constraints and probabilities influences several aspects of language acquisition and processing in infants and toddlers. First, it partly determines children's ability to detect word boundaries and learn new words. For example, 9-month-olds listen longer to target words when they were previously presented in a sentence context that provided good phonotactic cues (i.e., with low transitional probability at the boundary before and after the target word) than if they had heard them in a context that did not provide such cues (Mattys & Jusczyk, 2001). In a learning task, 18-month-olds look longer at objects that contain phonotactically legal than illegal labels (Graf Estes, Edwards, & Saffran, 2011). They also learn more common sound sequences faster (Graf Estes & Bowen, 2013; Schwartz & Leonard, 1982; Storkel, 2001; Storkel & Rogers, 2000) and earlier in development (Gonzalez-Gomez, Poltrock, & Nazzi, 2013) than rare sound sequences. Second, phonotactic probabilities influence children's ability to encode and maintain a new phonological sequence in memory. In a nonword repetition task, they are more accurate when repeating high- than low-phonotactic frequency nonwords (Coady & Aslin, 2004; Edwards, Beckman, & Munson, 2004; Zamuner, Gerken, & Hammond, 2004). And third, phonotactic probabilities have been shown to be involved in spoken word recognition in toddlers. Using a mispronunciation detection task, MacRoy-Higgins, Shafer, Schwartz, and Marton (2014) showed that 2-yearolds are better able to reject pseudowords that are created by changing one phoneme in words with high phonotactic probabilities than ones that are so created using words with low phonotactic probabilities. According to the authors, this result indicates that words with high phonotactic probabilities are better specified in memory than words with low phonotactic probabilities, leading to higher accuracy when detecting errors in pronunciation. In sum, important aspects of language acquisition are influenced by phonotactics, and sensitivity to this information is – at least partly – underpinned by procedural learning (Aslin & Newport, 2008), which is in turn supported by the procedural memory system (Lum et al., 2010).

1.3. The Influence of Phonotactic Probabilities on Language Processing in Children with SLI

Given that language acquisition partly relies on procedural learning, the linguistic difficulties observed in SLI could be partly explained by poor procedural learning mechanisms. Only a few studies have examined this possibility in children with language difficulties. Children with functional phonological delays (i.e., a specific deficit in the phonological component of language) are able to learn rare sound sequences from sparse neighborhoods to the same extent as vocabulary-matched children (Storkel & Hoover, 2010) and children matched for age (Storkel, Maekawa, & Hoover, 2010). As for SLI children, who exhibit a range of language difficulties beyond phonology, contradictory results have been reported in studies using different tasks. These studies are reported below.

SLI children's ability to rely on phonotactic probability during language processing has mainly been explored through repetition tasks in the English language. Using a nonword repetition task, Munson, Kurtz, and Windsor (2005) found that the sensitivity of children with SLI to phonotactic probability was greater than that of age-matched children, but similar to that of vocabulary-matched children. This result was not completely replicated in two other studies, which found children with SLI and age-matched children to be similarly influenced by phonotactic frequency when repeating nonwords (Coady, Evans, & Kluender, 2010a) and when repeating a target word within a meaningful sentence (Coady, Evans, & Kluender, 2010b).

Sensitivity to phonotactic probability in SLI has also been investigated through the implicit learning of artificial phonotactic rules. In a recent study in French, Mayor-Dubois, Zesiger, Van der Linden, and Roulet-Perez (2014) asked children with SLI aged between 8 and 14 years to draw a picture while listening to a continuous sequence of syllables. The probability of association between particular phonemes and syllables was determined by artificial phonetic rules: some were frequently associated in the sequence, whereas others were infrequently associated. After completing the task, the participants were asked to perform a lexical decision task including pseudowords that were either legal or illegal with respect to the artificial rules used to create the phonological sequences. The results indicated that children with SLI did not take into account phonotactic probabilities when performing the lexical decision task, contrary to age-matched children. A different pattern of results had previously been reported in English by Evans, Saffran, and Robe-Torres (2009). Using a similar procedure but a different task (forced-choice paradigm), the authors found that children with SLI are able to use statistical information to discover word boundaries, but that they require twice as much exposure to the stimuli as age-matched children in order to achieve equivalent performance.

The role of statistical learning in lexical development has been clarified by Mainela-Arnold and Evans (2014). The authors asked children with and without SLI to perform three different tasks: a statistical word segmentation task (same paradigm as in Evans et al., 2009), a gating task (which was supposed to tap into lexical-phonological processing), and a word definition task (in order to examine the activation of the lexical-semantic network). Statistical learning predicted lexical-phonological abilities but not lexical-semantic abilities in both groups. As a consequence, sensitivity to statistical sequential regularities seems particularly critical in order to develop lexical-phonological representations and needs to be further investigated in children with SLI.

