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Implicit statistical learning in language processing: Word predictability is the key ☆

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ABSTRACT

Fundamental learning abilities related to the implicit encoding of sequential structure have been postulated to underlie language acquisition and processing. However, there is very little direct evidence to date supporting such a link between implicit statistical learning and language. In three experiments using novel methods of assessing implicit learning and language abilities, we show that sensitivity to sequential structure – as measured by improvements to immediate memory span for structurally-consistent input sequences – is significantly correlated with the ability to use knowledge of word predictability to aid speech perception under degraded listening conditions. Importantly, the association remained even after controlling for participant performance on other cognitive tasks, including short-term and working memory, intelligence, attention and inhibition, and vocabulary knowledge. Thus, the evidence suggests that implicit learning abilities are essential for acquiring long-term knowledge of the sequential structure of language – i.e., knowledge of word predictability – and that individual differences on such abilities impact speech perception in everyday situations. These findings provide a new theoretical rationale linking basic learning phenomena to specific aspects of spoken language processing in adults, and may furthermore indicate new fruitful directions for investigating both typical and atypical language development.

1. Introduction

Understanding the role that learning and memory abilities play in language acquisition and processing remains an important challenge in the cognitive sciences. Towards this end, a major advance has been in recognizing that language consists of complex, highly variable patterns occurring in sequence, and as such can be described in terms of statistical or distributional relations among language units (Redington & Chater, 1997). Due to the probabilistic nature of language, rarely is a spoken utterance completely unpredictable; most often, the next word in a sentence will depend on the preceding context of the sentence (Rubenstein, 1973). Put another way, what a language speaker considers to be a "meaningful" sentence can be quantified in terms of how much the preceding context constrains or predicts the next spoken word (Miller & Selfridge, 1950). Due to the apparent importance of context and word predictability in language, sensitivity to such probabilistic relations among language units likely is crucial for successful language learning and understanding.

It is not surprising then, that it is now widely accepted that general abilities related to learning about complex

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structured patterns – i.e., implicit statistical learning[1] – are important for language processing (Altmann, 2002; Conway & Christiansen, 2005; Conway & Pisoni, 2008; Gupta & Dell, 1999; Kirkham, Slemmer, Richardson, & Johnson, 2007; Kuhl, 2004; Pothos, 2007; Reber, 1967; Saffran, 2003; Turk-Browne, Junge, & Scholl, 2005; Ullman, 2004). Implicit learning is thought to be important for word segmentation (Saffran, Aslin, & Newport, 1996), word learning (Graf Estes, Evans, Alibali, & Saffran, 2007; Mirman, Magnuson, Graf Estes, & Dixon, 2008), the learning of phonotactic (Chambers, Onishi, & Fisher, 2003) and orthographic (Pacton, Perruchet, Fayol, & Cleeremans, 2001) regularities, aspects of speech production (Dell, Reed, Adams, & Meyer, 2000), and the acquisition of syntax (Gómez & Gerken, 2000; Ullman, 2004). What is more surprising, however, is that despite the voluminous work on implicit learning, few if any studies have demonstrated a direct causal link between implicit learning abilities and everyday language competence. Although there is some evidence suggesting that implicit learning is disturbed in certain language-impaired clinical populations (e.g., Evans, Saffran, & Robe-Torres, 2009; Howard, Howard, Japikse, & Eden, 2006; Plante, Gomez, & Gerken, 2002; Tomblin, Mainela-Arnold, & Zhang, 2007), other studies have revealed no such relationship between implicit learning and language processing, and the reason for the discrepancy is not entirely clear (for additional discussion, see Conway, Karpicke, & Pisoni, 2007).

We propose that if implicit learning supports language, then it ought to be possible to demonstrate an empirical association between individual differences in implicit learning abilities in healthy adults and some measure of language processing. However, a challenge lies in choosing language and implicit learning tasks that purportedly tap into the same underlying processes. Toward this end, we use Elman's (1990) now classic paper as a theoretical foundation, in which a connectionist model – a simple recurrent network (SRN) – was shown to represent sequential order implicitly in terms of the effect it had on processing. The SRN had a context layer that served to give it a memory for previous internal states. This memory, coupled with the network's learning algorithm, gave the SRN the ability to learn about structure in sequential input, enabling it to predict the next element in a sequence, based on the preceding context. Elman (1990) and many others since have used the SRN successfully to model both language learning and processing (Christiansen & Chater, 1999) and, interestingly enough, implicit learning (Cleeremans, 1993).

The crucial commonality between implicit (sequence) learning and language learning and processing may be the ability to encode and represent sequential input, using preceding context to implicitly predict upcoming units. To directly test this hypothesis, we explore whether individual differences in implicit learning abilities are related to how well one is able to use sentence context – i.e., word predictability – to guide spoken language perception under degraded listening conditions.

2. Word predictability in spoken language perception

Previous work has shown that knowledge of the sequential probabilities in language can enable a listener to better identify – and perhaps even implicitly predict – the next word that will be spoken (Miller, Heise, & Lichten, 1951; Onnis, Farmer, Baroni, Christiansen, & Spivey, 2008; Rubenstein, 1973; c.f., Bar, 2007). This use of top-down knowledge becomes especially apparent when the speech signal is perceptually degraded, which is the case in many real-world situations. When ambient noise degrades parts of a spoken utterance, the listener must rely on long-term knowledge of the sequential regularities in language to implicitly predict the next word that will be spoken based on the previous spoken words, thus improving speech perception and comprehension (Elliott, 1995; Kalikow, Stevens, & Elliott, 1977; McClelland, Mirman, & Holt, 2006; Miller et al., 1951; Pisoni, 1996).

For example, consider the following two sentences, which end with highly predictable and non-predictable endings, respectively:

(1) Her entry should win first *prize*.
(2) The arm is riding on the *beach*.

When these two sentences are presented to participants under degraded listening conditions, long-term knowledge of language structure can improve perception of the final word in sentence (1) but not in (2). We argue then, that performance on the first type of sentence ought to be more closely associated with fundamental implicit learning abilities, because it relies on one's knowledge of word predictability that accrued implicitly over many years of exposure to language. On the other hand, performance on the second type of sentence simply relates to how well one perceives speech in noise, where knowledge of word predictability is less useful. Bilger and Rabinowitz (1979) further suggested the use of a metric for how well any individual subject can make use of context and word predictability in spoken language. Their metric is computed by taking the difference between how well one perceives the final word in high-predictability sentences (sentences of type 1) minus how well they perceive the final word in low- or zero-predictability sentences (sentences of type 2). This difference score provides a means of assessing how well an individual can use word predictability, based on the sentence context, to aid speech perception.

We propose that implicit learning abilities are used to implicitly encode the word order regularities of language, which, once learned, can be used to improve speech perception under degraded listening conditions. In the current study, we directly tested this hypothesis by assessing adult participants on both implicit learning and speech perception tasks. In the implicit learning tasks, learning was assessed by improvements to immediate memory span for statistically-consistent, structured sequences (Botvinick, 2005; Conway et al., 2007; Jamieson & Mewhort, 2005; Karpicke & Pisoni, 2004; Miller & Selfridge, 1950). This method for measuring implicit learning, based on improvement in the capacity of immediate memory, is arguably superior to the methods typically used because the

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[1] We consider implicit learning and statistical learning to refer to the same underlying phenomenon: inducing structure from input following exposure to multiple exemplars (Perruchet & Pacton, 2006). For brevity, we use the term "implicit learning" throughout the remainder of this paper.

dependent measure is indirect (Redington & Chater, 2002); that is, it does not require an explicit judgment from the participant. In the speech perception tasks, which also rely on an indirect processing measure, we use the difference score suggested by Bilger and Rabinowitz (1979), in which speech perception performance for highly predictable sentences and zero-predictability sentences under degraded listening conditions is measured (Elliott, 1995; Kalikow et al., 1977). Based on the preceding considerations, we predict that performance on the implicit learning task will be correlated with the difference score which reflects sensitivity to word predictability in spoken sentence perception.

