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Hearing Matters More Than Seeing: A Cross-Modality Study of Statistical Learning and Reading Ability

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ABSTRACT

There is growing interest in the link between implicit statistical learning (SL) and reading ability. Although learning to read involves both auditory and visual modalities, it is not known whether reading skills might be more strongly associated with auditory SL or visual SL. Here we assessed SL across both modalities in 36 typically developing children and 36 healthy adults using the classic triplet-learning paradigm. Auditory SL was significantly associated with sentence reading fluency (Woodcock Johnson III Test of Achievement) in the combined sample of children and adults after controlling for age and nonverbal intelligence. In further analysis of the child data, auditory SL was significantly associated with nonword reading accuracy (Woodcock Reading Mastery Test), a relationship which appeared to be mediated by phonological processing abilities (Comprehensive Test of Phonological Processing). These findings suggest that auditory SL might contribute more strongly to certain aspects of reading development compared to visual SL.

Introduction

Implicit learning of sequential regularities embedded in sensory inputs—statistical learning (SL)—contributes to spoken language acquisition (Arciuli & Torkildsen, 2012; Aslin & Newport, 2008; Romberg & Saffran, 2010). Infants and children learn native speech categories based on distributional statistics of speech sounds in their linguistic environment (Maye, Werker, & Gerken, 2002; Werker et al., 2007), detect word boundaries in a continuous stream of pseudospeech based on transitional statistics between syllables (Saffran, Aslin, & Newport, 1996), and acquire new vocabularies based on co-occurrence of statistical information between the sound and reference objects (Smith & Yu, 2008; Yu & Smith, 2007). There is a link between individual differences in SL abilities and children's vocabulary development (Evans, Saffran, & Robe-Torres, 2009; Mainela-Arnold & Evans, 2014) and grammatical ability (Kidd, 2012; Kidd & Arciuli, 2016). There is growing interest in how individual differences in SL are linked to reading ability.

The role of SL in reading development

Unlike oral language, which generally emerges spontaneously, learning to read is more effortful and is facilitated by formal instruction. Yet there is evidence of incidental word learning during exposure to written

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input (Protopapas et al., 2017; Tamura, Castles, & Nation, 2017). Moreover, for many languages, formal explicit instruction rarely conveys all the mappings between print and sound and all of the regularities concerning the way letters can and cannot be combined within words. As such, SL may be important for word-level reading development (Apfelbaum, Hazeltine, & McMurray, 2013; Chetail, 2017; Pacton, Perruchet, Fayol, & Cleeremans, 2001). For example, behavioral and computational modeling evidence shows that implicit and incremental learning of probabilistic relations between orthographic and phonological information provides a compelling account of how children assign lexical stress when reading aloud polysyllables in English (Arciuli, Monaghan, & Seva, 2010). In addition, SL may contribute to reading abilities through its relationship with spoken language acquisition. In particular, children learn phonological categories and phonotactic constraints from the statistical information embedded in their environmental inputs (Kuhl, Williams, Lacerda, Stevens, & Lindbolm, 2006; Maye et al., 2002). Individuals' ability to apply such knowledge during speech perception (i.e., via phonological awareness and phonological working memory) plays a pivotal role in children's ability to decode orthography (Hulme, Bowyer-Crane, Carroll, Duff, & Snowling, 2012; Melby-Lervåg, Lyster, & Hulme, 2012; Wagner, 1988).

SL can be viewed as a form of procedural learning due to its implicit nature. A set of brain regions including striatum and basal ganglia constitutes have been linked with implicit procedural memory (Poldrack & Rodriguez, 2004; Squire, 1992). Recent research suggests that the hippocampus also plays a role in encoding and extracting regularities during SL, thus pointing to a more expanded memory system underlying SL (Schapiro, Gregory, Landau, McCloskey, & Turk-Browne, 2014; Schapiro, Turk-Browne, Botvinick, & Norman, 2017; cf. Covington, Brown-Schmidt, & Duff, 2018). These studies suggest that SL is supported by multiple domain-general mechanisms underpinning attention, processing speed, and memory (see Arciuli, 2017, for a multicomponent account of SL). Paradoxically, some studies have reported varied learning capability across different domains within an individual, implicating neural constraints on learning that is tied to specific features of the stimuli (Conway & Christiansen, 2006; Erickson, Kaschak, Thiessen, & Berry, 2016; Frost, Armstrong, Siegelman, & Christiansen, 2015; Siegelman & Frost, 2015). Also, some individuals may exhibit modality-specific differences in SL due to specialist knowledge/skills (Mandikal Vasuki, Sharma, Demuth, & Arciuli, 2016; Mandikal Vasuki, Sharma, Ibrahim, & Arciuli, 2017).

When it comes to the task of reading, it seems possible that visual SL (VSL) might support the implicit acquisition of transitional probabilities between letters. Auditory SL (ASL) might support the implicit acquisition of phonological skills. Both VSL and ASL might contribute to implicit acquisition of regularities that reflect correspondences between orthography and phonology. Thus, it is worthwhile assessing SL in multiple modalities to comprehensively investigate the relationship between SL and reading development.

