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Implicit Statistical Learning and Language Acquisition:
Experience-Dependent Constraints on Learning

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Abstract

Acquiring spoken language involves implicitly learning the statistical relations among language units. In this chapter, we review recent behavioral and neurophysiological findings from our research group that illuminate the relation of this type of ‘implicit statistical learning’ (ISL) to language acquisition. First, we review evidence illustrating that ISL mechanisms enable the learner to predict upcoming language units. Second, we show modality constraints affecting the operation of ISL mechanisms, with auditory and visual learning biased to learn different types of patterns. Third, we demonstrate that under certain developmental conditions typical ISL abilities are altered, which can detrimentally affect subsequent language acquisition. These findings highlight the experience-dependent nature of ISL and its relation to typical and atypical language acquisition.

Introduction

Acquiring one’s native language involves at least to some extent implicitly learning the statistical or distributional relations among linguistic units. By “implicit” we simply mean that learning proceeds largely automatically, unintentionally, and often without the learner’s conscious awareness. By “statistical” we mean that language is made up of complex probabilistic associations among language units. There is a growing body of evidence suggesting that this kind of learning is present very early in life, allowing the infant to acquire knowledge about the statistical regularities of language input, which appears necessary for supporting typical language development.

In fact, these learning mechanisms are thought to be important not only in language but also in other domains. Especially relevant are situations involving learning items in a sequence: much of an individual’s everyday life requires understanding the order that certain units or

events occur in relation to other units in the sequence. Even relatively simple behaviors like starting a car, making a sandwich, or brushing one's teeth require a specific set of actions to complete, with each of the individual actions nested in a specific position in the larger sequence. This is what Karl Lashley referred to as the "serial order problem" (Lashley, 1951; Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007). The serial order problem is relevant not only for planning and producing motor behaviors, as in the previous examples, but also for *interpreting* stimuli from the environment. For example, infants learn to parse action stimuli by observing unbroken event streams (Bauer & Mandler, 1992; Sharon & Wynn, 1998) such as a ball passing underneath a bridge (Hespos, Saylor, & Grossman (2009).

In the case of an infant learning spoken language, he must not only perceive the sounds of speech, he must also be able to discern the order of the sounds in such a way to make the sound sequence meaningful. Thus, the process of serial order processing is central in the acquisition and development of many cognitive skills. Whereas learning many kinds of skills (like brushing one's teeth) involve relatively simple and repetitive action sequences, language consists almost entirely of complex probabilistic patterns. Rarely is a spoken utterance completely predictable or completely unpredictable – most often, the next word or linguistic unit that will be uttered is at least partly constrained by the previous context. In this way, language acquisition is both relatively similar to more basic sequencing skills and also more complex than most other cognitive domains because of the highly variable and probabilistic nature of the input to be learned. It is this type of learning – "implicit statistical learning" (ISL) – especially for sequential input, that we believe is so important for language acquisition and processing (Conway, Bauernschmidt, Huang, & Pisoni, 2010).

In one of the early papers first exploring ISL mechanisms in infants, Saffran, Aslin, and Newport (1996) showed that infants can parse made up, three syllable “words” from unbroken, fluent speech streams after only a few minutes of auditory input. It was concluded that this remarkable ability is the result of the broader human capacity to track co-occurrence statistics (although see Giroux & Rey, 2009). Thus, the infants were able to discern the “words” from the “non-words” because the syllables within a word co-occurred with a much higher frequency than the syllables at word boundaries. Though less well established, this type of co-occurrence information is also thought to be used in the acquisition of syntax. Saffran (2001) showed that, like words, phrases are more easily learned when structured with predictive dependencies. When exposed to nonsense languages, adult participants did significantly better when the grammar of the language contained structural dependencies than when it did not (Saffran, 2002).