1.4. The Present Study

Taken together, the results presented above provide a mixed picture of the ability of children with SLI to rely on phonotactic probabilities during language processing. This ability appears to depend on several factors, including the task used, the language under investigation, the number of learning trials, and the group used as control. In addition, the paradigms used thus far have focused essentially on the ability of children with SLI to extract words from a continuous speech stream and to temporarily maintain a phonological representation in memory. However, phonotactic probabilities also influence spoken word recognition. In a study by Vitevitch and Luce (1999), adults were found to respond faster and more accurately to low probability/density nonwords than high probability/density nonwords in a lexical decision task. According to the authors, nonwords with high probability patterns initiate larger lexical activation than nonwords with low probability patterns, resulting in slower response times and lower accuracy in the lexical decision task[1]. The influence of phonotactic probability on spoken word recognition is evidenced as early as age two (MacRoy-Higgins et al., 2014). Reliance on phonotactic cues might therefore considerably facilitate lexical access for children with SLI (see Mainela-Arnold & Evans, 2014 for a similar proposition), but the question of whether prior learning of high vs. low probability patterns impacts lexical access differentially remains open. Given this context, the present study was designed to address the two following research questions:

Do French-speaking children with SLI rely on phonotactic probability during lexical access?

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[1] Note, however, that the authors did not distinguish between phonotactic probability and neighborhood density in their study: it may be a confounding variable.

To investigate this question, the participants had to perform a lexical decision task with pseudowords containing either high- or low-probability phonotactic transitions. An auditory lexical decision task was chosen as the most suitable to shed light on the basic processes involved in lexical access (Goldinger, 1996). We chose to use pseudowords because they have been shown to be more sensitive to phonotactic probabilities than words (Vitevitch & Luce, 1998). In addition, words convey several other properties that may also interfere with lexical decision (lexical frequency, semantic properties, etc… see Goldinger, 1996 for a review) and prevent or minimize the impact of phonotactic probability when performing the task. Finally, contrary to Mainela-Arnold and Evans (2014) who examined the relationship between statistical learning and *word* recognition in a gating task, focus on pseudoword processing in the present study will shed light on the processes involved in lexical access as independently of children's vocabulary as possible (by keeping phonological neighborhood density constant across conditions).

If children with SLI rely on phonotactic probability during lexical access, they should exhibit higher error rates and longer reaction times to pseudowords with high than with low phonotactic probability, as the high-probability patterns are more "French-like" than the low-probability patterns (Vitevitch & Luce, 1999).

Does this reliance differ from that of typically developing children?

The performance of children with SLI was compared to that of a group of children matched for chronological age and a group of children matched for receptive vocabulary. These comparisons will provide information on the nature of the difficulties of children with SLI.

2. Methods

2.1. Participants

Twenty French-speaking children with SLI (*M* = 10;1; *SD* = 22 months, range = 6;9-13;1), 20 typically developing children matched for chronological age (AMC: age-matched controls;

M = 10;0; *SD* = 22 months; range = 5;8–13;0), and 20 typically developing children matched for receptive vocabulary (VMC: vocabulary-matched controls; *M* = 7;4; SD = 7 months; range = 6;4-8;2) participated in the study. Each child with SLI was matched individually with two typically developing children: one matched for vocabulary, and one matched for chronological age.

Children with SLI were recruited from a special school for children with severe language difficulties in the city of Liège (Belgium), and the children in the two control groups were recruited from mainstream schools near the city of Liège (Belgium). They were diagnosed by a multidisciplinary team based on a medical assessment as well as neuropsychological and psycholinguistic testing. Parents also completed a medical history questionnaire in order to ensure that all children were monolingual French speakers and to screen for previous neurological disorders, neurodevelopmental delay, or sensory impairment. All the participants had hearing thresholds below 20 dB HL at frequencies from 0.25 to 8 kHz.

The linguistic and cognitive abilities of all participants were assessed to ensure that children with SLI had at least two language measures more than 1.25 SD below the mean despite normal intelligence (Leonard, 2014). These tests also allowed us to verify that the control participants had no cognitive or linguistic difficulties. A summary of the results is presented in Table 1.

[Insert Table 1 about here]

Nonverbal intelligence was measured by the Wechsler Nonverbal Scale of Ability (WNV, Wechsler & Naglieri, 2009), and linguistic abilities were assessed by the expressive and receptive subtests of the 'Evaluation du Langage Oral' [Oral language assessment] (ELO, Khomsi, 2001) and 'Langage Oral, Langage Ecrit, Mémoire et Attention' [Oral language, written language, memory and attention] (L2MA2, Chevrie-Muller, Maillart, Simon, & Fournier, 2010) tests for French-speaking children. Finally, the EVIP (Echelle de Vocabulaire en Images Peabody, Dunn, Theriault-Whalen, & Dunn, 1993) receptive vocabulary test, a French adaptation of the Peabody Picture Vocabulary Test, was used to match the children with SLI to children with an equivalent level of vocabulary.

