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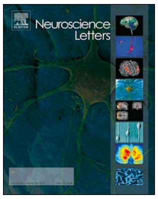

Research article

Adults with Specific Language Impairment fail to consolidate speech sounds during sleep

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ABSTRACT

Specific Language Impairment (SLI) is a common learning disability that is associated with poor speech sound representations. These differences in representational quality are thought to impose a burden on spoken language processing. The underlying mechanism to account for impoverished speech sound representations remains in debate. Previous findings that implicate sleep as important for building speech representations, combined with reports of atypical sleep in SLI, motivate the current investigation into a potential consolidation mechanism as a source of impoverished representations in SLI. In the current study, we trained individuals with SLI on a new (nonnative) set of speech sounds, and tracked their perceptual accuracy and neural responses to these sounds over two days. Adults with SLI achieved comparable performance to typical controls during training, however demonstrated a distinct *lack* of overnight gains on the next day. We propose that those with SLI may be impaired in the consolidation of acoustic-phonetic information.

1. Introduction

Specific Language Impairment (SLI; also known as language learning disability) is a common idiopathic condition that affects an estimated 7% of the U.S. population [1]. The disorder is traditionally associated with impaired acquisition of grammar in childhood [2], however, subtle deficits in speech perception are found to persist throughout development [3–5]. Speech perception deficits are often linked to poor speech sound representations, that is, the mental instantiation of the sounds of speech, such as/d/or/u/. Substantial research suggests that impoverished speech representations may be central to the SLI etiology, and that the consequent inefficiency in speech processing prevents the timely acquisition of grammar [6,7]. Although several theoretical accounts now consider impoverished speech sound representations to be a hallmark of SLI, the precise mechanism(s) by which these representations become impoverished remains unknown. In the current investigation, we propose that differences in overnight consolidation, potentially driven by atypical sleep, contribute to atypical speech sound representations in SLI.

Sleep's importance in language learning is rapidly gaining empirical support [8–10]. One group of studies that track changes in perceptual ability on a trained nonnative contrast (dental/d̪/and retroflex/ɖ/stops in Hindi) suggests that sleep is crucial for forming new, functional speech sound categories [11–13]. For example, a ~12-h interval containing sleep, but not a comparable period of wake state, is observed to enhance accuracy on perceptual tasks and promote cross-talker generalization [11,12]. In a subsequent study [13], sleep duration was measured with a commercial EEG headband [14], and changes in neural sensitivity to the contrast were measured using the mismatch negativity (MMN) response of the electroencephalogram (EEG) [15]. MMNs are evoked by presenting a train of stimuli in an oddball paradigm, and the magnitude of the MMN response is considered a measure of pre-attentive detection of the designated oddball. Sleep duration was found to predict overnight changes to perceptual ability on a trained nonnative contrast. Moreover, the magnitude of behavioral changes correlated with changes in MMN amplitude. In other words, overnight changes to behavior seem to reflect changes in neural sensitivity to the distinctions between the trained sounds.

Interestingly, several lines of research suggest that SLI is associated with atypical EEG patterns during sleep [16,17], inviting the suggestion that offline consolidation may be impaired in SLI [18–21]. Therefore, the primary goal of this study was to determine if individuals with SLI demonstrate atypical patterns of overnight consolidation of speech information. We present an extension of data published previously on

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typical adults [13], to include a concurrently collected dataset on adults with a history of SLI.[1] In the present study, we ask 1) if adults with SLI can be comparably trained to perceive nonnative speech with respect to controls, and 2) if so, does the SLI group demonstrate heightened sensitivity to the trained contrast following sleep-mediated consolidation, and finally, 3) does neural sensitivity, as measured by the MMN response, track with changes in behavioral sensitivity? If individuals with SLI show general deficits in learning non-native speech sound information, this points to a lingering issue with phonological learning and the component processes thereof. If initial training performance is typical, but overnight consolidation and retention of target information is atypical, a different source of the phonological deficit in SLI is implicated, namely one in which offline overnight consolidation plays a key role. Finally, obtaining MMN responses to the same contrast allows us to track training-induced changes to neural sensitivity that are independent of behavioral task performance. This is crucial, given that language impairment, by its nature, carries the potential that differences in metalinguistic task *strategy* might lead to differences in behavioral measures of perception. The answers to these questions have significant etiological and clinical consequences, in that the linguistic challenges experienced by those with SLI may reflect an impairment in the memory processes crucial to building functional linguistic categories.