Interestingly, not only does ISL appear to be important for learning about the environment, it also appears to scaffold subsequent memory and learning (Perruchet & Vinter, 2009). In a recent review, Zacks and Swallow (2007) point to evidence from three recent studies using populations of typical adult participants. One study using older adults found that participants who were better able to segment parts from still pictures were also more likely to remember the details of an event sequence (Zacks, Speer, Vettel, & Jacoby, 2006). Another set of studies (Hard, Lozano, & Tversky, in press; Lozano, Hard, & Tversky, in press) looked at people’s ability to organize sequence information hierarchically. Participants were asked to watch sequences of action events and then perform the sequence themselves. Those who were better able to organize the sequence information into hierarchical units showed higher levels of learning the procedures. Taken together, these studies indicate that across the lifespan, the ability

to segment information from perceptual streams may aid in development and cognitive processing.

While a substantial body of work has shown that ISL is important for typical development, we still know very little regarding the environmental or maturational factors that might influence the effectiveness of such learning. It has sometimes been argued that the ability to implicitly learn patterns from the environment is amodal, automatic, and innate (Reber, 1993). Under this view, there may be minimal individual differences in implicit learning both within and across species, with the basic processing ability present in most higher order species (e.g., see Conway & Christiansen, 2001). In addition, implicit learning would be more or less constant within an individual over time (i.e., developmental invariance) as well as happen automatically, without voluntary control (Zacks & Swallow, 2007). In fact, it does appear that infants possess and utilize this ability from an extremely young age (Fiser & Aslin, 2002; Jusczyk, Houston, & Newsome, 1999; Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999). The issue of amodality has been suggested from studies showing that patterns that are learned in one sensory modality or domain (e.g., audition) can sometimes be transferred to other modalities or domains (e.g., vision) (e.g., Altmann, Dienes, & Goode, 1995).

In this chapter, we present research work from our lab that has attempted to elucidate the developmental and neural mechanisms underlying ISL. Specifically, we show that each of these three common assumptions of ISL --- lack of individual differences, amodality, and developmental invariance – may be incorrect. First, we present recent work showing that individual differences in ISL are related to the ability to make (presumably unconscious) predictions about stimuli in the environment, which directly impacts language processing.

Second, we present evidence suggesting that the modality in which stimuli are presented affects how stimuli are interpreted and learned. Third, we present recent evidence suggesting heightened ISL abilities early in development, with typically developing children showing an advantage compared to adults. We close by considering whether impairments to ISL may help explain the presence of disorders of both spoken and written language. We discuss these findings in terms of understanding the environmental and developmental factors that influence ISL abilities and the implications for language acquisition and processing.

Implicit Statistical Learning and Prediction in Language

It has been suggested that one of the main functions of the human brain is to predict what will occur next in an individual's environment (Hawkins, 2004; Kveraga, Ghuman, & Bar, 2007). The ability to predict in turn depends on the ability to acquire and to store in memory environmental patterns that have been encountered in the past, and to use this knowledge to foresee probable events in the future. Successful prediction mitigates the cognitive and behavioral costs of relearning and increases the organism's chance of survival. Under this view, statistical learning mechanisms can potentially play an enormous role in the brain's ability to predict: without the ability to learn environmental patterns, successful predictions cannot be successfully made. This claim receives additional indirect support from computational models like Elman's (1991) simple recurrent network, which is able to mimic some aspects of human language behavior, using a predictive-based mechanism, after learning language-like input patterns.

In most natural language utterances, some features of the utterance downstream are predictable based on the initial part of the utterance. For example, a phrase that begins with "the"

is most likely followed by a noun or an adjective, as in “the silly girl.” The expectation of a noun or adjective significantly decreases the options of words that may follow “the,” increasing the probability that an individual will identify the correct word when interpreting the utterance. Indeed, establishing this type of knowledge of syntactic processing is a significant challenge in first language acquisition. Semantic knowledge can also be used for prediction, because only some nouns make sense following particular verbs. Although there is good reason to believe that ISL is important for a wide range of prediction-based activities in language processing, there is very little empirical evidence for it. Furthermore, the extent of variability, or individual differences, in prediction-based mechanisms in humans is unknown. Are some individuals more skilled at ISL, and if so, does this affect their ability to better acquire and to process (i.e. predict) upcoming language units?