The link between individual differences in SL and reading

Individual differences in ASL and VSL have been associated with reading ability and reading-related skills in the general population (Arciuli & Simpson, 2012; Frost, Siegelman, Narkiss, & Afek, 2013; Gabay, Thiessen, & Holt, 2015; Spencer, Kaschak, Jones, & Lonigan, 2015). Many studies on this topic have used the well-established triplet paradigm with participants being exposed to a continuous stream of stimuli containing a number of sequentially presented items that co-occur in triplets during a familiarization phase (i.e., the three stimuli within each triplet are always presented following the same sequential order). Typically, participants' learning of these triplets is assessed in a subsequent surprise test phase.

Individual differences between SL and reading accuracy have been associated with VSL in studies using triplet-learning tasks (e.g., the study of children and adults reading in English by Arciuli & Simpson, 2012; the study of adults reading in Hebrew as L2 by Frost et al., 2013). Gabay et al. (2015) showed a correlation between individual differences in ASL using a triplet-learning task and English reading accuracy within a dyslexic group *and within a healthy control group*. A study of Spanish children reported a link between visual triplet-learning and some aspects of

spelling but not reading—a null result for reading that the authors attributed to the transparent nature of Spanish orthography or low statistical power (Nigro, Jiménez-Fernández, Simpson, & Defior, 2015).

Spencer et al. (2015) assessed ASL and VSL in English-speaking children, as well as a number of skills related to literacy development including oral language, vocabulary, and phonological processing. Results showed that both ASL and VSL were associated with reading-related skills but ASL seemed to be related to more of these skills than VSL. The SL tasks used by Spencer et al. differed in critical ways. The ASL task utilized verbal stimuli and followed the standard triplet-learning paradigm, where learning was measured by discrimination accuracy between a familiar triplet and a novel triplet in two-alternative forced-choice trials following a familiarization phase. The VSL task utilized nonverbal stimuli and followed the Simon paradigm, where SL was measured as the difference in accuracy between reproducing sequences with statistical patterns and reproducing random sequences. Spencer et al. argued that these tasks reflected different aspects of SL: extraction of statistical regularities (auditory task) versus integration of statistical regularities (visual task). However, because the tasks differed in utilization of nonverbal versus verbal stimuli, and in utilization of visual versus auditory modalities, it is difficult to tease apart competing explanations for their findings. In the current study we used VSL and ASL tasks that followed the triplet-learning paradigm.

Current study

We investigated whether sensitivity to statistical information in the visual and auditory modalities is equally strongly associated with reading abilities. Statistical learning outcomes can be affected by attention, perceptual processing, and memory systems, all of which develop across age (Arciuli & Conway, *in press*; Arciuli & Simpson, 2011; Schlichting, Guarino, Schapiro, Turk-Browne, & Preston, 2017). In addition, literacy skills grow during school years through to early adulthood. Therefore, we examined SL in both typically developing children and healthy adults. Our primary outcome measure was sentence reading fluency—the ability to utilize word-level reading skills for the purpose of comprehension. In follow-up analyses of the child data, we examined the relationship between SL and both word/nonword reading accuracy and whether a relationship might be mediated by phonological processing.

Our ASL and VSL tasks were modeled after the commonly used triplet-learning paradigm and utilized the same nonverbal stimuli used by Arciuli and Simpson (2011) and Saffran, Johnson, Aslin, and Newport (1999), respectively. Advancing on previous studies, we included a novel target-detection cover task during the familiarization phase for each SL task that was designed to measure online SL in addition to the traditional two-alternative-forced-choice (2AFC) task administered immediately after familiarization.

If sensitivity to both visual and auditory regularities contributes equally in predicting variability in sentence reading fluency, the association with each of the SL tasks should be comparable. We expected that we might see a stronger association between ASL and sentence reading fluency, especially if the relationship between SL and reading accuracy is mediated by phonological-processing abilities, which may draw more heavily on auditory than visual skills.

Methods

Participants

Thirty-six typically developing children (M age = 12;2, range = 8–16, 20 girls) and 36 healthy adults (M age = 24;0, range = 18–34, 25 women) were recruited from the Greater Boston Area. All were native English-speaking, right-handed, with normal hearing and vision, with normal nonverbal IQ (M = 111.0, range = 82–149; Kaufman Brief Intelligence Test, Second Edition; Kaufman & Kaufman, 2004), and had no known speech or language impairments. The study was approved by the Committee on the Use of Humans as Experimental Subjects at the Massachusetts Institute of Technology.