2. Materials and methods

2.1. Participants

Participants provided informed written consent in accordance with the University of Connecticut Institutional Review Board. All participants were monolingual, native speakers of American English, 18–24 years of age. Participants reported no history of neurological, socioemotional, or attention disorders, and passed a pure tone hearing screening. Participants obtained a standard score > 85 for nonverbal IQ on the Wechsler Abbreviated Scale of Intelligence [22], and were not on mood-altering medications, at the time of the study. See Table 1 for assessment and demographic profiles of our participants.

Control (n = 25): The description of the control cohort has been reported previously [13]. In addition to meeting all inclusionary criteria, those included in this cohort were good readers (obtained scores no lower than 1 SD below the mean on reading measures).

SLI (n = 19): Participants in the SLI cohort reported a history of receiving language and/or reading services, and were identified as being language impaired by the procedures described in [23]. This method has been widely used to identify adults with SLI [e.g. 24,25] and is emerging as the standard by which researchers identify adults with SLI. Adults who met criteria for SLI, but who also met criteria for developmental dyslexia [26,27], were excluded from analyses, as partially distinct mechanisms are thought to underlie the phonological deficits observed in SLI and dyslexia [28].

Our sample size was pre-determined prior to study completion based on a power analysis conducted for our repeated measures design ($\alpha = 0.05$, 2-tailed), assuming bivariate normal distributions of variables and an r^2 of 0.5. This calculation suggested a minimum of 16 participants/Group, and we therefore aimed to enroll 22–26 participants/Group, anticipating the potential for attrition of up to 20%. To note, this sample size is comparable to others who have investigated a consolidation mechanism in SLI [18,19].

Table 1
Participant demographics.

		Control (n = 25)	SLI (n = 19)
Demographics			
	Age	20.52 (1.33)	20.60 (1.50)
	Sex	15 F, 10 M	15 F, 4 M
	Handedness	27 R, 1 L	18 R, 1 L
Assessment scores			
WASI	Nonverbal IQ	110.4 (9.80)	100 (7.67)*
WRMT – III	Word ID	108.24 (8.16)	98.11 (8.31)*
	Word Attack	110.96 (9.92)	97.05 (12.02)*
	Passage Comprehension	109 (8.98)	95.33 (12.61)*
TOWRE	Sight Word Efficiency	105.72 (8.24)	95 (11.36)*
	Phonemic Decoding	112.76 (7.83)	96.95 (10.16)*
	Total	110.76(6.73)	95.47 (11.52)*
Language screen	Spelling (raw)	13.24 (6.27)	7.32 (1.87)*
	Modified Token Test (raw)	39 (6.15)	35.05 (4.07)
	Index	−1.42 (.86)	0.44 (.44)*
WAIS-IV	Digit Span Composite	11.56 (3.32)	8.95 (2.01)
BRIEF	Global Executive Composite	47.79 (6.94)	51.56 (7.72)
RAN	Numbers	112.44 (6.12)	110.78 (6.39)
	Letters	112.08 (6.21)	108.89 (5.25)
	2-Set	114.92 (8.72)	112.11 (7.05)

Participant demographic and assessment profiles. Tests were administered and scored by the first author or a trained graduate student, and rescored by one of two trained undergraduate students. Discrepancies in scoring were flagged by the second scorer and resolved by the first author.

WASI: Wechsler Abbreviated Scale of Intelligence [22]; WRMT-III: Woodcock Reading Mastery Tests – III [47], TOWRE: Test of Word Reading Efficiency [38]; RAN: Rapid Automatized Naming Test [27]; WAIS-IV: Wechsler Adult Intelligence Scale – Fourth Edition [39]; BRIEF: Behavior Rating Inventory of Executive Function—adult Version [40].

*Denotes statistically significant difference between Control and SLI at .05 level after Bonferroni correction.

Note: Our samples differed on nonverbal IQ, due to above-average IQ by Controls, combined with average performance by SLI. This is consistent with the proposal that a relative weakness in nonverbal IQ is an inherent characteristic of SLI [41].