2.2. Stimuli

Two sets of 60 bisyllabic pseudowords with a CVCV syllabic structure, one with high phonotactic probability and one with low phonotactic probability, were created for the purposes of the experiment. The pseudowords' phonotactic probabilities were computed from the frequency of their constituent biphones, as proposed by Storkel (2004; see also Majerus et al., 2002). Biphone frequency was estimated from the Manulex-Infra database of French vocabulary for children (Peereman, Lété, & Sprenger-Charolles, 2007). This database provides token frequency of all French biphones: that is, the frequency of each biphone occurring in the language weighted by the lexical frequency of the words in which they occur, according to their position within words. To create the two sets we selected a set of biphones from the most frequent 25% of biphones and from the least frequent 25% of biphones in French in each of the two positions (initial and final). We then combined the most frequent biphones in initial and final positions to form the high phonotactic probability stimuli, and the least frequent biphones in initial and final positions to form the low phonotactic probability stimuli. Finally, we ensured that the central biphone constituted by the second and third phonemes (e.g., the /al/ sequence in /ma.ly/) was legal in French, and either frequent (high phonotactic probability condition) or rare (low phonotactic probability condition). Importantly, we ensured that the mean number of phonological neighbors for each pseudoword (provided by the phonological neighborhood Lexique Toolbox generator, New & Pallier, 2001) did not differ between the two conditions, $t(118) = 1.46$, $p = .15$. Stimuli were recorded by a female native speaker of French on a Zoom H2n microphone. An overview of these stimuli is presented in Table 2, and the full set of stimuli is presented in Appendix A.

[Insert Table 2 about here]

Statistical analyses indicated that the two sets of pseudowords significantly differed in terms of the phonotactic probability of the initial biphone, $t(118) = 8.60$, $p < .001$, the central biphone, $t(118) = 3.08$, $p = .003$, and the final biphone, $t(118) = 3.56$, $p < .001$. The summed frequency of biphone phonotactic probability in initial, median and final position was also higher in the high phonotactic probability condition than in the low phonotactic probability condition, $t(118) = 9.90$, $p < .001$.

For the purpose of the lexical decision task, 120 words were included in the task. They were all bisyllabic nouns with a CVCV structure, and they were matched to pseudowords in terms of phonotactic probability (see Table 2). Their mean frequency was 54.17 occurences per million (Manulex[2], Lété, Sprenger-Charolles, & Colé, 2004).

Finally, since the task was long and demanding for children with SLI, the full set of items (i.e., 120 items) was divided into two lists, with the same number of words (n = 60) and pseudowords (n = 60) and the same proportions of stimuli with high (n = 60) and low (n = 60) phonotactic probability in each list.

2.3. Procedure

The participants were tested individually in a quiet room in their school. Stimulus presentation and data collection were controlled using E-Prime software (version 2, Schneider, Eschmann, & Zuccolotto, 2002). The participants were seated in front of a Sony Vaio laptop screen with Laptec headphones over their ears. In order to make the lexical decision task attractive and easier to understand for children, it was described as a game. They

[2] Most of the words were not indexed in the French lexical databases that provide information about age of acquisition (Ferrand, Grainger, & New, 2003; Lachaud, 2007). Manulex (Lété, Sprenger-Charolles, & Colé, 2004) provides frequency counts for words from a corpus of French primary school reading books.

were presented with a little flowerpot named "Florie" that was learning to speak French. They were told that Florie would tell them words, which would sometimes be "true" words, and sometimes they would be "alien" words. They were asked to decide as quickly as possible whether the presented words were "true" by pressing the "smiley" key on the keyboard, or "alien" by pressing the red cross key on the keyboard.[3] The subject's response (i.e., word vs. nonword) and response latency were recorded.

The timing of each trial was as follows: Simultaneous appearance of (1a) the little flowerpot at the center of the screen and (1b) an auditory stimulus through headphones at a comfortable listening level, immediately followed by (2) the appearance of the two response cues beneath the flowerpot picture (a smiley in the bottom right-hand corner and a red cross in the bottom left-hand corner) for a maximum of 5000 ms to indicate to the participants that they could give their answer by pressing the appropriate key, and finally (3) the presentation of a blank screen for 1000 ms.