3. Experiment 1

In the first experiment, participants engaged in a visual implicit learning task that indirectly assessed learning through improvements to immediate memory span for sequences containing redundant statistical structure (Conway et al., 2007; Karpicke & Pisoni, 2004; Miller & Selfridge, 1950). Participants also completed a speech perception in noise task that used degraded sentences varying in the predictability of the final word. If implicit learning abilities are important for acquiring long-term knowledge of sequential probabilities of words in sentences, we should expect that performance on the learning task will be positively correlated with the difference score metric derived from the speech perception task.

3.1. Method

3.1.1. Participants

Twenty-three undergraduate students (age 18–22 years old) at Indiana University received course credit for their participation. All subjects were native speakers of English and reported no history of a hearing loss, speech impairment, or other cognitive/perceptual/motor impairments at the time of testing.

3.1.2. Apparatus

For the implicit learning task, a *Magic Touch*® touch-sensitive monitor displayed visual sequences and recorded participant responses. For the sentence perception task, digital audio recordings were played through Beyer Dynamic DT-100 headphones.

Table 1
Constrained and control grammars used in Experiment 1.

Colors/ locations (n)	Constrained grammar ($n+1$)				Control grammar ($n+1$)			
	1	2	3	4	1	2	3	4
1	0.0	0.5	0.5	0.0	0.0	0.33	0.33	0.33
2	0.0	0.0	1.0	0.0	0.33	0.0	0.33	0.33
3	0.5	0.0	0.0	0.5	0.33	0.33	0.0	0.33
4	1.0	0.0	0.0	0.0	0.33	0.33	0.33	0.0

Note: Grammars show transition probabilities from position n of a sequence to position $n+1$ of a sequence for four colors labeled 1–4.

3.1.3. Stimulus materials

3.1.3.1. Visual implicit learning task. We used two artificial grammars to generate the stimuli (c.f., Jamieson & Mewhort, 2005). These grammars, depicted in Table 1, specify the probability of a particular element occurring given the preceding element. The grammar on the left was used to create constrained sequences whereas the control grammar on the right was used to create pseudorandom (unconstrained) sequences (all stimuli are listed in Appendix A). For each sequence, the starting element (1–4) was randomly determined and then the probabilities were used to determine each subsequent element, until a desired length was reached.

The constrained grammar was used to generate 48 unique sequences for the learning phase and 20 sequences for the test phase. The control grammar was used to generate twenty sequences for the test phase as well.

3.1.3.2. Auditory-only sentence perception task. We used 50 English sentences that varied in terms of the final word's predictability (Kalikow et al., 1977): 25 high-predictability sentences with a final target word that is predictable given the preceding context of the sentence; 25 zero-predictability sentences with a final target word that is not predictable (see Appendix B). The two sets of sentences were balanced in terms of length and word frequency (for details, see Clopper & Pisoni, 2006). All 50 sentences were spoken by a male speaker and were acoustically degraded by processing them with a sinewave vocoder (www.tigerspeech.com) that reduced the signal to six spectral channels.

3.1.4. Procedure

All participants completed the implicit learning task first and the sentence perception task second.

3.1.4.1. Visual implicit learning task. Input sequences consisted of colored squares (red, blue, yellow, green) appearing one at a time, in one of four possible quadrants on the screen (upper left, upper right, lower left, lower right). The task was to reproduce each sequence immediately following presentation by touching the colored squares displayed on the touch-sensitive monitor in the correct order. Fig. 1 is a depiction of the task. No feedback was given. For each participant, the mapping of color to screen location was randomly determined, as was the mapping between the four sequence elements (1–4) to each of the four quadrants/colors; however, for each subject, the mapping remained consistent across all trials.

Unbeknownst to participants, the task consisted of two parts, a learning phase and a test phase, which differed only in terms of the sequences used. In the learning phase, the 48 constrained learning sequences were presented once each, in random order. After completing the learning phase, the experiment seamlessly transitioned into the test phase, which used the 20 novel constrained and 20 unconstrained test sequences, presented in random order, once each.

3.1.4.2. Auditory-only sentence perception task. In the speech perception task, participants were told they would listen to spoken sentences that were distorted, making

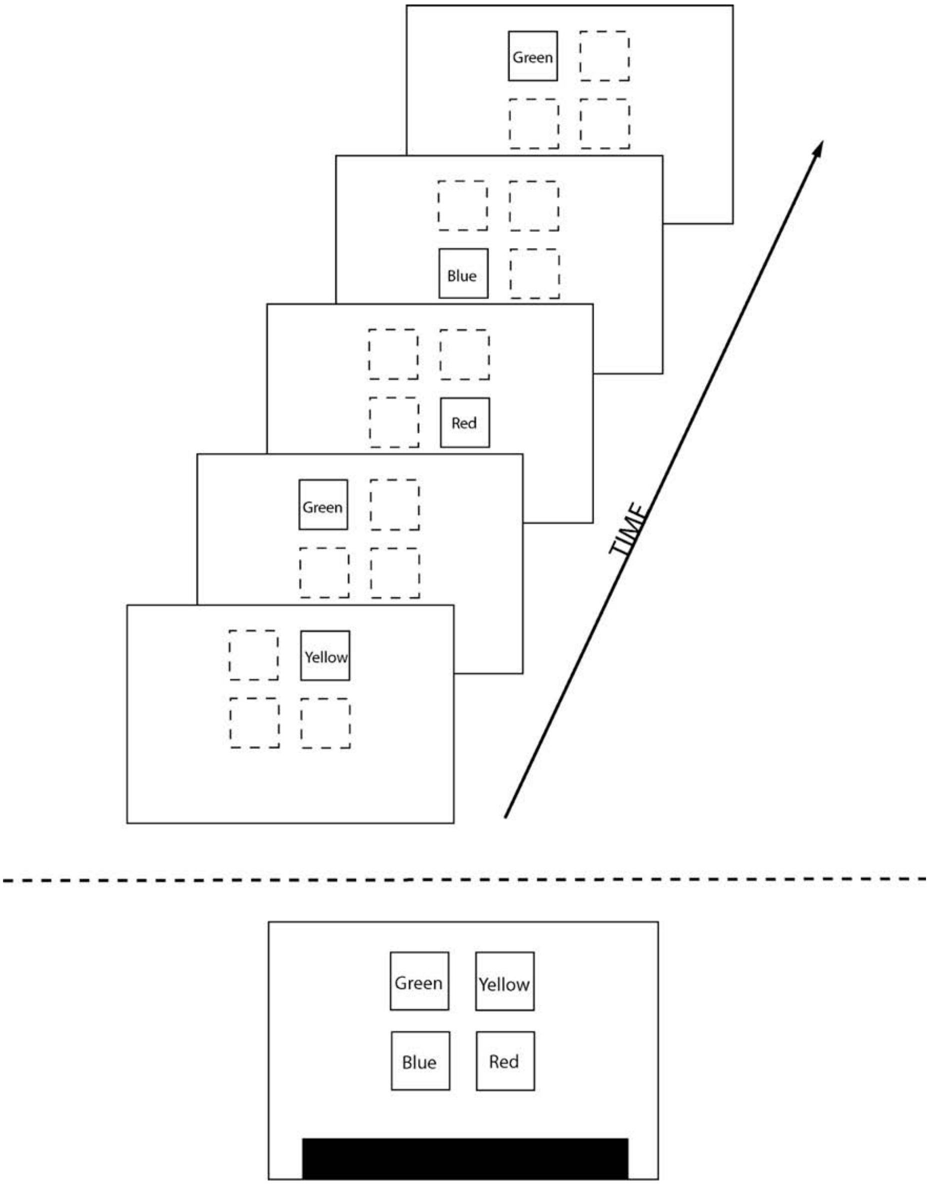

Fig. 1. Depiction of the visual implicit learning task used in Experiments 1 and 3, similar to that used in previous work (Conway et al., 2007; Karpicke & Pisoni, 2004). Participants view a sequence of colored squares (700-ms duration, 500-ms ISI) appearing on the computer screen (top) and then, 2000-ms after sequence presentation, they must attempt to reproduce the sequence by pressing the touch-panels in correct order (bottom). The next sequence occurs 2000-ms following their response.

them difficult to perceive. Their task was to identify the last word in each sentence and write that word down on a sheet of paper provided to them. Sentences were presented using a self-paced format. The 50 sentences described above were presented in random order.