In order to answer these questions, Conway, Bauernschmidt, Huang, and Pisoni (2010) investigated whether individual differences in implicit learning are related to an individual’s ability to utilize linguistic dependencies to make predictions about upcoming language units, thus facilitating speech perception. Two tasks were used in the study: a sentence perception task and a non-linguistic statistical learning task. In the sentence perception task, participants heard sentences that either ended with a predictable word or an unpredictable word. The sentences were auditorily degraded and the task was to judge what the final word in the sentence was. Below are two sentences from the study:

Sentence 1: Her entry should win first *prize*.

Sentence 2: The arm is riding on the *beach*.

In the two sentences above, only the target word in the first sentence should be predictable based on the first part of the sentence. The target word in the second sentence should not be predictable

because the sentence is semantically vacuous. Participants were presented with a corpus of sentences like those presented above, half of which were predictable based on the context of the sentence, half of which were not. Each participant received a score based on how well they could use sentence context to perceive the target words in each sentence.

To determine whether participants' performance on the sentence perception task is based on non-language specific statistical learning processes, we also measured participants' performance on a separate implicit learning task. In the learning task, four colored squares appeared on a screen and were lit up in a particular sequence. Following each sequence of squares, participants were asked to replicate the sequence by tapping the appropriate squares displayed on a touch screen monitor in the proper order. During the first half of this task, all of the sequences conformed to particular underlying statistical regularities. During the last half of the task, unconstrained sequences (sequences that did not follow the same regularities presented in the initial part of the task) were introduced. Since the sequences varied in length, participants' scores were calculated using a weighted method in which the number of correct responses for a given length was multiplied by the length, and then all were added together. This score represents how well each individual successfully replicates the sequences, with more weight given to longer sequences.

For the sentence perception task, the number of target words correctly identified in the low predictability condition was subtracted from the number of target words correctly identified in the high predictability condition in order to represent how well the participant was able to use the context of the sentence to identify the target. In the visual statistical learning task, a learning score was calculated by subtracting participants' score on the unconstrained items from their score on the constrained items. The results showed that these two scores were significantly

correlated ($r = .458, p \leq .05$), demonstrating that the participants who were better able to learn the underlying statistical structure on the implicit learning task were also better at utilizing linguistic context to interpret spoken language. A subsequent experiment demonstrated that this relationship was robust. When an auditory implicit statistical learning task was used (Experiment 2), the association between implicit learning and sentence perception was even stronger ($r = .503, p \leq .05$) even after controlling for linguistic competence, measured using the Reading/Vocabulary and Reading/Grammar subtests of the Test of Adolescent and Adult Language (TOAL-3; Hammill, Brown, Larsen, & Wiederholt, 1994) and general intelligence. In a final replication (Experiment 3), a multiple regression was used to determine whether visual implicit learning, forward digit span, backward digit span, executive control, and nonverbal intelligence were predictive of the sentence perception score. Using a stepwise regression, the results showed that only the visual implicit learning was significantly predictive of participants' performance on the sentence perception task, suggesting that the relationship between these two cognitive processes is unique, and not attributable to other cognitive abilities such as executive control, verbal working memory, or nonverbal intelligence.