Each participant was administered the two lists of 120 items, and cognitive and linguistic tests were administered between the two lists. They completed 12 practice trials (including six words and six pseudowords) representative of the experimental stimuli before completing the two experimental lists without feedback. The order of list presentation was counterbalanced, and the order of presentation of the items within each list was randomized.

3. Results

3.1. Data Analyses

Two pseudowords were eliminated from the analysis because of error rates more than 3 SDs from the mean (/motɔ̃/: 39%; /molɛ̃/: 45%). In addition, three participants with SLI were excluded from data analyses because of their high error rates overall (81.67%, 82.50%, and

[3] A red cross and a smiley were stuck on the appropriate keys on the keyboard (q and p keys, respectively) to help the participants locate the appropriate keys.

95.83%). The results of the six participants matched to these three children with SLI were also discarded before performing the analyses. Finally, RTs were log-transformed to correct a rightward skew (Ratcliff, 1993).

Two dependent measures were used to test sensitivity to phonotactic probability: the percentage of pseudowords correctly rejected (accuracy) and the time needed to reject them correctly (RTs) as a function of the phonotactic probability (high or low)

The analyses on accuracy and RTs (for correct rejections of pseudowords only) were performed using linear mixed-effect models, which make it possible to simultaneously take into account random effects of participants and items (Baayen, Davidson, & Bates, 2008). A generalized linear mixed-effects model analysis was carried out using the LmerTest package (Kuznetsova, Brockhoff, & Christensen, 2014) in the statistical software R (Version 3.0.2, R Development Core Team, 2012), with two fixed factors (Probability: high vs low; Group: SLI, AMC, VMC) and their interaction, and two random effects for the intercept (participants and items).

3.2. Accuracy

Figure 1 sets out the mean percentages of correctly rejected pseudowords by group and phonotactic probability.

[Insert Figure 1 about here]

The model revealed a main effect of group, $F(2, 82) = 26.88$, $p < .001$. Children with SLI ($M = 82.52\%$) were less accurate than children matched for age ($M = 91.95\%$, $p < .001$) and for vocabulary ($M = 88.24\%$, $p < .001$), but the two control groups did not differ from each other, $p = .072$. The main effect of probability was significant, $F(1, 116) = 4.51$, $p = .036$, and interacted with group, $F(2, 5501) = 3.42$, $p = .033$. Planned comparisons indicate that children with SLI were less successful at rejecting high phonotactic probability pseudowords than low phonotactic probability pseudowords, $F(1, 116) = 6.47$, $p = .012$, but not age-matched children, $F(1, 116) = 0.05$, $p = .83$, or children matched for vocabulary, $F(1, 116) = 2.83$, $p = .095$.

3.3. Latencies

Latencies were measured from the offset of the target items, since the pseudowords in the high phonotactic probability condition took slightly longer to pronounce than the stimuli in the low phonotactic probability condition (mean duration of 506 vs. 557 ms; $t(112) = 3.79$, $p < .001$). As a consequence, measuring RTs from the onset of target presentation would have biased the results. The mean RTs for correct responses to pseudowords as a function of the group and probabilities are represented in Figure 2.

[Insert Figure 2 about here]

The results indicated a main effect of group, $F(2, 78) = 11.32$, $p < .001$. Children with SLI ($M = 840$ ms) were faster than children matched for age ($M = 904$ ms, $p < .001$) but were not faster than children matched for vocabulary ($M = 871$ ms, $p = .62$)[4]. However, the two control groups did not differ from each other ($p = .40$). The model also revealed a main effect of probability, $F(1, 112) = 11.45$, $p < .001$, which significantly interacted with group, $F(2, 4884) = 3.49$, $p = .031$. Planned comparisons showed that children with SLI responded more slowly to pseudowords with high phonotactic probability than to those with low phonotactic probability, $F(1, 110) = 13.76$, $p < .001$, unlike vocabulary-matched children, $F(1, 113) = 2.58$, $p = .11$, or age-matched children, $F < 1$.

[4] This speed/accuracy trade-off was not observed for word processing. The main effect of group was significant on accuracy, $F(2, 91) = 12.38$, $p < .001$: Children with SLI were less accurate than children matched for vocabulary, $t = 3.93$, $p < .001$ and for age, $t = 4.02$, $p < .001$. However, there was no effect of group on RTs, $F(2, 77) = 1.71$, $p = .19$.

3.4. Additional analyses

Given that the pseudowords varied in terms of number of neighbors, we tested a posteriori the effect of phonological neighborhood density on lexical access. Neighborhood density affected neither error rates, nor response latencies (both Fs < 1), and there was no interaction between neighborhood density and group (for accuracy: $F < 1$, for latencies: $F(2, 4883) = 1.81$, $p = .16$).