2.2. Procedures

The study took place on two consecutive days, in the evening (7–9 PM; Day 1), and the following morning (8 10 AM; Day 2; see Fig. 1a). On Day 1, participants completed screening measures, followed by an EEG/ERP pre-training session for a baseline biomarker of discrimination ability, defined as the ability to detect a difference between the two sounds being trained. The session ended with category identification training of the nonnative contrast, in which participants were presented with two ‘words’ (/d̪ug/and/ɖug/) to map onto novel visual objects. During trials, participants were played a ‘word’, and were asked to indicate the object to which the word belongs. We measured category identification ability at two time points: immediately after training, and on the next day. We also tracked perceptual ability through behavioral discrimination (indicating if two sounds played in sequence are the same or different) at three time points: immediately before training, immediately after training, and on the next day. As participants were trained in identification, post-training discrimination scores reflect cross-task generalization of phonetic learning.

On Day 2, behavioral reassessments were followed by a second EEG/ERP session, and then by the administration of the remaining language/reading tests. As per journal guidelines, procedures described elsewhere are omitted from the present paper. Please refer to [13] for methodological details pertaining to the perceptual training of nonnative speech, and the recording and preprocessing procedures for the EEG/ERP experiment.

Participants were provided with commercial sleep-monitoring

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[1] As the present focus is not whether or not the overnight effects are sleep-specific (as previously established in [11,12]), but rather whether overnight effects differ between SLI and controls, we did not include a wake-state control for the current work.

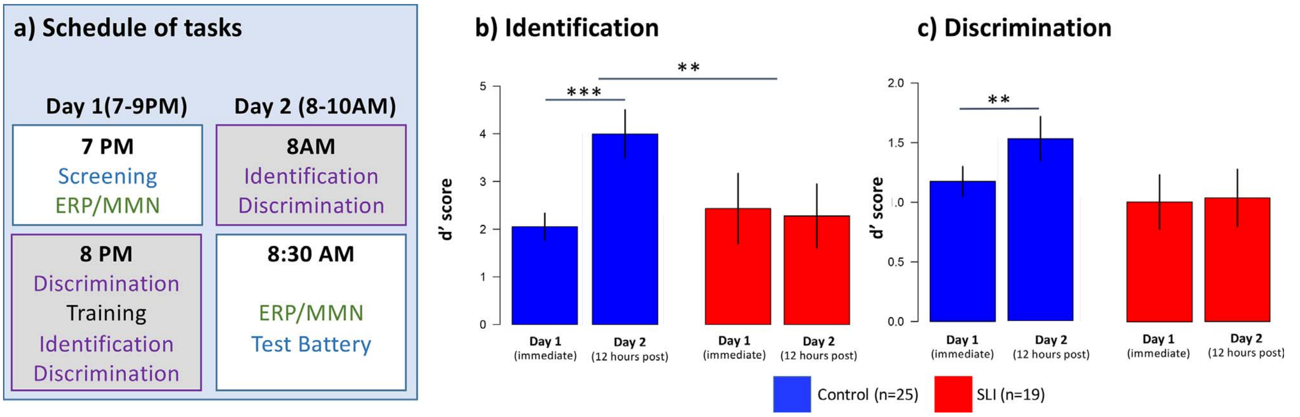


Fig. 1. Behavioral performance on perceptual tasks after training. a) The schedule of tasks according to the experiment protocol. b) Controls and SLI demonstrate comparable performance immediately after training. Following a period of sleep (Day 2), Control participants demonstrate a significant increase in Identification, whereas the SLI group does not. c) Controls and SLI are statistically equivalent in Discrimination immediately after training. Control participants make gains overnight that is lacking in SLI. Error bars denote standard error of the mean. ** denotes statistical significance at .01 level, *** denotes statistical significance at .001 level.

headbands to record sleep duration between the two test sessions [14]. While polysomnography (PSG) conducted by a trained technician is considered the gold standard for sleep research, an advantage in a commercial device is that the participants are able to obtain sleep in their natural environment. The particular device used in the current study has been independently validated to obtain sleep/wake measures at an average of 92% agreement with PSG scores read by trained technicians [29]. As in our previous study [13], we excluded data points that revealed missing segments due to signal dropout during the recording period ($n = 7$). As this only left us with 12 data points for the SLI cohort, our sleep measures were not included in the primary analyses for the current work. Please see Supplementary Materials for sleep information on the SLI cohort.