3.2. Results

Data from three participants were excluded from the final analyses because their performance on one or both tasks was greater than two standard deviations from the mean, leaving a total of twenty participants included. This was done in order to reduce the undesirable effect that outliers might have on the correlation results.

In the implicit learning task, a sequence was scored as correct if the participant reproduced each test sequence correctly in its entirety. Span scores for the ‘‘grammatical” (i.e., constrained) and ‘‘ungrammatical” (i.e., pseudorandom) test sequences were calculated using a weighted span method, in which the total number of correct test sequences at a given length was multiplied by the length, and then scores at all lengths added together. Eqs. (1) and (2) show the grammatical (G_{span}) and ungrammatical (U_{span}) span scores, respectively.

$$G_{span} = \sum(g_c^* L) \tag{1}$$

$$U_{span} = \sum(u_c^* L) \tag{2}$$

In Eq. (1), g_c refers to the number of grammatical test sequences correctly reproduced at a given length, and L refers to the length. For example, if a participant correctly reproduced four grammatical test sequences of length 4, 4 of length 5, 3 of length 6, 2 of length 7, and 1 of length 8, then the G_{span} score would be computed as $(4 * 4 + 4 * 5 + 3 * 6 + 2 * 7 + 1 * 8) = 76$.

The U_{span} score is calculated in the same manner, using the number of ungrammatical test sequences correctly reproduced at a given length, u_c.

For each subject we also calculated a learning score (Eq. (3)), which is the difference between grammatical and ungrammatical span scores. The LRN score measures the extent that sequence memory spans improved for sequences that are constrained compared to pseudorandom sequences.

$$\mathrm{LRN} = G_{\mathrm{span}} - U_{\mathrm{span}} \tag{3}$$

For the sentence perception task, a sentence was scored correct if the participant wrote down the correct final word. For each participant, a word predictability difference score was calculated (Eq. (4)), which is the proportion of correctly identified target words in high-predictability sentences ($\mathrm{HighPred}_{\mathrm{corr}}$) minus the proportion of correctly identified target words in zero-predictability sentences ($\mathrm{ZeroPred}_{\mathrm{corr}}$). This difference score reflects the participant's ability to make use of context and word predictability to better perceive degraded speech.

$$\mathrm{PredDiff} = \mathrm{HighPred}_{\mathrm{corr}} - \mathrm{ZeroPred}_{\mathrm{corr}} \tag{4}$$

A summary of the descriptive statistics is shown in Table 2. The average implicit learning score was significantly greater than 0 ($t(25) = 2.2$, $p < .05$), demonstrating that as a group, participants showed better memory for predictable test sequences compared to pseudorandom sequences. For the sentence perception task, participants' correct identification of high-predictability and zero-predictability target words was 74.0% and 55.0%, respectively. The word predictability difference score was significantly greater than 0 ($t(19) = 6.87$; $p < .001$), showing that participants were better on the task when context was present (i.e., when the final word in the sentence was highly predictable based on the preceding context).

We next computed a Pearson correlation between implicit learning and the word predictability score. If implicit learning is associated with long-term knowledge of word predictability in sentences, we would expect these two scores to be significantly positively correlated. This in fact was the case ($r = .458$, $p < .05$).

Table 2
Summary of descriptive statistics for the measures used in Experiment 1.

Measure	*M*	*SD*	Observed score range	
			Minimum	Maximum
GramSpan	90.00	11.96	67.00	109.00
UngramSpan	60.05	15.50	32.00	84.00
LRN	29.95	13.95	5.00	58.00
HighPred	0.74	0.11	0.56	0.92
ZeroPred	0.55	0.08	0.40	0.64
PredDiff	0.19	0.12	−0.08	0.40

Note: GramSpan, grammatical sequence span; UngramSpan, ungrammatical sequence span; LRN, implicit learning score; HighPred, number of high-predictability sentences correct; ZeroPred, number of zero-predictability sentences correct; PredDiff, word predictability difference score.

4. Experiment 2

Experiment 1 demonstrated a statistically significant correlation between visual implicit learning and the use of knowledge of word order predictability in auditory-only speech perception. Experiment 2 served two purposes. First, it was designed to replicate the main finding of Experiment 1 but with a change in both the sensory modalities of the two experimental tasks (see Table 3) and the type of underlying structure used to generate the input sequences in the implicit learning task. If a significant correlation is still found between the two tasks even with these relatively dramatic changes, it would provide a convincing replication of the results of Experiment 1. Second, and perhaps more importantly, several additional measures were collected from participants in this study in order to determine whether there is a third mediating variable – such as general language abilities or intelligence – responsible for the observed correlation. Observing a correlation between the two tasks even after partialing out the common sources of variance associated with these other measures would provide additional support for the conclusion that implicit learning is *directly* associated with knowledge of word order predictability in language, rather than being mediated by a third underlying factor.

4.1. Method

4.1.1. Participants

Twenty-two undergraduate students (age 20–25 years old) at Indiana University received monetary compensation for their participation. All subjects were native speakers of English and reported no history of a hearing loss, speech impairment, or other cognitive/perceptual/motor impairment at the time of testing.

4.1.2. Apparatus

For the implicit learning task, Beyer Dynamic DT-100 headphones were used to present auditory sequences and a head-mounted microphone was used to record the participants' spoken responses. For the audiovisual spoken sentence perception task, the video display of the talker's face was presented on a Sony brand computer

Table 3
Input and output modalities used in Experiments 1–3.

Modality/format	Experiments 1 and 3		Experiment 2	
	IL	SP	IL	SP
Input modality	V (color/space)	A (words)	A (nonwords)	A/V (words)
Output response	manual	written	spoken	written

Note: IL = implicit learning task; SP = sentence perception task; V = visual; A = auditory; A/V = audiovisual.

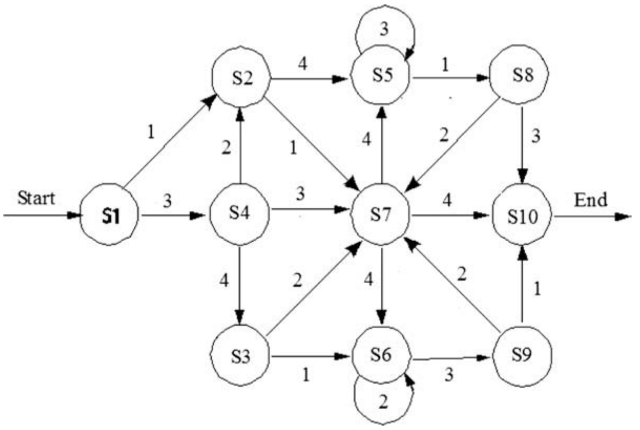

Fig. 2. Artificial grammar used in Experiment 2. Each numeral was mapped onto one of four spoken nonwords.

screen and the auditory signal was played through the headphones.