Table 1. Demographic and Behavioral Characteristics of Participants

	Adults	Children
<i>N</i>	36 (25 F)	36 (20 F)
<i>M</i> age (<i>SD</i>)	24.03 (5.03)	12.15 (2.41)
<i>M</i> Nonverbal IQ (<i>SD</i>)	106.44 (12.15)	115.63 (16.08)
<i>M</i> Sentence reading fluency (<i>SD</i>)	123.56 (13.94)	119.97 (10.10)
<i>M</i> Word Identification (<i>SD</i>)	—	118.74 (14.39)
<i>M</i> Word Attack (<i>SD</i>)	—	114.43 (11.72)
<i>M</i> Phonological abilities (<i>SD</i>)	—	11.06 (1.76)

Note. All test scores are standard scores. Reading fluency: Woodcock Johnson III Test of Achievement Sentence Reading Fluency subtest; Word identification = Woodcock Reading Mastery Test–Revised Normative Update (WRMT) Word Identification task; Word attack = WRMT Word Attack task; Phonological abilities = average scores of four Comprehensive Test of Phonological Processing subtests (Blending Words, Elision, Digit Span, and Nonword Repetition).

Reading and phonological measures

The Sentence Reading Fluency subtest from the Woodcock Johnson III Test of Achievement (WJ-III; Woodcock, McGrew, & Mather, 2001) was used to assess children and adults' reading ability.¹ Within a time limit of 3 min, participants read simple sentences and answered a yes/no comprehension question after each sentence. Participants' raw accuracy score and total time for completion were both accounted for in the standard scores. The children also undertook assessments of real word reading via Word Identification and nonword reading via Word Attack from the Woodcock Reading Mastery Test–Revised Normative Update (WRMT; Woodcock, 1998). Four subtests (Elision, Blending Words, Memory for Digits, and Nonword Repetition) from the Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999) measured children's phonological abilities. An intraclass correlation analysis using R package ICC 2.3.0 (Wolak, Fairbairn, & Paulsen, 2012) showed high-level consistency among the subtests (intraclass correlation = 0.281, $p < .001$). Therefore, a composite score was calculated by averaging the standardized scores of the four subtests (Table 1).² Both groups performed above population average across these standardized tests, which is likely related to a self-selection bias in the urban and collegial location of the study.

SL test materials and design

Both SL tests comprised a familiarization phase and a subsequent test phase. During familiarization, participants performed a target detection cover task while being exposed to a continuous stream of stimuli containing embedded triplet patterns. During the test phase, participants completed 2AFC trials to identify a learned versus a foil triplet (Figure 1).

VSL task

Modeled after Arciuli and Simpson (2011, 2012), 12 unique alien images were divided into four groups of three images to create four base triplets in Language 1 (each letter represents an image: ABC, DEF, GHI, and JKL) and Language 2 (HCJ, KFG, ELA, and BID). For the familiarization phase, base triplets were randomly concatenated in a continuous stream for a total of 96 triplets randomly ordered in a continuous stream, with the only restriction that no triplet was repeated twice in a row. Aliens were presented one at a time on a computer screen for 800 ms each with 200 ms of interstimulus interval. The duration of the

¹From previous research, we have found that a timed reading measure, such as sentence reading fluency, provides a wider range of performance for us to study individual differences when we recruit participants from the Greater Boston area. Word reading and nonword reading measures were not collected from adult participants because we unfortunately had limited allocated time for adults' lab-based assessments.

²Four children had missing data in either phonological ability (2) or both reading and phonological abilities (2), because they did not complete the assessments. A total of 32 children completed WJ-III sentence reading fluency test, 35 children completed the WRMT reading assessments, and 34 children completed the Comprehensive Test of Phonological Processing phonological assessments. We included all the children who had complete records of relevant scores to investigate the relationship between SL and reading and phonological measures.

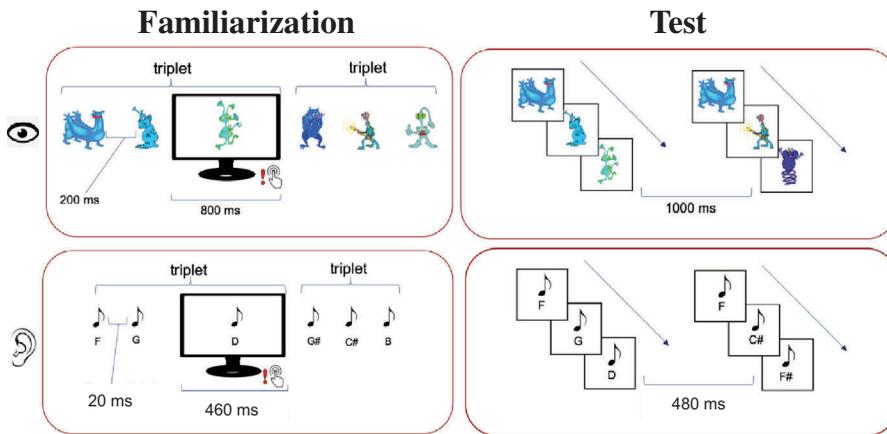


Figure 1. Visual statistical learning (VSL) and auditory statistical learning (ASL) task procedure.