3. Results

3.1. Pre-training sensitivity

After converting raw scores on behavioral tasks to d' [30], we first compared baseline (pre-training) discrimination performance between the SLI and Typical Groups, using an independent samples *t*-test. The difference in performance between the two Groups was non-significant ($t_{42} = 1.405$, $p = .167$), suggesting that no inherent differences in perceptual discrimination ability for the target sounds existed prior to training.

3.2. Training efficacy

To address our first question, which is whether the SLI cohort can be perceptually trained comparably to controls, we conducted an independent samples *t*-test on the immediate post-training identification scores (Fig. 1b). There was no significant difference in performance between the two Groups immediately after training ($t_{42} = -0.647$, $p = .521$). Furthermore, in order to determine if both Groups comparably generalized identification training to discrimination ability, we conducted a 2 × 2 ANOVA on discrimination scores with Group as the fixed factor and Time (baseline and Day 1 post-training) as the within-subjects factor (Fig. 1c). This resulted in a main effect of Time ($F(1,42) = 20.694$, $p < .001$, $\eta^2 = 0.330$), but no Group main effect ($F(1,42) = 1.579$, $p = .216$, $\eta^2 = 0.036$), nor any interaction ($F(1,42) = 0.009$, $p = .833$, $\eta^2 = 0.001$), suggesting that training generalized to improved discrimination to a comparable degree. These results indicate that the SLI group achieved comparable levels of perceptual learning of the/d̪/-/ɖ/contrast relative to controls when assessed immediately after training.

3.3. Post-training changes in behavior

The next set of analyses were conducted in order to determine if the two Groups differed in the pattern of sleep-mediated changes in performance. To this end, we conducted separate mixed model ANOVAs for identification and discrimination post-training scores, with Time (Day 1 post-training vs. Day 2 Post-training) as the within-subjects factor, and Group as the between-subjects factor. We report our results by task below (See Fig. 1b, c).

3.3.1. Identification performance

There was a main effect of Time ($F(1,42) = 8.252$, $p = .006$, $\eta^2 = 0.801$) and a significant interaction between Time and Group ($F(1,42) = 11.219$, $p = .002$, $\eta^2 = 0.905$), but no Group main effect ($F(1,42) = 1.326$, $p = .256$, $\eta^2 = 0.203$). Subsequent paired *t*-tests (Bonferroni correction applied) confirmed that the source of the interaction is driven by a significantly higher performance on Day 2 compared to Day 1 for the controls ($t_{24} = -4.853$, $p < .001$, $d = 0.419$), combined with no significant change in performance across Days in SLI ($t_{18} = .307$, $p = .793$, $d = -0.070$). Taken together, results indicate that the overnight improvement in performance observed in controls is absent in SLI.

3.3.2. Discrimination performance

There was a significant main effect of Time ($F(1,42) = 5.979$, $p = .019$, $\eta^2 = 0.666$) and a trending interaction between Time and Group ($F(1,42) = 3.903$, $p = .055$, $\eta^2 = 0.288$), but no Group main effect ($F(1,42) = 2.190$, $p = .304$). Subsequent paired *t*-tests (Bonferroni correction applied) confirmed the source of trending interaction as a significant gain by the Controls between Days 1 and 2 ($t_{24} = -2.926$, $p = .007$, $d = 0.354$), combined with no significant gains in performance overnight for the SLI cohort ($t_{18} = -0.412$, $p = .685$, $d = 0.095$). Again, the effect of sleep on perceptual performance appears to differ between Groups, with the Control group showing overnight improvement in perception, but no such improvement in the group with SLI.

Our main findings are supported through the re-analyses of our data using a Bayesian approach. Please see Supplementary Materials for this information.

3.4. ERP responses to nonnative speech

The MMN component [15] of the ERP is often used as a pre-attentive measure of neural discrimination of stimuli. For auditory stimuli with a subtle difference, peak MMNs have been identified as a fronto-central component that occurs between 150 and 200 ms post-stimulus onset [31]. We therefore calculated the area under the curve for the response waveforms recorded at Fz for the standard (dental) and deviant (retroflex) conditions separately. One-sample *t*-tests were conducted on the standard vs. deviant trials. Averaged across cohorts, we found significant MMNs on both days (Day 1: $t_{43} = 2.90$, p = .006, $d = .0.884$; Day 2: $t_{43} = 2.41$, p = .020, $d = 0.735$). The difference between the two waveforms (deviant-standard) was used to characterize individual MMN values.