4.1.3. Stimulus materials

4.1.3.1. Auditory implicit learning task. An artificial grammar (Reber, 1967) was used to generate the stimuli (see Fig. 2 and Appendix C): 18 sequences for the learning phase and 16 additional sequences for the test phase. Sixteen ungrammatical test sequences were also created by randomizing each grammatical test sequence and making sure that none of them were grammatical with respect to the grammar.

Four spoken nonwords (“tiz”, “neb”, “dup”, and “lok”) were recorded from a 22 year-old female speaker and used to create four sound files, roughly 700 ms in duration. These nonwords were mapped onto each of the four elements (1–4) of the grammar, randomly determined for each participant. For example, if the mapping for a particular participant was 1 = “lok”; 2 = “neb”; 3 = “dup”; 4 = “tiz”, then the sequence 1–4–1–3 would be translated into the nonword sequence, “LOK–TIZ–LOK–DUP”.

4.1.3.2. Audiovisual sentence perception task. For the audiovisual sentence perception task, we used 25 high-predictability and 25 zero-predictability sentences, listed in Appendix D. The same female speaker used for the implicit learning task was video recorded speaking all 50 sentences. The recordings were then converted into video clips using Final Cut Pro HD for the Macintosh. The audio portion of the clips were then processed digitally and degraded to two spectral channels.[2]

4.1.4. Procedure

The experimental tasks for this experiment took place in a sound-attenuated booth (Industrial Acoustics Company). All participants did the auditory implicit learning task first, the audiovisual sentence perception task second, and the language and intelligence assessments last.

4.1.4.1. Auditory implicit learning task. The procedure was identical to the one used in Experiment 1 except that auditory sequences were presented instead of visual color patterns. Each nonword sequence was presented in the clear through the headphones at a level of 66–67 dB (SPL). The task was to verbally repeat each sequence immediately following presentation (see Fig. 3). The timing parameters were identical to those used in Experiment 1. Sequence presentation was self-paced. Unbeknownst to participants, the task consisted of two parts, a learning phase and a test phase, which differed only in terms of the sequences used. In the learning phase, the 18 learning sequences were presented twice each, in random order. After completing the learning phase, the experiment seamlessly transitioned into the test phase, which used the 16 grammatical and 16 ungrammatical test sequences, presented in random order, once each.

4.1.4.2. Audiovisual sentence perception task. The procedure was identical to the auditory-only version of the task used in Experiment 1 except that participants watched a video of a person speaking the sentences and the auditory (but not visual) signal was distorted. Like Experiment 1, the participants' task was to identify the last word in each sentence and write it down on paper.

4.1.4.3. Language assessment. Following the two experimental tasks, participants were given the Reading/Vocabulary and Reading/Grammar subtests of the Test of Adolescent and Adult Language (TOAL-3; Hammill, Brown, Larsen, & Wiederholt, 1994). These subtests were used to assess receptive language abilities, specifically vocabulary and knowledge of grammar. In the Reading/Vocabulary subtest, participants read three stimulus words which all relate to a common concept. From four possible responses, the participant chooses the two words that are associated more closely with the three stimulus words. In the Reading/Grammar subtest, the participant reads five sentences that are meaningfully similar but syntactically different and then selects the two that most nearly have the same meaning. Participants completed a total of 30 Reading/Vocabulary items and 25 Reading/Grammar items and received a standardized, age-normed score for each subtest.

4.1.4.4. Intelligence test. Participants completed a brief (15-min) online intelligence test (www.intelligencetest.com) consisting of 30 questions. Upon completion, the test provides a standardized, age-normed, score. The test has been found to be moderately correlated with other standardized tests of intelligence, including the Raven Progressive Matrices ($r = 0.42$) and the Wechsler Scales ($r = .32$).

4.2. Results

As in Experiment 1, outliers on the implicit learning or sentence perception tasks (two participants with scores >±2 *SD*) were excluded from the final analyses, leaving a total of 20 participants included.

A summary of the descriptive statistics for the measures used in Experiment 2 are presented in Table 4. The implicit

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[2] Pilot studies revealed that in the audiovisual speech perception task, only 2 spectral channels were needed to achieve performance comparable to the 6-channel audio-only speech perception task.

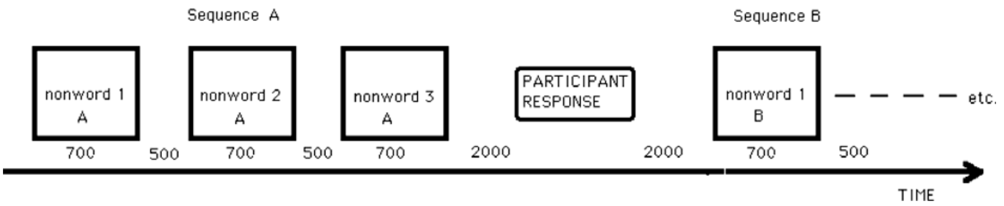

Fig. 3. Depiction of the auditory implicit learning task used in Experiment 2. Participants listened to nonword sequences (700-ms duration, 500-ms ISI) through headphones and then, 2000-ms after sequence presentation, they must attempt to verbally reproduce the sequence by speaking into a microphone. The next sequence occurs 2000-ms following their response.

Table 4
Summary of descriptive statistics for the measures used in Experiment 2.

Measure	*M*	*SD*	Observed score range	
			Minimum	Maximum
GramSpan	28.60	19.85	5.00	74.00
UngramSpan	22.60	19.45	0.00	75.00
LRN	6.00	6.79	−7.00	16.00
HighPred	0.64	0.22	0.21	0.96
ZeroPred	0.34	0.14	0.08	0.68
PredDiff	0.30	0.14	−0.20	0.52
TOAL-Vocab	13.15	2.03	9.00	15.00
TOAL-Grammar	12.85	1.39	10.00	14.00
IQ	117.60	13.01	93.00	135.00

Note: GramSpan, grammatical sequence span; UngramSpan, ungrammatical sequence span; LRN, implicit learning score; HighPred, number of high-predictability sentences correct; ZeroPred, number of zero-predictability sentences correct; PredDiff, word predictability difference score; TOAL-vocab, vocabulary as assessed by the TOAL-3 Reading/Vocabulary subscale; TOAL-grammar, knowledge of grammar as assessed by the TOAL-3 Reading/Grammar subscale; IQ, intelligence as assessed by www.intelligencetest.com.

learning score was significantly greater than 0 ($t(19) = 3.9$, $p < .01$), demonstrating that participants had better memory for test sequences generated from the grammar compared to random sequences. For the sentence perception task, participants' correct identification of high-predictability and zero-predictability target words was 68.0% and 37.0%, respectively; the word predictability difference score was significantly greater than 0 ($t(19) = 9.2$; $p < .001$).

Like Experiment 1, the correlation between the implicit learning and word predictability scores was positive, and nearly statistically significant ($r = .423$, $p = .06$, 2-tailed). Although non-significant, the strength of this correlation is strikingly similar to Experiment 1, suggesting that both sensory modality and the type of artificial grammar used have negligible effects on the nature of the association between implicit learning abilities and knowledge of word predictability.

We also computed additional correlations that partialed out the combined variance due to the TOAL-3 Reading/Vocabulary, Reading/Grammar, and intelligence scores, which actually resulted in a numerically stronger and statistically significant correlation: $r = .503$, $p < .05$, 2-tailed). Thus, it appears that the association between implicit learning and knowledge of word predictability is mediated neither by general linguistic knowledge nor global intelligence.