Note. During the familiarization phase (left), participants were exposed to a continuous stream of visual (upper) or auditory (lower) stimuli containing triplet patterns, while performing a target detection cover task. During the test phase (right), participants completed a two-alternative forced choice task.

familiarization phase was 4 min 48 s. Each base triplet was presented 24 times. For the test phase, four foil triplets were created. The relative position of each image in a triplet was the same as the base triplets, but the images were grouped into four foil triplets (Language 1: AEI, DHL, GKC, and JBF; Language 2: HFA, KLD, EIJ, and BCG). Each base triplet was presented with each foil triplet twice. Across 32 test trials each base triplet was seen eight times and each foil triplet was seen eight times. The base triplet was presented before the foil triplet for half of the trials.

ASL task

Modeled after Saffran et al. (1999), 12 pure tones within the same octave (a full chromatic scale starting from middle C) were divided into four base triplets in Language 1 (FGD, G#C#B, CF#D#, and EAA#) and Language 2 (F#DE, ABC, C#A#F, and GD#G#). Each language was constructed such that no triplet resembled any familiar melodies. We considered auditory perceptual preference and employed a faster presentation speed in our ASL task by comparison with our VSL task (Conway & Christiansen, 2009; Emberson, Conway, & Christiansen, 2011), and a greater number of triplet repetitions in our ASL task. The duration of each tone was 460 ms with 20 ms interstimulus interval. Each base triplet was presented 48 times for a total of 192 triplets randomly ordered in a continuous stream, similar to previous studies that included four triplets with each repeated 45 times (Johnson & Jusczyk, 2001; Mcnealy, Mazziotta, & Dapretto, 2006; Saffran et al., 1996). As in the VSL task, the ASL contained 32 trials of base triplets versus foil triplets in the test phase.

SL assessment procedure

Participants completed a visual and an auditory SL task, hosted on a secured website (<https://www.cogscigame.co>)³ (See Figure 1). Three adults were removed from the ASL analyses because their data were

³All the children took the online SL tasks at home as part of a larger study. Their IQ, reading, and phonological skills were measured during their previous lab visit at Massachusetts Institute of Technology (MIT). In view of this, standard scores were used in all analyses as they are expected to be relatively stable across age. All the analyses within the child group controlled for the test interval between behavioral assessments and SL tasks. All the adult participants completed the behavioral assessments followed by the online SL tests on the same day in the laboratory at MIT. To confirm that the laboratory-based testing environment did not inflate participants' SL performance, we invited a separate group of 12 adults to complete the same online SL tasks from their home computers. Their test accuracy in both tasks was similar to the overall performance of the adult participants in the current study ($p_s > .5$).

not recorded due to technical issues. Task order (VSL or ASL first) was counterbalanced across participants and had no significant effect on SL test accuracy in either task for children or adults ($ps > .19$).

VSL

Each participant was randomly exposed to one of the two languages and randomly assigned with one of the four possible target images for the target detection cover task. During the familiarization phase, participants were instructed to press the space bar as quickly as possible whenever the target alien appeared on the screen. The target alien image was always the third alien of one of the four base triplets, so that online learning could be measured via response time acceleration over 24 target trials during exposure. The 2AFC test phase was introduced after the familiarization phase. On test trials participants were asked to identify which of the two triplets (embedded vs. foil) seemed more like what they saw during the familiarization phase. There were no time constraints for responses and no feedback on accuracy of answers. Order of test trials was randomized across participants. VSL test performance did not differ between Language 1 and Language 2 ($p = .75$) or between triplets with the target image versus triplets without the target image ($p = .95$).

ASL

The procedure was identical to that of VSL except that the target tones used in the target-detection task during familiarization were constrained to only the lowest and highest notes of the final tones of the four triplets to facilitate identification. Two practice trials before the continuous stream of tones ensured that participants could distinguish the target tone. Response time was measured over 48 target trials. ASL test performance did not differ between Language 1 and Language 2 ($p = .91$) or between triplets with the target tone versus triplets without the target tone ($p = .13$).

The task reliability was computed by the Cronbach's alpha coefficient (Cronbach, 1951) for the 32 test items. The alpha coefficients for VSL were 0.87 (Language 1) and 0.86 (Language 2). The alpha coefficients for ASL were 0.79 (Language 1) and 0.71 (Language 2). The task reliability in children and adults are reported separately in Table 2.

Analyses

SL performance was measured in two ways: by the linear slope of response time (RT) acceleration across valid target trials during the familiarization phase (RT slope) and the response accuracy during the 2AFC trials in the test phase (test accuracy). A target detection response for the target stimulus was considered valid only if button press occurred between the onsets of the previous stimulus before the target and the next stimulus after the target to allow both anticipatory hits and target-evoked hits. Accordingly, an average of 97% of the VSL targets ($SD = 4\%$) and 73% of the ASL targets ($SD = 19\%$) were preserved for RT slope measures.⁴

Table 2. Task Reliability (Cronbach's Alpha) of the SL Accuracy Measures in Children and Adults

	Children		Adults		All Participants	
	Language 1	Language 2	Language 1	Language 2	Language 1	Language 2
VSL	0.88	0.84	0.89	0.89	0.87	0.86
ASL	0.78	0.79	0.85	0.79	0.79	0.71

Note. VSL = visual statistical learning; ASL = auditory statistical learning.