In addition, an analysis of RTs and error rates to pseudoword targets shows that chronological age, score on the EVIP test or score on the ELO vocabulary production test do not explain significantly pseudoword processing scores in vocabulary matched controls (all Fs < 1). However, score on the ELO vocabulary reception test tends to explain accuracy in pseudoword rejection, $F(1,14) = 4.05$, $p = .064$.

4. Discussion

Children with SLI have severe and persistent difficulties with language acquisition, which are often associated with non-linguistic deficits. The procedural deficit hypothesis was proposed to account for these disorders: its core suggestion is that SLI results from abnormalities in the brain structures underlying the procedural system, which are highly associated with the ability to identify probabilistic sequences in the environment (Ullman & Pierpont, 2005). The aim of the present study was to examine whether children with SLI develop sensitivity to the probability of association of phonemes in their native language, and more particularly whether they rely on this information during lexical access to the same extent as age-matched or vocabulary-matched children.

The results showed that only children with SLI were significantly influenced by phonotactic probability when performing a lexical decision task. Pseudowords with high phonotactic probability were more difficult to process than pseudowords with low phonototactic probability: they were rejected less accurately and more slowly. As such, the frequent combination of phonemes in the high phonotactic condition constitutes a kind of trap for children with SLI: they rely more heavily than their peers on statistical information during lexical access, and reliance on this information interferes with the lexical decision because items with high phonotactic probability are generally real words. As a consequence, children with SLI tend to reject them less accurately and take more time to correctly reject them. Thus, not only do they develop sensitivity to phonotactic probability, but also they rely on this sensitivity when making a decision about an item's lexicality.

To our knowledge, this is the first report of enhanced sensitivity to phonotactic probability in children with SLI in comparison to typically developing children. At least two differences between our study and earlier studies may explain the differences in the patterns of results. First, earlier studies have found children with SLI to display similar sensitivity to phonotactic probability as do controls on a nonword repetition task (Coady et al., 2010a, 2010b; Munson et al., 2005). However, although both tasks require the processing of novel phonological strings, the nonword repetition task involves an additional motor component. SLI children perform particularly poorly on this task (Graf Estes, Evans, & Else-Quest, 2007) most likely because of the articulatory complexity of some stimuli (Bishop, North, & Donlan, 1996). By definition, sequences of phonemes of low phonotactic probability correspond to less trained sequences of articulator movements. Therefore, phonotactic probability could also impact the efficiency of motor program of sounds sequences in production tasks (Bybee and Hooper, 2001)[5]. As a consequence, results from receptive tasks may be more representative of the mechanisms involved in language perception, and thus more appropriate to draw on investigating the ability of children with SLI to make use of phonotactic probability during language processing.

[5] Note that this is not the sole driving force behind frequency effects in production, see for example Plante, Bahl, Vence, and Gerken (2011).

Second, another study of French-speaking children with SLI found children with SLI to be less sensitive to phonotactic frequency in a task based on the implicit learning of artificial phonotactic rules (Mayor-Dubois et al., 2014). The children in that study had to learn artificial rules, whereas the rules tested in the present study are those of the children's native language. The artificial learning paradigm might thus underestimate the ability of children with SLI to develop sensitivity to phonotactic probabilities. In line with this argument, the study of Evans et al. (2009) showed that when additional trials were provided to children with SLI, they could learn these probabilities. Learning artificial rules might be difficult for children with SLI, while the use of the rules used in their native language might better reflect their sensitivity to phonotactic probability.

Our findings do not appear to fit with Ullman and Pierpont's (2005) hypothesis that SLI can be explained by a procedural deficit wherein grammar is highly impaired while vocabulary is relatively spared. On the contrary, our results suggest that children with SLI are more prone to rely on phonotactic probability than vocabulary-matched children during lexical access. Therefore, an explanation of the performance of children with SLI exclusively based on the PD hypothesis is not sustainable. The present study suggests that the developmental trajectory of phonological representations in children with SLI differs from that of typically developing children. Several theories have focused on the prominent role of phonological deficits in SLI (e.g., Gathercole & Baddeley, 1990; Joanisse & Seidenberg, 1998, 2003; Tallal & Piercy, 1974) but these theories did not provide for an in-depth analysis of SLI children’s ability to process the regularities in associations between phonological constituents.