Finally, the implicit learning task provides a "built-in" measure of short-term memory for sequences in terms of each participant's memory spans for the ungrammatical sequences in the test phase. Because the ungrammatical sequences contain no internal structure, this score presumably reflects short-term, immediate recall. When controlling for ungrammatical sequence memory spans, the correlation between implicit learning and the word predictability difference score is also statistically significant, $r = .511$, $p < .05$.

5. Experiments 1 and 2 combined

Fig. 4 shows a scatterplot of the data from both Experiments 1 and 2 combined (using standardized *z*-scores for the implicit learning task). As can be seen from the plot, the overall correlation between implicit learning and the word predictability difference score is positive and statistically significant ($r = .418$, $p < .01$, 2-tailed).

6. Experiment 3

Experiments 1 and 2 demonstrated that implicit learning abilities are associated with the ability to use knowledge of word order predictability to aid speech perception. This association remained strong even after controlling for the common variance associated with linguistic knowledge, general intelligence, and short-term sequence memory capacity. As a final replication and extension of these findings, we next include, in addition to a visual implicit learning and auditory-only sentence perception task, measures of immediate verbal recall and working memory (i.e., forward and backward digit spans), non-verbal intelligence as measured by the Raven standard progressive matrices (Raven, Raven, & Court, 2000), and attention and inhibition as measured by the Stroop Color and Word Test (Golden & Freshwater, 2002).

6.1. Method

6.1.1. Participants

Sixty-four undergraduate students (age 18–32 years old) at Indiana University received monetary compensation for their participation. All subjects were native speakers of English and reported no history of a hearing loss, speech impairment, or other cognitive/perceptual/motor impairment at the time of testing.

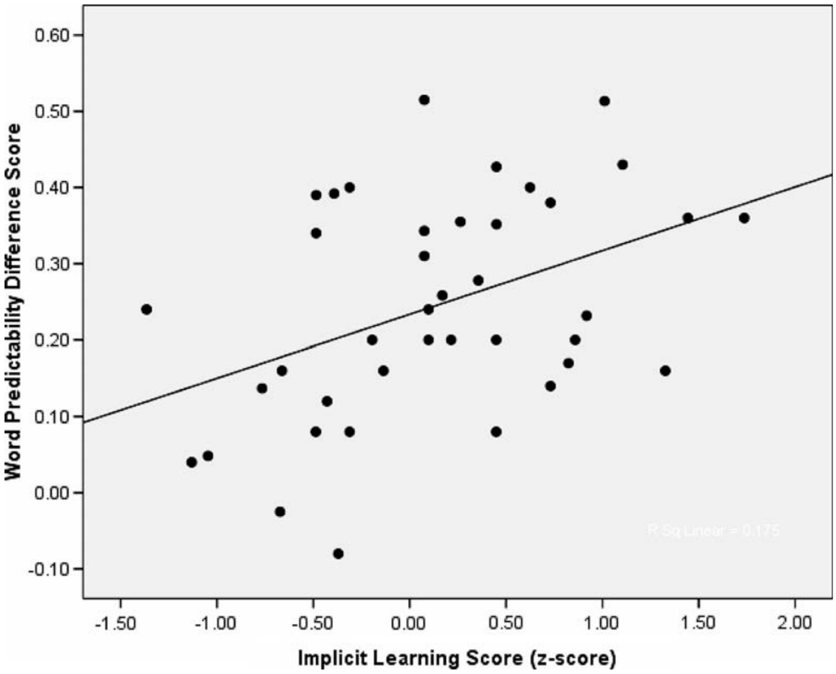

Fig. 4. Scatterplot of data from Experiments 1 and 2 ($n = 40$). The x-axis displays the implicit learning scores; the y-axis displays the word predictability difference scores for the spoken sentence perception task. The best-fit line was drawn using SPSS 16.0.

6.1.2. *Apparatus*

Experiment 3 used the same equipment as used in Experiment 1.

6.1.3. *Stimulus materials*

6.1.3.1. Visual implicit learning task. The stimuli for the visual implicit learning task were identical to those used in Experiment 1.

6.1.3.2. Auditory-only sentence perception task. Like Experiment 1, the sentence perception task incorporated two types of sentences: high-predictability and zero-predictability (18 of each, see Appendix E). Half of each sentence type were spoken by a female speaker and half by a male speaker. All sentences were degraded by reducing them to six spectral channels.

6.1.4. *Procedure*

All participants engaged in the implicit learning task first, the sentence perception task second, and the remaining assessments last.

6.1.4.1. Visual implicit learning task. The procedure for the visual learning task was identical to that used in Experiment 1.

6.1.4.2. Auditory-only sentence perception task. The procedure for the auditory-only sentence perception task was identical to that used in Experiment 1, with the only exception being that there were 36 sentences total, which were presented to participants in random order.

6.1.4.3. Forward and backward digit spans. The procedure and materials followed that outlined in Wechsler (1991). In the forward digit span task, subjects were presented with lists of pre-recorded spoken digits with lengths (2–10) that became progressively longer. The subjects' task was to repeat each sequence aloud. In the backwards digit span task, subjects were also presented with lists of spoken digits with lengths that became progressively longer, but they were asked to repeat the sequence in reverse order. Digits were played over headphones and recorded by a desk-mounted microphone. Subjects received a weighted score based on the number of sequences correctly recalled at each length for each digit span task. Generally, the forward digit span task is thought to reflect the involvement of processes that maintain and store verbal items in short-term memory for a brief period of time, whereas the backward digit span task reflects the operation of controlled attention and higher-level executive processes that manipulate and process the verbal items held in memory (Rosen & Engle, 1997).

6.1.4.4. Raven standard progressive matrices. The Raven standard progressive matrices are a series of non-verbal reasoning tasks in which participants are asked to identify which of the given pictures will best complete the larger pattern in the matrix. The difficulty of the test item increases as the test goes on, so that each of the five subsets is progressively more difficult than the last. Subjects received either the odd half or the even half of a 60 item set taken from Raven et al. (2000). Responses were scored by total number of test items correct (out of 30).

6.1.4.5. Stroop Color and Word Test. We used the paper test created by Golden and Freshwater (2002). In this classic task, which measures the participant's ability to inhibit their tendency to read a *word* and not the *color,* participants are asked to read three lists aloud. The first list is a list of words 'red', 'green', and 'blue' in random order printed in black ink. The second list is a list of xxx's in red, blue, or green ink in random order. The last list is a random list of the words 'red', 'green' and 'blue' in ink color that is incongruent with the word. Each list is 100 items long. The responses are scored on how many items in the list were said aloud in 45 s. A standardized interference score is calculated as per Golden and Freshwater (2002), which represents how well a participant is able to selectively attend to the color of the word and inhibit the automatic reading response.

Table 5
Summary of descriptive statistics for the measures used in Experiment 3.

Measure	*M*	*SD*	Observed score range	
			Minimum	Maximum
GramSpan	88.34	25.23	8.00	120.00
UngramSpan	69.63	27.50	4.00	120.00
LRN	17.68	19.08	−18.00	54.00
HighPred	0.79	0.07	0.61	0.94
ZeroPred	0.79	0.11	0.50	1.00
PredDiff	0.00	0.11	−0.22	0.22
FWdigit	57.29	19.81	14.00	108.00
BWdigit	32.32	19.38	4.00	74.00
Raven	27.59	2.37	17.00	30.00
Stroop	57.66	7.89	39.00	80.00

Note: GramSpan, grammatical sequence span; UngramSpan, ungrammatical sequence span; LRN, implicit learning score; HighPred, number of high-predictability sentences correct; ZeroPred, number of zero-predictability sentences correct; PredDiff, word predictability difference score; FWdigit, forward digit span; BWdigit, backward digit span; Raven, non-verbal intelligence as measured by the Raven Progressive Matrices; Stroop, Stroop interference score.