⁴Two adults and three children were removed from analyses involving ASL RT slope, due to fewer than 25% valid trials but we retained their ASL test accuracy score. Removing these participants from the analyses on test accuracy score did not change the significant relationship between ASL accuracy and reading fluency.

Results

SL task performance

In terms of test accuracy, both adults and children groups performed significantly better than chance (50%) for VSL (adults: $M = 0.78$, $SD = 0.19$; Wilcoxon rank sum $V = 645.5$, $p = 1.19 \times 10^{-8}$; children: $M = 0.71$, $SD = 0.19$; $V = 598.5$, $p = 1.31 \times 10^{-7}$) and ASL (adults: $M = 0.69$, $SD = 0.17$; $V = 497$, $p = 9.88 \times 10^{-7}$; children: $M = 0.64$, $SD = 0.13$; $V = 528$, $p = 4.66 \times 10^{-10}$; **Figure 2A**). Pairwise Spearman correlations revealed that VSL performance was not associated with ASL performance within individuals (accuracy: $\rho = 0.16$, $p = .20$; RT slope: $\rho = 0.07$, $p = .61$).⁵

We analyzed the fixed effects of task (VSL vs. ASL) and group (children vs. adults) on test accuracy using mixed-effects logistic regression (Barr, Levy, Scheepers, & Tily, 2013; Jaeger, 2008). The dependent measure was the binomial accuracy in each test trial. The model included random intercepts for participants and random by-participant slopes of task. Collapsed across groups, participants performed significantly better in VSL than ASL ($b = 0.78$, $SE = 0.22$, $z = 3.46$, $p = .0005$). Collapsed across tasks, accuracy was not different between adults and children ($b = -0.23$, $SE = 0.18$, $z = -1.28$, $p = .20$). There was no interaction between task and group ($b = -0.33$, $SE = 0.31$, $z = -1.07$, $p = .28$). Post hoc analyses showed that the task difference was statistically significant in adults ($V = 386$, $p = .02$) but not in children ($V = 393$, $p > .1$).

RT slope during VSL familiarization was significantly lower than 0 (adults: $V = 139$, $p = .002$; children: $V = 144$, $p = .002$; **Figure 2B**) and was negatively associated with test accuracy, suggesting gradual acceleration of target detection over the course of learning. However, RT slope during ASL familiarization was not significantly different from 0 (adults: $V = 195$, $p = .13$; children: $V = 378$, $p = .49$). As ASL stimuli were presented for a shorter duration than VSL stimuli, participants had a shorter time window to respond in the cover task during ASL compared to VSL, resulting in faster overall RT (Supplementary Figure 1). Due to these differences between ASL and VSL, we analyzed the fixed effects of group and target trial order on RT using mixed-effects linear regression in the two tasks separately. The dependent variable was the response time for each valid target detection. The model included random intercepts for participants and random by-participant slopes of trial order. Participants responded more quickly in later than earlier trials in VSL ($b = -2.48$, $SE = 0.87$, $t = -2.84$, $p = .006$) but showed no significant changes across trials in ASL ($b = -0.59$, $SE = 0.50$, $t = -1.18$, $p = .24$). There was no significant difference in RT

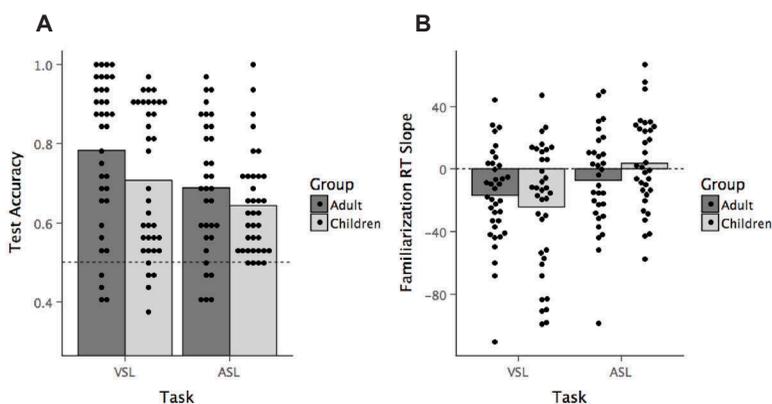


Figure 2. Mean statistical learning (SL) performance in adults and in children.

Note. (A) Test accuracy in the 2AFC task. Dotted line represents the chance level. (B) Linear slope of response time change during familiarization phase. More negative values indicate greater learning during familiarization.

⁵Separate analyses within adults and children also showed no correlation between VSL and ASL performance.

Table 3. Spearman Correlation Matrix of Statistical Learning Performance and Sentence Reading Fluency in the Full Sample

	VSL Slope	ASL Accuracy	ASL Slope	Sentence Reading	Age	IQ
VSL Accuracy	<u>-0.39***</u>	0.16	0.00	0.22 [†]	0.16	0.18
VSL Slope		0.14	0.07	-0.06	0.01	-0.02
ASL Accuracy			-0.09	<u>0.50***</u>	0.09	0.15
ASL Slope				-0.20	-0.11	-0.10
Sentence reading					0.03	0.31**
Age						-0.35**

Note. Underlined correlations remained significant after Bonferroni correction for multiple comparisons. VSL = visual statistical learning; ASL = auditory statistical learning.