To determine Group-level differences in mean MMN amplitudes, we conducted a 2 × 2 mixed models ANOVA with Time as the within-subjects factor and Group as the between-subjects factor. This yielded no interaction ($F(1,42) = .004$, $p = .950$, $\eta^2 < 0.001$) nor any main effects (Time: $F(1,42) = 0.002$, p = .967, $\eta^2 < 0.001$; Group: $F(1,42) = 2.130$, $p = .152$, $\eta^2 < 0.001$), suggesting that, on average, MMN amplitudes did not differ across Groups or over Time.

In order to address whether, on an individual level, *changes* to neural sensitivity over time could predict changes to perceptual behavior, we then compared changes to MMN amplitude to changes to discrimination performance (rather than identification, as MMN is characterized as an index of neural *discrimination*). We conducted a linear regression for overnight change in discrimination performance, with overnight change in MMN amplitude, Group, and the interaction between change in MMN and Group as predictors. The model significantly accounted for overnight change in discrimination ($F(3,40) = 1.913$, $p = .009$, $r^2 = 0.25$). Model coefficients were significant for overnight changes to MMN (β = 0.631, $t_{43} = 3.542$, $p = .001$, $d = 1.080$), not significant for Group ($\beta = -.054$, $t_{43} = -0.395$, $p = .695$, $d = -0.120$), and there was a trend for an interaction between changes to MMN and Group ($\beta = -0.327$, $t_{43} = -1.842$, $p = .073$, $d = -0.562$). Thus, it appears that overnight changes in neural sensitivity accompany overnight changes in perceptual performance. See Fig. 2 for a summary.

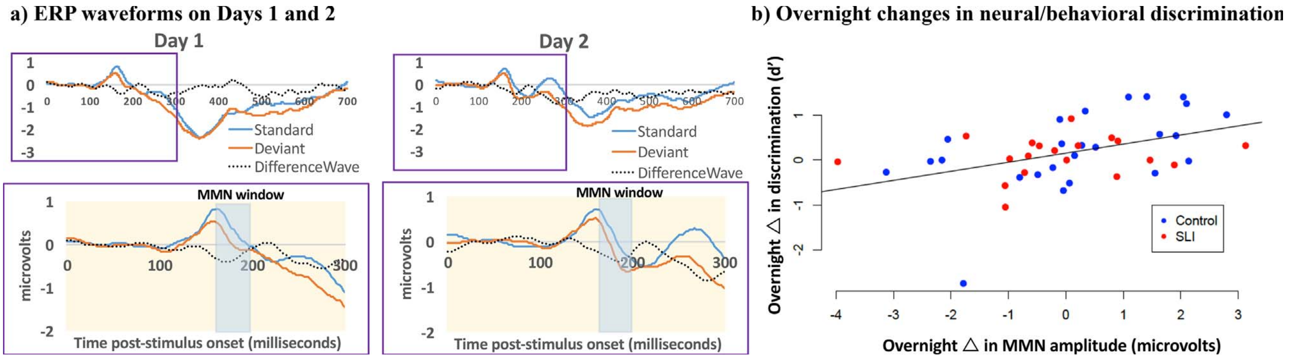
To summarize, perceptual performance was statistically equivalent between SLI and controls on Day 1, both before and after training. On Day 2, significant Group differences emerged. While the control cohort significantly improved on both perceptual tasks overnight, the SLI cohort maintained the same performance. In addition, on an individual level, overnight changes to discrimination ability appear to reflect overnight changes (or lack of changes) to neural sensitivity to the target contrast, with the caveat that changes to MMN and Group only showed a statistical trend, rather than a significant interaction. Taken together, our data suggests that the sleep-mediated consolidation of speech is impaired in those with SLI.