6.2. Results

As in Experiment 1, outliers on the implicit learning or sentence perception tasks (1 participant with a score >±2 *SD*) were excluded from the final analyses, leaving a total of 59 participants.

A summary of the descriptive statistics for the measures used in Experiment 3 are presented in Table 5. The implicit learning score was significantly greater than 0 ($t(58) = 7.12$, $p < .001$). For the sentence perception task, participants' correct identification of both high-predictability and zero-predictability target words was 79.0%; unlike Experiments 1 and 2, performance was not better for high-predictability versus low-predictability sentences. Although there were no differences as a group on the two sentence types, there was still a range of individual variability, with some participants showing improvements for the high-predictability sentences, and others not. Therefore, the primary question remains: are participants who show the best implicit learning abilities also the ones who demonstrate the best use of sentence context to aid speech perception?

Fig. 5 shows a scatterplot of the implicit learning and word predictability difference scores. Like the previous experiments, the correlation between these scores was positive and statistically significant ($r = .308$, $p < .05$, 2-tailed). The correlation remained positive and statistically significant even when controlling for the combined common variance associated with the forward and backward digit spans, Stroop interference score, and non-verbal intelligence ($r = .285$, $p < .05$, 2-tailed).

We also conducted a step-wise multiple regression analysis using the word predictability difference score as the dependent measure, and the following scores as predictors: implicit learning, forward digit span, backward

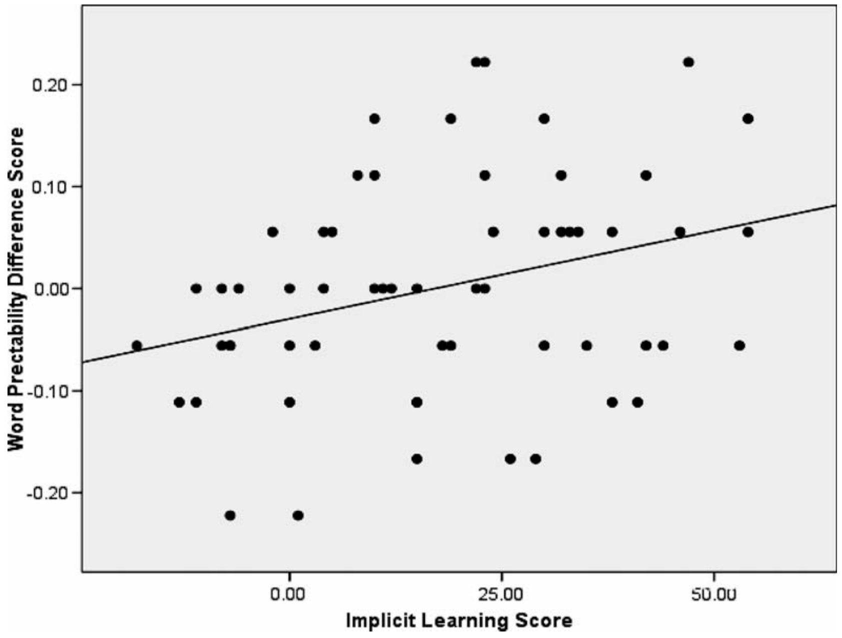

Fig. 5. Scatterplot of data from Experiment 3 ($n = 59$). The x-axis displays the implicit learning scores; the y-axis displays the word predictability difference scores for the spoken sentence perception task. The best-fit line was drawn using SPSS 16.0.

digit span, Stroop interference score, and non-verbal intelligence. The results showed that only implicit learning ($ß = 0.31$, $p < .05$) was a significant predictor. None of the other measures were significant predictors: forward digit span ($ß = 0.14$, n.s.), backward digit span ($ß = -0.12$, n.s.), Stroop interference score ($ß = 0.02$, n.s.), and non-verbal intelligence ($ß = -0.11$, n.s.). The overall model fit was $R^2 = 0.31$.

In sum, these results provide converging evidence that the ability to implicitly learn visual sequential patterns is specifically associated with the ability to use knowledge of word predictability to guide speech perception. Importantly, the association between implicit learning and knowledge of word predictability does not appear to be mediated by short-term or working memory, attention and inhibition, or non-verbal intelligence.

7. General discussion

The data from these three experiments show that performance on an implicit learning task is significantly correlated with performance on a spoken language measure that assesses sensitivity to word predictability in speech. The implicit learning tasks involved observing and reproducing visual color or auditory nonword sequences; a learning score was calculated for each individual by measuring the improvement to immediate serial recall for sequences with consistent statistical structure. The spoken language tasks involved perceiving degraded sentences that varied on the predictability of the final word; a difference score reflecting the use of sentence context (word predictability) to better perceive the final word was calculated by subtracting performance on zero-predictability sentences from performance on highly predictable sentences. A significant correlation between these two scores was found in all three experiments, even after controlling for sources of variance associated with intelligence (Experiments 2 and 3), short-term and working memory (Experiment 3), attention and inhibition (Experiment 3), and knowledge of vocabulary and syntax (Experiment 2). We conclude that the common factor involved in both tasks – and which mediated the observed correlations – is sensitivity to the underlying statistical structure contained in sequential patterns, independent of general memory, intelligence, or linguistic abilities. We propose that superior implicit learning abilities result in more detailed and robust representations of the word order probabilities in spoken language. Having a more detailed veridical representation of word predictability in turn can improve how well one can rely on top-down knowledge to help implicitly predict, and therefore perceive, the next word spoken in a sentence.

The role of top-down knowledge in influencing subsequent processing of input sequences has been mechanistically explored using a recurrent neural network model (Botvinick & Plaut, 2006). Unlike other models, Botvinick and Plaut's (2006) model captures key findings in the domain of immediate serial recall while also simulating the role that background knowledge (previous learning) has on the processing of current sequences, in a manner analogous to our implicit learning task. We imagine that this model, too, could be used to capture the data on our speech perception task, showing that background knowledge of word predictability improves processing.[3] The model of Botvinick and Plaut (2006), then, appears to offer an explicit instantiation of the cognitive process that we have identified as being important: using previous knowledge to implicitly predict upcoming items in a sequence. In the terms of Botvinick and Plaut (2006), this involves the "decoding" of imperfectly specified sequence representations through the use of long-term knowledge of sequential regularities. This model thus provides a computational link between sequence learning and semantic context effects, and is therefore a nice complement to the current findings with human participants.

An important finding from our experiments is that performance on the implicit learning task did not correlate simply with any task requiring verbalizing input (i.e., digit span tasks) or engaging linguistic knowledge (TOAL subtests). That is, implicit learning did not correlate with conventional measures of Reading/Vocabulary, Reading/Grammar, or digit spans. This suggests that despite the implicit learning task involving input patterns that are easy to verbalize,[4] performance on the learning task is not simply due to general language processing abilities. Instead, implicit learning as assessed by this task is involved in language processing in a highly *specific* way: acquiring knowledge about the *predictability* of items in a sequence.

Our sentence perception task involved materials that varied in word predictability, or semantic context (Kalikow et al., 1977). There is also evidence that implicit learning is important for other aspects of language processing too, such as syntax (Ullman, 2004) and phonotactics (Chambers et al., 2003). From our perspective, both syntax and phonotactics can be described in terms of the predictability of items (words and phonemes, respectively) in a spoken sequence, and thus, these processing domains may be two additional aspects of language that

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[3] Of course, the dependent variable in our task is word identification, not recall, but at an abstract level, the underlying mechanism – relying on background knowledge to improve subsequent processing – may be fundamentally the same.