[†] $p < .1$. ** $p < .01$. *** $p < .001$.

slope between adults and children in either task (VSL: $b = -1.15$, $SE = 1.24$, $t = -0.93$, $p = .36$; ASL: $b = 1.03$, $SE = 0.71$, $t = 1.45$, $p = .15$; Supplementary Figure 1). Overall, VSL RT slope was significantly associated with test accuracy ($\rho = -0.39$, $p < .001$), but ASL RT slope was not associated with test accuracy ($\rho = -0.09$, $p = .48$; Table 3).

Individual difference in SL and reading abilities

As adults performed similarly to children for VSL and ASL measured by both test accuracy and RT slope, we combined adult and child data to examine the relationship between SL and the standardized scores of sentence reading fluency (WJ-III). We also examined the relationship between SL and the standardized scores of word and nonword reading accuracy (WRMT) in our sample of children (word and nonword reading accuracy data was not collected for adults). WJ-III sentence reading fluency was significantly associated with nonverbal IQ, test accuracy in ASL (Figure 3), and RT slope in ASL, and it was marginally associated with test accuracy in VSL (Table 3). Word Identification (real word reading) and Word Attack (nonword reading) in children were both significantly associated with the RT slope in ASL, age, and nonverbal IQ. In addition, children's RT slope in ASL was significantly associated with nonverbal IQ (Table 4).

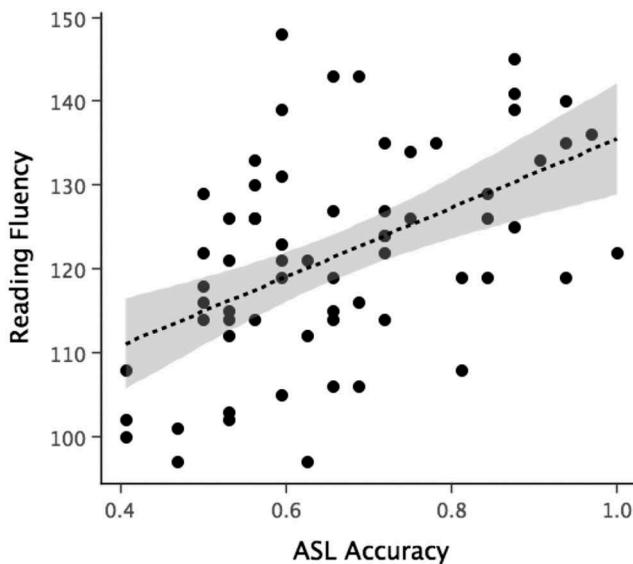


Figure 3. Significant correlation between auditory statistical learning (ASL) test accuracy and sentence reading fluency in the full sample.

Note. Dotted line represents a linear fit of the correlation and the shaded ribbon represents 95% confidence interval.

Table 4. Spearman Correlation Matrix of Statistical Learning Performance, Reading Skills, and Phonological Skills in the Children Sample

	VSL Slope	ASL Accuracy	ASL Slope	Sentence Reading	Word Identification	Word Attack	Phonological Skills	Age	IQ
VSL accuracy	-0.24	0.03	0.20	-0.01	0.04	0.11	0.18	0.13	0.19
VSL slope		0.21	-0.008	-0.03	0.09	0.17	0.14	-0.07	0.09
ASL accuracy			0.15	0.25	-0.07	-0.07	-0.26	0.17	0.07
ASL slope				-0.18	-0.49**	-0.35*	-0.26	0.09	-0.34*
Sentence reading					<u>0.71***</u>	0.71***	0.33 [†]	-0.24	0.45**
Word Identification						<u>0.84***</u>	0.45**	-0.50**	0.61***
Word Attack							<u>0.59***</u>	-0.41*	<u>0.58***</u>
Phonological skills								0.30 [†]	
Age									-0.22**

Note. Underlined correlations remained significant after Bonferroni correction for multiple comparisons. VSL = visual statistical learning; ASL = auditory statistical learning.

[†] $p < .1$. * $p < .05$. ** $p < .01$. *** $p < .001$.

To examine the unique contribution of SL in explaining individual variance of reading abilities, we controlled for age and nonverbal IQ. Partial correlations revealed that sentence reading fluency was not significantly associated with VSL accuracy ($\rho = 0.17, p = .17$) but was significantly associated with ASL accuracy ($\rho = 0.48, p = 1.50 \times 10^{-5}$). The partial correlation between reading fluency and ASL accuracy was significantly stronger than that between reading fluency and VSL accuracy ($z = 2.05, p = .02$; Steiger, 1980). The significant correlation was found in the adult group ($\rho = 0.53, p < .001$) but not in the children group ($\rho = 0.28, p = .13$; Supplementary Figure 2). However, the correlation strength was not statistically different between adults and children ($z = 1.20, p = .23$). Stepwise model selection by AIC for multiple regression analysis showed that ASL accuracy was a significant predictor, which uniquely accounted for 20.5% of the variance in WJ-III reading fluency scores ($b = 37.92, SE = 8.86, t = 4.28, p = 6.59 \times 10^{-5}$). Nonverbal IQ and ASL accuracy together accounted for 28.3% of the variance.