One hypothesis is that the format of phonological representations in children with SLI is of a different nature from that of controls: they are able to capture the regularities of the language, but they have difficulties to abstract rules from the language input (see Gopnik &

Goad, 1997, for a similar account of the morphological deficit in children with SLI). Beckman, Munson, and Edwards's (2007) model of speech-sound knowledge proposes that phonological knowledge is multi-level, and that there is a developmental progression from more specific and concrete knowledge to more abstract knowledge of sound structure (see Pierrehumbert (2003) for a similar proposition). According to Coady et al. (2010a, see also Munson, Edwards, & Beckman, 2012), children with SLI experience difficulties in the abstraction of a "phonological grammar" from speech. These difficulties are observed in the nonword repetition task, where children with SLI are poorer than their chronological age peers at generalizing the correct phoneme production to unfamiliar or unattested sequences (Munson et al., 2005). The possibility for typically developing children to rely on abstract phonological representations allows them to form representations for novel strings more efficiently than if these strings were interpreted solely relative to existing articulatory and acoustic representations. By contrast, the difficulties experienced by children with SLI in generalizing sublexical patterns over the lexicon prevents them from repeating sequences in reference to their lexical knowledge, leading to more mistakes when repeating infrequent patterns in comparison to their peers. Therefore, the increased processing of phonotactic probabilities during lexical access observed in the present study in children with SLI might result from the difficulty they have abstracting phonological representations derived from the processing of acoustic parameters.

Another hypothesis is that the lexical representations of children with SLI are of lower quality than that of the controls. Claessen, Leitão, Kane, and Williams (2013) have already shown that children with SLI have lower quality phonological representations than younger children matched for language: they are less able than their peers to reject inaccurate productions of multi-syllabic words in an auditory lexical discrimination task. Despite the close match between the scores of the two groups on the EVIP test of vocabulary (Dunn et al.,

1993) based on the quantity of lexical entries, the performance of the children with SLI on the ELO test (Khomsi, 2001) was poorer than that of the two groups of controls for both receptive and expressive vocabulary. The analysis of lexical decisions on words also indicates that the children with SLI were less accurate overall than the vocabulary-matched children when deciding whether a word exists or not (82.52% vs. 88.24% correct responses respectively, $t(1412) = 3.93$, $p < .001$). The score on the EVIP test, which is typically used as a matching measure when creating a control group of children matched for receptive vocabulary in French (Leclercq, Maillart, & Majerus, 2013; Maillart, Schelstraete, & Hupet, 2004; Pizzioli & Schelstraete, 2011) may not be sensitive enough to reveal the more complex qualitative differences between the groups in the richness of lexical phonological representations. Children with SLI might rely more heavily on phonotactic probability than typically developing children because their phonological representations are of lower quality, imprecise or because the mechanisms involved in lexical access are different. Our study does not make it possible to distinguish between these hypotheses, and further studies are necessary to test them.

SLI children's greater reliance on phonotactic probability in comparison to typically developing children might reflect a compensatory mechanism that they have developed in an attempt to overcome their difficulties with developing and accessing phonological representations. It is indeed possible that vocabulary-matched children rely more on lexical representations to perform the task compared to children with SLI. According to Vitevitch and Luce (1998), spoken word recognition implies the activation of a sublexical and a lexical level of representation, whose activation is influenced by phonotactic probability and neighborhood density, respectively. By keeping the number of phonological neighbors constant in both conditions (high and low phonotactic probability), we sought to exclusively shed light on the influence of phonotactic probability on pseudoword processing. Since the lexical decision task primarily requires the activation of lexical knowledge, one hypothesis is that typically developing children mainly rely on their phonological lexicon when performing the task. To our knowledge, the impact of phonotactic probability on lexical decision has been reported only in adults (Vitevitch & Luce, 1999), even though sensitivity to phonotactics during spoken word recognition has also been evidenced in toddlers with another paradigm (MacRoy-Higgins et al., 2014).

In parallel, given the difficulties children with SLI have in developing abstract phonological representations and accessing phonological representations in memory in comparison to vocabulary-matched children (Claessen & Leitão, 2012; Claessen et al., 2013; Maillart et al., 2004), they might rely more heavily than their peers on sublexical processes when performing lexical decision tasks. Young children's sensitivity to phonotactic probability is generally considered to be derived from bottom-up processing of speech, particularly since their lexicon only provides limited knowledge to extract words from speech (Cutler,1996; Jusczyk, 1997). In line with this idea, Seiger-Gardner and Schwartz (2008) have shown that children with SLI are more likely to rely on phonological information than semantic information during lexical access.

The present study was not designed to test the effect of neighborhood density on lexical access, but the pseudowords included in the experiment varied on this measure. This variability made it possible to test the effect of phonological neighborhood density on lexical access afterwards. Neither the neighborhood density effect, nor the interaction between neighborhood density and group were significant. These results do not make it possible to draw conclusions with respect to the involvement of the sublexical vs. lexical levels of processing in a lexical decision task. In addition, scores on vocabulary tests tended to explain pseudoword processing scores in vocabulary matched controls. The latter result suggests that the controls might rely on different information than children with SLI when performing the task: SLI children's high level of sensitivity to phonotactics, in comparison to the control group, might reflect a greater reliance on bottom-up cues when accessing the lexicon. Additional studies are needed to further investigate this hypothesis.