[4] The visual learning tasks involved sequences of colors that can be easily encoded into a verbal format. When using visual implicit learning stimuli that were not as easily verbalizable, Conway et al. (2007) did not find a significant correlation with speech perception for high-predictable sentences. This suggests that although the association between implicit learning and knowledge of word predictability does not appear to depend upon the sensory modality of the input, it may indeed depend upon whether the implicit learning task incorporates input that is easy to verbalize, i.e., encode into phonological and lexical representation in immediate memory. In turn, this suggests a possible dissociation between phonological and non-phonological forms of implicit learning. In fact, there is some reason to believe that implicit learning may be at least partly mediated by a number of separate, specialized neurocognitive mechanisms (Conway & Christiansen, 2006). Goschke, Friederici, Kotz, and van Kampen (2001) showed that Broca's aphasics perform normally on a spatiomotor implicit sequence learning task but are significantly impaired on one involving phonological sequences. We suggest that there may exist partially non-overlapping verbal and non-verbal implicit learning components, in a manner similar to Baddeley's (1986) theory of working memory.

depend upon implicit learning. However, given our present results, it may be the case that an association between implicit learning and syntax or phonotactics will best be revealed only when the language tasks rely on an implicit processing measure, not one that requires an explicit judgment. Toward this purpose, it should be possible to create an analogue of the present degraded speech perception task but to manipulate the underlying syntax or phonotactics of the sentences, rather than semantic context, while measuring improvements to speech perception.

In addition to exploring the role of implicit learning in other aspects of language processing, such as syntax and phonotactics, additional future work might fruitfully explore the role of implicit learning in language development specifically. For instance, a longitudinal design with typically-developing children could help determine if implicit learning abilities predict subsequent speech and language abilities assessed several years later (see Bernhardt, Kemp, & Werker, 2007; Gathercole & Baddeley, 1989; Newman, Bernstein Ratner, Jusczyk, Jusczyk, & Dow, 2006; Tsao, Liu, & Kuhl, 2004). Such a finding would provide support for the hypothesis that implicit learning plays a *causal* role in language development. The current approach is also promising for exploring whether break-downs in implicit learning can help explain the underlying factors contributing to certain language and communication disorders, such as specific language impairment, dyslexia, and the language delays associated with profound congenital hearing loss in children (Conway, Pisoni, & Kronenberger, 2009; Conway et al., 2007).

Implicit statistical learning has often been studied under the guiding assumption that it is important for language acquisition and processing (but see Casillas, 2008). The present work bolsters the claim that general learning mechanisms are important for language, consistent with other recent evidence in neurophysiology (Christiansen, Conway, & Onnis, 2007; Friederici, Steinhauer, & Pfeifer, 2002) and clinical neuropsychology (Evans et al., 2009; Grunow, Spaulding, Gómez, & Plante, 2006; Howard et al., 2006; Menghini, Hagberg, Caltagirone, Petrosini, & Vicari, 2006; Plante et al., 2002; Tomblin et al., 2007; Ullman, 2004; Vicari, Marotta, Menghini, Molinari, & Petrosini, 2003). However, to our knowledge, no other studies – apart from our own preliminary findings (Conway et al., 2007) – have uncovered an association between individual differences in implicit learning and spoken language comprehension. One recent exception is Misyak and Christiansen (2007), who showed that adults' implicit learning performance was correlated with reading comprehension abilities. In fact, individual differences in implicit learning has been a topic that has not been explored in great depth in the past (though see Feldman, Kerr, & Streissguth, 1995; Karpicke & Pisoni, 2004; Reber, Walkenfeld, & Hernstadt, 1991). Thus, the present results suggest that studying individual differences in implicit learning may in fact be a fruitful direction for future research, in the same way that it has been in other cognitive domains.

Finally, although not our primary aim, our data also showed that implicit learning task performance did not correlate with measures of verbal short-term or working memory as assessed by the forward and backward digit spans (Experiment 2). Indeed, that implicit learning in this sequence reproduction task appears to be independent of verbal memory spans suggests that although serial order memory may be *necessary* in order to learn sequential patterns, it may not be *sufficient*. That is, the ability to encode and hold a series of items in immediate memory surely is necessary in order to learn about sequence structure; however, something else in addition – i.e., mechanisms involved in learning the underlying regularities – may be needed, as well. The exact relation between immediate memory capacity and implicit learning is an area in need of additional exploration (see Frensch & Miner, 1994; Karpicke & Pisoni, 2004). In fact, counter-intuitively, some research suggests that *smaller* memory capacities may actually be beneficial for learning complex input because it acts as a filter to reduce the complexity of the problem space, making it more manageable (Elman, 1993; Kareev, Lieberman, & Lev, 1997; Newport, 1990). Using the model of Botvinick and Plaut (2006) once more as a mechanistic framework, one could test the effect that larger or smaller sequence spans (see their footnote 9, p. 213) may have on the model's ability to learn sequence structure (i.e., implicit learning).

In sum, we have presented empirical evidence showing that variation in implicit learning abilities in adulthood is directly related to sensitivity of word predictability in speech perception, specifically, sentence perception under degraded listening conditions. The correlation between the two tasks is striking given their apparent dissimilarity on the surface: one task involves using long-term knowledge of semantics and sentence context to guide speech perception, whereas the other task has to do with short-term learning and sensitivity to visual sequential patterns where there is no explicit semantic system. Everyday speech communication is characterized by the use of context-based redundancy to facilitate real-time comprehension; thus, these findings may be important for elucidating the underlying mechanisms involved in language processing and development, as well as for understanding and treating language and communication disorders.

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Appendix A. Learning and test sequences used for Experiments 1 and 3 visual ISL task

Sequence length	Learning sequence	Test sequence (C)	Test sequence (UC)
3	4–1–2		
	1–3–4		
	2–3–4		
	3–4–1		
	4–1–3		
	1–3–1		
	1–2–3		
	2–3–1		
4	4–1–2–3	1–2–3–1	1–4–3–4
	3–4–1–3	1–3–4–1	2–1–2–4
	3–1–3–1	4–1–3–4	4–2–4–3
	2–3–1–2	4–1–3–1	1–4–1–2
	1–2–3–4		
	2–3–1–3		
	3–4–1–2		
	2–3–4–1		
5	2–3–1–3–4	4–1–3–4–1	4–1–2–3–2
	1–2–3–4–1	2–3–4–1–2	1–2–1–3–1
	3–4–1–3–1	3–4–1–2–3	1–4–2–3–1
	4–1–2–3–1	4–1–3–1–3	3–1–4–2–4
	2–3–4–1–3		
	3–4–1–3–4		
	4–1–2–3–4		
	2–3–1–2–3		
6	2–3–4–1–3–4	2–3–4–1–2–3	2–1–4–1–3–2
	3–1–3–4–1–3	3–4–1–2–3–1	4–1–3–4–3–2
	1–2–3–4–1–2	2–3–1–3–1–2	3–1–2–3–4–3
	2–3–1–2–3–1	3–1–3–1–3–1	2–1–2–1–3–4
	1–3–4–1–2–3		
	4–1–2–3–4–1		
	1–3–1–2–3–4		
	2–3–4–1–3–1		
7	4–1–3–4–1–3–1	3–4–1–3–4–1–3	2–3–1–2–3–1–3
	3–1–3–1–3–1–3	1–2–3–4–1–2–3	2–3–2–4–3–4–2
	1–2–3–4–1–3–1	3–1–3–1–2–3–4	4–3–4–2–3–2–4
	4–1–2–3–4–1––2	2–3–1–2–3–1–2	4–3–1–3–2–4–3
	3–4–1–3–1–2–3		
	2–3–1–3–1–3–4		
	1–3–1–3–4–1–2		
	3–1–3–4–1–2–3		
8	2–3–4–1–3–4–1–2	3–4–1–2–3–1–2–3	1–3–1–4–3–1–2–4
	1–3–1–3–4–1–2–3	2–3–1–2–3–1–3–1	4–3–4–2–3–4–2–4
	3–1–3–4–1–3–4–1	1–2–3–4–1–2–3–4	2–4–2–1–2–1–2–3
	3–4–1–3–4–1–3–4	3–4–1–2–3–4–1–2	2–3–2–3–1–4–2–4
	4–1–2–3–1–3–4–1		
	2–3–4–1–2–3–1–3		
	1–2–3–4–1–2–3–1		
	3–1–3–1–3–4–1–2		

Note: (C), constrained; (UC), unconstrained.