To test whether the association between reading and ASL existed at single word/nonword levels, we examined the relationship between ASL performance and the available WRMT real-word and nonword reading scores in 33 children with valid ASL data. After controlling for age and nonverbal IQ we found that children who showed greater acceleration of target detection during ASL familiarization (more negative RT slope) scored higher in nonword reading ($\rho = -0.51, p = .001$; Figure 4). Nevertheless, neither ASL test accuracy nor any measure relating to VSL performance was associated with either word-level reading measures ($ps > .15$; Table 5). The correlation between Word Attack scores and ASL RT slope was significantly stronger than that between Word Attack

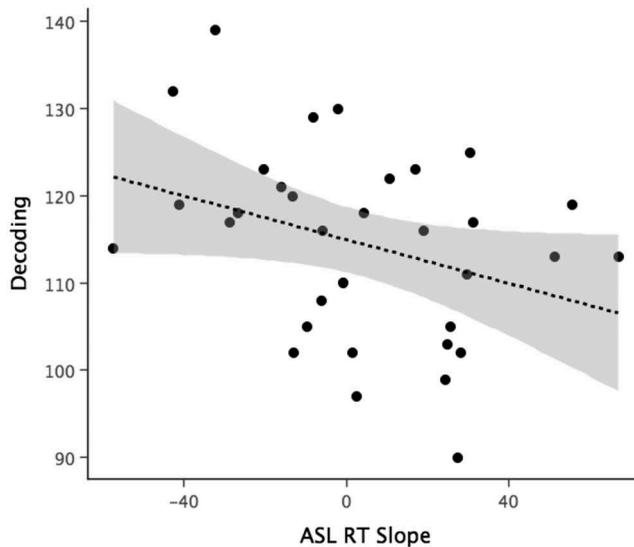


Figure 4. Significant correlation between auditory statistical learning reaction time (ASL RT) slope during familiarization and nonword decoding in children.

Note. Dotted line represents a linear fit of the correlation and the shaded ribbon represents 95% confidence interval.

Table 5. Partial Spearman Correlation Between Statistical Learning Performance and Word-Level Reading in Children After Controlling for Age, Nonverbal IQ, and Test Interval

	VSL Accuracy	VSL Slope	ASL Accuracy	ASL Slope
Word Identification (words)	-0.03	-0.07	0.25	-0.08
Word Attack (nonwords)	0.11	0.07	0.03	-0.51**

Note. VSL = visual statistical learning; ASL = auditory statistical learning.

** $p < .005$, significant after Bonferroni correction for multiple comparisons.

scores and VSL RT slope ($z = 2.43, p = .007$). Mediation analysis implemented using the *mediation* R package (Tingley et al., 2014) further revealed that the relationship between ASL RT slope and Word Attack scores was significantly mediated by children's phonological abilities (total effect: $b = -0.14, p = .01$; direct effect: $b = -0.07, p = .21$; mediation indirect effect: $b = -0.07, p = .05$; proportion of effect mediated by phonological abilities: 51%; 1,000 simulations). The significant relationship between phonological abilities and reading, however, was not mediated by ASL RT slope (total effect: $b = 3.54, p < .001$; direct effect: $b = 3.83, p < .001$; mediation indirect effect: $b = -0.29, p = .22$; proportion of effect mediated by reading abilities: 8%; 1,000 simulations).

Discussion

Previous studies have shown a link between SL and reading accuracy or reading-related abilities in the general population (Arciuli & Simpson, 2012; Frost et al., 2013; Gabay et al., 2015; Spencer et al., 2015), but it is not clear whether ASL or VSL might be more strongly associated with reading. In the current study, participants showed better learning on the VSL task than the ASL task (for accuracy and RT slope); however, it was variability in ASL performance that was related to individual differences in reading performance. Somewhat surprising, ASL *accuracy* was associated with sentence reading fluency whereas ASL *RT slope* was associated with nonword reading. Our results suggest that the ability to learn regularities from auditory inputs rather than visual inputs might play a relatively more influential role in the literacy skills we assessed in the current study.

SL and sentence reading fluency

We found that individual differences in sentence reading fluency were associated with accuracy on both ASL and VSL tasks (albeit marginally significant in the case of VSL). However, when nonverbal IQ and age were taken into consideration the association between sentence reading fluency and ASL was stronger than that between sentence reading fluency and VSL. In addition to measuring grapheme-to-phoneme decoding at word level, sentence reading fluency also engages other linguistic knowledge including vocabulary, grammar, and pragmatics. No doubt the reading accuracy assessed in a covert sentence reading fluency task, which likely draws upon skills other than decoding, differs from overt assessment of reading accuracy. However, our findings suggest that the holistic integration of these skills required for sentence reading fluency is linked with individuals' ability to learn statistics from auditory inputs.