Increased sensitivity to phonotactics during lexical access is not necessarily an indicator of adequate processing of oral language. The reliance of children with SLI on phonotactics might be an efficient strategy to discriminate between words and pseudowords, but an inefficient strategy when learning new words. According to Erickson and Thiessen (2015) vocabulary learning is also supported by the implicit system. Noting that children with SLI have a deficit with respect to extracting chunks from the input (e.g., Lum et al., 2010), Erickson and Thiessen (2015) suggest that poor lexical representations arise from a more general deficit in statistical learning abilities. The significant correlation between statistical learning and vocabulary in typically developing children but not in children with SLI reported by Evans et al. (2009) supports this argument. Atypical processing of phonotactic probabilities might prevent them from developing adequate lexical representations and, more generally, interfere with language development. In line with this hypothesis, children with SLI have been shown to experience greater competition from words with similar phonological sequences in spoken word recognition and production tasks (Mainela-Arnold, Evans, & Coady, 2008; McMurray, Samelson, Lee, & Tomblin, 2010; Seiger-Gardner & Brooks, 2008), which interferes with lexical acquisition. As a consequence, the particular sensitivity of children with SLI to phonotactic probability during lexical access might help them to process some aspects of oral language but not others.

In conclusion, the present study shows for the first time that children with SLI rely on phonotactic probability during lexical access, unlike control children matched with respect to age or vocabulary. Typically-developing children may be more influenced by lexical knowledge than children with SLI when performing a lexical decision task, but additional studies are needed to test this hypothesis. The reliance of children with SLI on phonotactic probability might reflect a strategy that allows them to compensate for their difficulty activating lexical information during language processing.

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Highlights

Spoken word recognition involves the processing of phonotactic regularities

We examined the ability of children with SLI to rely on these regularities

They were more influenced by phonotactic regularities than control children

SLI does not result from a deficit in the detection of statistical regularities

Table1

Table 1.

Group characteristics and performance on cognitive and language measures (standard deviations in parentheses)

		SLI (*n* = 20)	AMC (*n* = 20)	VMC (*n* = 20)
Chronological age (in months)		121 (22)	120 (22)	88 (7)
WNV Nonverbal IQ		98.10 (9.91)	107.79 (11.38)	105.05 (10.41)
EVIP lexical age (in months)		102 (29)	164 (62)	101 (27)
ELO				
Receptive vocabulary	% acc	78.50 (10.27)	92.19 (7.06)	85.00 (5.38)
	z-score	-1.61 (1.42)	0.72 (0.87)	0.60 (0.48)
Expressive vocabulary	% acc	55.90 (14.36)	76.63 (9.20)	74.70 (7.74)
	z-score	-1.22 (1.04)	0.40 (0.89)	1.46 (0.83)
Syntactic comprehension	% acc	56.88 (16.68)	80.47 (6.80)	66.41 (16.44)
	z-score	-1.72 (1.75)	0.76 (0.74)	2.62 (1.89)
Syntactic production	% acc	50.00 (21.50)	93.50 (8.37)	82.40 (12.47)
	z-score	-4.55 (2.88)	0.93 (0.69)	1.01 (0.62)
L2MA2				
Pseudoword repetition	% acc	39.75 (14.28)	68.65 (8.14)	73.25 (14.17)
	z-score	-3.72 (1.57)	-0.95 (0.91)	0.87 (1.66)
Sentence repetition	% acc	47.42 (18.87)	85.51 (9.97)	79.39 (15.04)
	z-score	-4.01 (2.20)	-0.08 (1.00)	-0.35 (1.23)

Note. EVIP: Echelle de Vocabulaire en Images Peabody; ELO: Evaluation du Langage Oral; L2MA2: Langage oral, langage écrit, mémoire, attention, 2ème version. % acc : Percentage of correct responses.

Table2

Table 2.

Mean biphone frequency and number of phonological neighbors for pseudowords and words (standard deviations in parentheses)

	Pseudowords			Words
Phonotactic probability	Low	High	Overall	
N	60	60	120	120
Initial biphone	1139 (663)	5705 (4058)	3422 (3693)	3384 (3650)
Median biphone	1412 (1376)	2808 (3228)	2110 (2568)	2338 (2108)
Final biphone	710 (696)	1676 (1983)	1193 (1557)	1193 (1557)
Summed frequency	1848 (659)	7305 (4050)	4576 (3982)	4578 (3841)
Phonological neighbours	12.73 (6.50)	14.73 (8.37)	13.73 (7.52)	13.34 (6.09)

Figure1

Figure 1. Percentages of correctly rejected pseudowords by group and phonotactic probability. Error bars represent standard errors.