4. Discussion

Prior to this investigation, there had been several reports on offline consolidation in SLI [18–21], but the precise role of sleep, and its relationship with language, remained unclear. While these prior studies focused on tracking the retention of skill learning [18–20] or learned information [21] across periods that included sleep, all but one [18] found differences in *initial* learning between those with and without SLI. As differences in initial encoding have been shown to mediate the magnitude of offline consolidation effects [32], differences in learning over multiple days could have reflected a slower initial learning phase that set the SLI group behind their typical counterparts. In addition, only one of these [21] investigated the learning and retention of linguistic (word-level) knowledge directly. However, the *Phonological Deficit Hypothesis* [6,7] predicts that word-level learning would be already compromised by an instability in phonological representations (a prediction that appears to be supported by the authors' [21] findings). Therefore, the focus on nonnative phonetic training provided an opportunity to examine the time course of acquiring linguistic information that is relatively independent of the quality of pre-existing linguistic representations.

A particularly important role of sleep in language learning appears to be in the abstraction of salient, or common, features across stimuli away from wake-state episodes (i.e. encoded in the hippocampus), and transferring these features to cortical networks (see *Complementary Systems Account* of learning [33]; [8,14,34]). This process of abstraction and integration of new information with the old, allows the aggregate knowledge to exert top-down influence over future perceptual events. In other words, the robustness of conceptual and perceptual (including linguistic) categories depend on this habitual transfer of wake-state experience during sleep. Applying our findings to habitual experience, we might suppose that adults with SLI are less able to convert speech information from linguistic episodes to long-term memory compared to those with typical language. Differences in offline consolidation may explain *how* phonological representations become impoverished in those with SLI, to then further compromise the efficiency of spoken language processing.

Our interpretation of behavioral results is partially supported by the MMN findings, which was our objective measure of neural sensitivity to the target speech contrast. The literature contains many examples of consolidation-related changes to the MMN response. For example, post-training MMN has been shown to differ in magnitude recorded at 24 and 48 h post-training [34]. Furthermore, increased MMN amplitudes have been found to emerge on the day following initial training, even prior to changes in behavioral measures of perception [35]. In contrast, our behavioral evidence for offline consolidation was more robust than our MMN indexes of change, in that while we observed significant performance gains in behavior overnight, MMN differences between days did not reach statistical significance at group level. This may reflect greater variability in learning effects following dental-retroflex training, compared to training in a VOT contrast [36] or a non-speech auditory pattern contrast [34]. Supporting this, it has been found that while training-induced improvement in behavioral discrimination correlates with changes to MMN amplitude, that significant MMN



a) ERP waveforms on Days 1 and 2

b) Overnight changes in neural/behavioral discrimination

Fig. 2. Summary of ERP/MMN results. a) Depiction of response waveforms for the standard (dental) and deviant (retroflex) tokens, and the difference waveform, collapsed across Groups. b) The relationship between overnight change in ERP indexes of neural discrimination and change in behavioral discrimination. Participants in the Control cohort are in blue, participants with SLI are in red.

enhancements are only found for easy, rather than difficult, target contrasts [36].

There are several important limitations to consider in the current study. The first is that our sample sizes are fairly small, which may constrain our assumptions regarding the broader SLI population. Second, we do not have sufficient information about sleep quality in the two groups to determine if the observed lack of consolidation effects stem from differences in sleep specifically, although the timing of our two experimental sessions helped to limit the potential variability in non-sleep activity. Previous observations of atypical EEG activity during sleep [16,17], combined with the current data, suggest qualitative differences in the sleep architecture of individuals with SLI that may interfere with consolidation of acoustic-phonetic features. These potential differences in sleep may also influence daytime alertness and neurocognitive function, which may have cascading impacts on perceptual learning and performance. Disentangling the effects of impaired sleep-mediated consolidation and the broader consequences of variable sleep is a potential target for future research.

Finally, our behavioral evidence alone is insufficient for detailing the *nature* of the consolidation deficit in SLI. The lack of sleep-mediated improvement in performance may reflect either a failure in the offline transfer of information itself, or in the degradation of the information sampled from the hippocampus to be carried to long-term store. This distinction in potential mechanisms has direct implications for the quality of post-sleep phonetic representation, and consequent speech sound processing. Thus, these questions will direct the focus of future investigations into sleep quality and memory processes in SLI.

5. Conclusions

Previous literature on the retention of information in SLI has documented deficits in performance observed *immediately* after training [19–21], resulting in poor retention. In the case of speech however, we report *delayed* emergence of a perceptual deficit, following apparently typical performance immediately after training. Specifically, this deficit appears as the absence of benefit from sleep, suggesting that compromised sleep-mediated consolidation may be part of the underlying etiology of SLI.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.neulet.2017.12.030.

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