Appendix B. Sentences used for Experiment 1 auditory-only spoken sentence perception task

High predictability	Zero predictability
Eve was made from Adam's *rib*	The bread gave hockey loud *aid*
Greet the heroes with loud *cheers*	The problem hoped under the *bay*
He rode off in a cloud of *dust*	The cat is digging bread on its *beak*
Her entry should win first *prize*	The arm is riding on the *beach*
Her hair was tied with a blue *bow*	Miss Smith was worn by Adam's *blade*
He's employed by a large *firm*	The turn twisted the *cards*
Instead of a fence, plant a *hedge*	Jane ate in the glass for a *clerk*
I've got a cold and a sore *throat*	Nancy was poured by the *cops*
Keep your broken arm in a *sling*	Mr. White hit the *debt*
Maple syrup was made from *sap*	The first man heard a *feast*
She cooked him a hearty *meal*	The problems guessed their *flock*
Spread some butter on your *bread*	The coat is talking about six *frogs*
The car drove off the steep *cliff*	It was beaten around with *glue*
They tracked the lion to his *den*	The stories covered the glass *hen*
Throw out all this useless *junk*	The ship was interested in *logs*
Wash the floor with a *mop*	Face the cop through the *notch*
The lion gave an angry *roar*	The burglar was parked by an *ox*
The super highway has six *lanes*	For a bloodhound he had spoiled *pie*
To store his wood, he built a *shed*	Water the worker between the *pole*
Unlock the door and turn the *knob*	The chimpanzee on his checkers wore a *scab*
We heard the ticking of the *clock*	Miss Brown charged her wood of *sheep*
Playing checkers can be *fun*	Tom took the elbow after a *splash*
That job was an easy *task*	We rode off in our *tent*
The bloodhound followed the *trail*	The king shipped a metal *toll*
He was scared out of his *wits*	David knows long *wheels*

Appendix C. Learning and test sequences used for Experiment 2 auditory ISL task

Sequence length	Learning sequence	Test sequence (G)	Test sequence (UG)
4	1–4–1–3		
	3–4–2–4		
5	1–1–4–1–3	1–1–4–3–1	3–1–4–1–3
	1–4–3–1–3	1–4–1–2–4	1–1–2–4–4
	3–2–4–1–3	3–3–4–1–3	4–3–1–3–3
	3–3–4–3–1	3–4–1–3–1	4–1–3–3–1
6	1–1–4–2–3–1	1–4–3–1–2–4	1–2–4–3–4–1
	3–2–1–4–1–3	3–2–4–1–2–4	4–2–2–4–1–3
	3–3–4–1–2–4	3–3–4–3–1–3	3–3–1–4–3–3
	3–4–1–2–3–1	3–4–2–4–1–3	3–4–1–4–3–2
7	1–1–4–3–3–1–3	1–1–4–2–2–3–1	1–2–4–3–1–2–1
	3–2–1–4–3–2–4	3–2–1–4–1–2–4	1–1–2–3–4–3–2
	3–3–4–3–3–1–3	3–3–4–2–2–3–1	1–2–3–3–2–3–4
	3–4–2–4–3–2–4	3–4–2–4–1–2–4	2–4–3–4–1–4–2
8	1–1–4–3–3–1–2–4	1–4–3–1–2–4–3–1	4–2–1–1–3–1–4–3
	3–2–1–4–3–3–1–3	3–3–4–2–2–3–2–4	4–4–3–3–2–2–3–2
	3–3–4–3–3–1–2–4	3–4–1–3–2–4–1–3	3–1–2–4–3–4–3–1
	3–4–2–4–2–3–2–4	3–4–2–4–3–3–1–3	3–1–4–2–3–3–4–3

Note: (G), grammatical; (UG), ungrammatical.

Appendix D. Sentences used for Experiment 2 audiovisual spoken sentence perception task

High predictability	Zero predictability
A bicycle has two *wheels*	A duck talks like an *ant*
Ann works in the bank as a *clerk*	All the sailors were in *bloom*
Banks kept their money in a *vault*	For your football I prescribed a *cake*
Bob was cut by the jackknife's *blade*	Lubricate the kitten to chew the *draft*
Break the dry bread into *crumbs*	Mr. White swam with their *mugs*
Cut the meat into small *chunks*	My teacher has a glad *screen*
It was stuck together with *glue*	Peter played and swabbed a white *bruise*
Kill the bugs with this *spray*	Ruth robbed the *hay*
Paul hit the water with a *splash*	She parked the camera with brief *sheets*
Paul was arrested by the *cops*	She tracked a bill in her *cap*
Raise the flag up the *pole*	Spread some soup from the *pad*
Ruth had a necklace of glass *beads*	Stir the class into *strips*
The bird of peace is the *dove*	Syrup is a fine *sport*
The boat sailed across the *bay*	The prickly bath knew about the *track*
The bride wore a white *gown*	The rosebush slept along the *coast*
The cigarette smoke filled his *lungs*	The sailor was followed from old *wheat*
The cow gave birth to a *calf*	The sand was filled with *pine*
The nurse gave him first *aid*	The stale game was spoken by *steam*
The poor man was deeply in *debt*	The steamship employed his *crop*
The shepherds guarded their *flock*	The steep man sat with the *wax*
The wedding banquet was a *feast*	The storm was trained by a *dive*
The witness took a solemn *oath*	The turn twisted the *cards*
Tree trunks are covered with *bark*	The useless knees escaped with the *hive*
Watermelons have lots of *seeds*	They milked a frightened entry of *gin*
We swam at the beach at high *tide*	This bear won't drive in the *lock*

Appendix E. Sentences used for Experiment 3 auditory-only spoken sentence perception task

High predictability	Zero predictability
He was scared out of his *wits*	Mr. White hit the *debt*
Greet the heroes with loud *cheers*	The problem hoped under the *bay*
He rode off in a cloud of *dust*	Nancy was poured by the *cops*
Her entry should win first *prize*	Jane ate in the glass for a *clerk*
Her hair was tied with a blue *bow*	The ship was interested in *logs*
He's employed by a large *firm*	The turn twisted the *cards*
Instead of a fence, plant a *hedge*	The stories covered the glass *hen*
I've got a cold and a sore *throat*	It was beaten around with *glue*
Keep your broken arm in a *sling*	The problems guessed their *flock*
The baby slept in his *crib*	Discuss the sailboat on the *bend*
The candle flame melted the *wax*	Face the cop through a *notch*
The drowning man let out a *yell*	The king shipped a metal *toll*
The fruit was shipped in wooden *crates*	The low woman was gladly in the *calf*
The furniture was made of *pine*	The old cloud broke his *lungs*
The honey bees swarmed round the *hive*	Water the worker between the *poles*
The little girl cuddled her *doll*	We scared a bomb of clever *geese*
The lonely bird searched for its *mate*	They milked a frightened entry of *gin*
The railroad train ran off the *track*	The rosebush slept along the *coast*

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