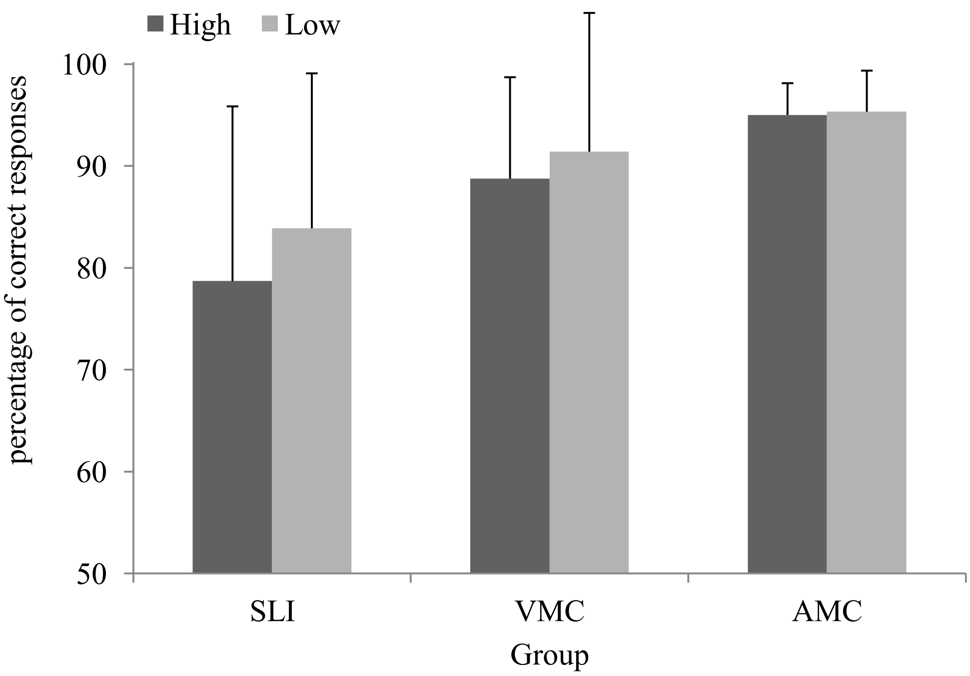
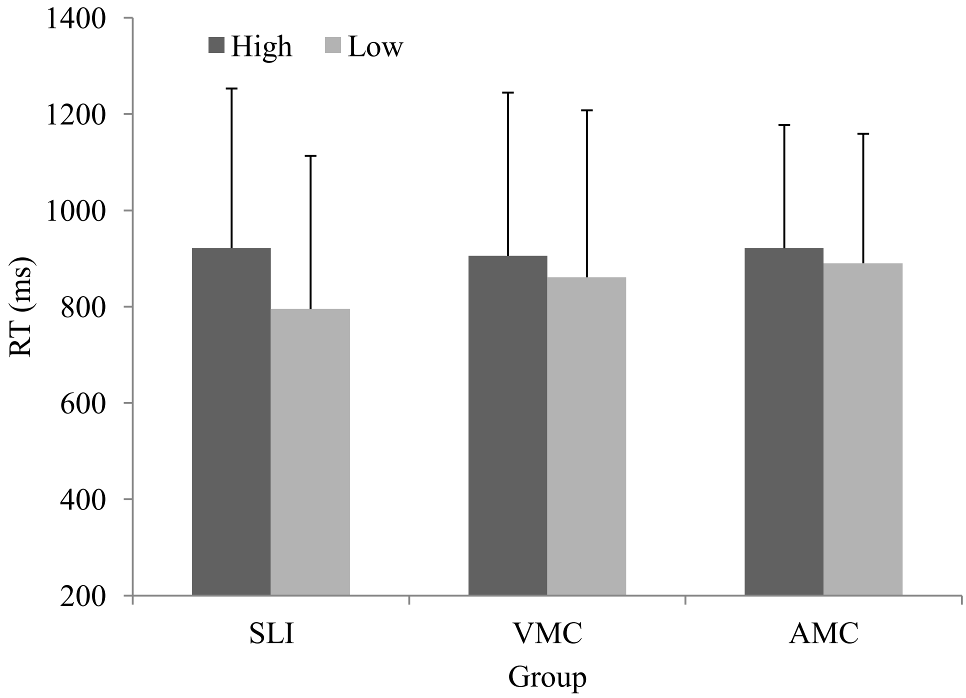


Figure2

Figure 2. Mean RTs for correctly rejected pseudowords by group and phonotactic probability. Error bars represent standard errors.



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