SL, word/nonword reading, and phonological abilities

Our follow-up analyses of children examined whether SL is related to individuals' reading accuracy skills. These analyses revealed that variability in online ASL (RT slope) was linked with nonword reading accuracy but not real-word reading accuracy. Further, the effect of ASL on children's nonword reading was mediated by their phonological abilities. These results may reflect the central role of phonological processing in reading development. The acquisition of phonemes present in one's native language that constitute the earliest steps toward phonological development require perceptual sensitivity to acoustic features in speech as well as distributional patterns embedded in the auditory inputs (Kuhl et al., 2008; Maye et al., 2002; Werker et al., 2007). Numerous studies undertaken with typically developing children and children with dyslexia have acknowledged the pivotal role phonological skills play in reading acquisition (Hulme et al., 2012; Lu et al., 2016; Melby-Lervåg et al., 2012; Saygin et al., 2013; Wagner, 1988). Our findings suggest that ASL abilities might facilitate the acquisition of grapheme-to-phoneme mapping via the honing of phonological skills. Nonword reading, as a measure of decoding ability, may rely more on phonological skills than real-word reading, and phonological skills likely relate more strongly to detecting regularities in auditory rather than visual input

(Gabay & Holt, 2015). However, because our data do not directly speak to the causal relationship between ASL and reading skills, it is also possible that more practice in reading in turn sharpens learners' sensitivity to the statistical patterns in auditory input.

The RT slope from the ASL task appeared to be noisier than that from the VSL task. Moreover, although VSL RT slope was associated with VSL accuracy, ASL RT slope was not associated with ASL accuracy. This suggests the ASL cover task undertaken during familiarization, unlike the VSL cover task, might be more susceptible to poor perceptual acuity and/or poor attention. Therefore, the significant relationship among ASL RT slope, phonological abilities, and nonword reading might be partially explained by individual differences in auditory perception and attention. Future studies are necessary to explore the contribution of perceptual processes to both ASL and other skills associated with reading development.

The results of the present study differ from previous studies that observed a link between VSL and reading accuracy for real words (Arciuli & Simpson, 2012; Frost et al., 2013) and a link between ASL and reading accuracy for both real words and nonwords (Gabay et al., 2015). Aside from some differences in sample sizes, the reading measures used, and the languages assessed, the nature of the SL tasks differed across these previous studies and differed from the current study (e.g., in terms of the nature of instructions, presence of a cover task during familiarization, stimulus presentation times during familiarization, whether learning was assessed during and/or immediately after familiarization, and number of 2AFC trials during the test phase). In addition, there were some differences in the ASL and VSL tasks in the present study. ASL triplets were presented twice as fast for twice as many times during familiarization (48 times each with 480 ms of stimulus onset asynchrony (SOA)) compared to VSL triplets (24 times each with 1,000 ms of SOA). These methodological differences were implemented to accommodate different perceptual processing preferences across two sensory modalities, but studies comparing the effects of such parameters on studies of individual differences, and the link with reading ability, need to be further investigated. Also noteworthy, the self-selected samples from the Greater Boston region might have contributed to better SL performance in terms of test accuracy by comparison with some previous studies. Future research should explore the impact of all of these factors. In addition, it would be valuable to look beyond phonological abilities to additional mediating variables, some of which may relate more strongly to individual differences in VSL and reading ability (e.g., knowledge of letters that combine to form graphemes; knowledge of spelling patterns concerning double letters and silent letters in some words; sensitivity to bigram/trigram frequencies and how these larger "chunks" map on to aspects of phonology such as lexical stress).

Modality-specific constraints of SL

We measured adults' and children's SL across visual and auditory domains with separate triplet-learning tasks that utilized nonverbal stimuli. The lack of an association between ASL and VSL performance confirms the findings from previous studies in which individuals' capacity to learn statistical information varied across modalities (Conway & Christiansen, 2005, 2006; Erickson et al., 2016; Mandikal Vasuki et al., 2016; Mandikal Vasuki et al., 2017; Siegelman & Frost, 2015). The lack of relationship between ASL and VSL could indicate that modality-specific perceptual processing might contribute substantially to individuals' capacity to learn statistical patterns. However, we have noted that there were some differences in our ASL and VSL tasks that may, in part, explain the lack of a relationship between ASL and VSL in the current study. In any case, it is likely that SL is governed by both modality-specific bottom-up processes and domain-general top-down processes (Daltrozzo & Conway, 2014; Frost et al., 2015). Although research on this issue is ongoing, our study demonstrates why it is important to examine SL in multiple modalities when exploring individual differences between SL and reading.

Conclusion

Individual differences in ASL appear to be more strongly related to sentence reading fluency and nonword reading than VSL. This may be because ASL underpins phonological development, which is essential for decoding during reading acquisition. Additional research with a larger sample of children and adults, a broader array of reading measures, and systematic manipulation of the perceptual and attentional demands of ASL and VSL tasks will further our understanding of the link between SL and reading.

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