In a more recent study, Conway, Walk, Anaya, and Pisoni (under review) attempted to provide additional evidence for the link between ISL and the use of prediction in spoken language by looking at a case of atypical language processing: deaf children with a cochlear implant (CI). A cochlear implant is a surgically implanted device that bypasses the eardrum and electrically stimulates the cochlea, allowing profoundly deaf individuals access to residual hearing. In this study, we presented a set of lexically controlled sentences (Eisenberg et al., 2002) to the participants who were tested on their ability to accurately report three target words in each. We compared the performance of deaf children with at least one cochlear implant who

heard the sentences without any auditory alteration to that of normal hearing children who heard the sentences presented under degraded listening conditions. The results of this study revealed that whereas the typically hearing children showed an effect of word position, in which performance increased for the final word positions, there was no effect of word position for the deaf group. Since the final word in a sentence is more predictable than the earlier words, one way to interpret this study is that the typically hearing children were using the first and second words in the sentence to predict the final target word, while the children with cochlear implants were not using sentence context to help predict and perceive subsequent words, instead perceiving a sentence as a “string of unrelated words”. Furthermore, within the deaf group, there was an association between their ability to use sentence context to perceive the final words in the sentence and their performance on a visual statistical learning task (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). This finding suggests that, like the typically hearing adults in Conway et al. (2010), for children with a language delay due to hearing impairment, the ability to process and predict upcoming linguistic units is based on domain-general statistical learning abilities. Furthermore, the deaf children with cochlear implants showed disturbances to visual statistical-sequential learning compared to the normal-hearing children (Conway, Pisoni et al., 2011). This last result will be discussed more fully in the next section.

In summary, the findings from these two studies suggest that there are meaningful variations in ISL abilities across individuals and that these variations may have very real effects on the ability to learn and process language and possibly other input domains. Other recent empirical work also supports this claim (e.g., Arciuli & Simpson, 2012; Kidd, 2012; Misyak & Christiansen, 2012). Furthermore, in atypical language situations including deaf or hard of hearing children, individual differences in ISL might help elucidate variations in language

outcomes (Conway et al., 2011). Importantly, these findings suggest that disturbances to ISL might not affect all aspects of language processing but specifically those related to learning and using knowledge of the structure of language to make predictions about upcoming language units. However, what causes some of the observed variability in ISL? And, does any given individual possess just a single learning ability or are there multiple learning mechanisms for different domains and situations?

Modality Constraints on Implicit Statistical Learning

Some of the earliest characterizations of implicit learning was that it was amodal. Reber (e.g. 1967; 1989), who made popular the use of artificial grammars to study implicit learning, provided evidence that knowledge of a learned grammar can be transferred between studied and novel stimuli sets as long as the underlying grammatical structure remained the same (although see Kirsner, Milech, & Standen, 1983). Some have taken this to mean that people encode the abstract rules underlying the grammar in a domain-general and amodal manner. Perhaps environmental regularities are stored as a mental representation that is independent of any given sensory modality or input domain. Work from our lab indicates, however, that such a characterization may be an oversimplification of how implicit learning manifests in humans. We have found that, contrary to the traditional view, the modality in which the stimuli are encoded is an important factor influencing implicit learning (Conway & Christiansen, 2005; 2006; 2009; Conway, Pisoni, & Kronenberger, 2009; Emberson, Conway, & Christiansen, 2011). In this section, we discuss three projects that lend credence to the claim that modality is indeed an important environmental factor affecting the efficiency of implicit learning.

Conway and Christiansen (2005) conducted an investigation into how statistical learning operates in vision, audition, and touch. To test statistical learning in touch, we created a device that generated vibrotactile pulses to the five digits of the participant's dominant hand. A five element finite-state grammar was used, with each element in the grammar corresponding to a digit on the hand. In the learning phase, participants passively felt their fingertips being stimulated in sequences corresponding to strings generated by the artificial grammar. In the test phase, participants were told that the order in which their fingers were stimulated followed a set of rules. They were then given a set of novel sequences and were asked to respond "yes" or "no" in terms of whether the sequence followed the same rule structure.

Comparable statistical learning tasks were designed to compare performance in touch to performance in the auditory and visual domains. To this end, we used the same finite state grammar as before, but mapped the five elements onto visual locations arranged horizontally on a computer screen for the visual task, and five pure tones that were played over headphones for the auditory task. Importantly, none of the three tasks utilized linguistic stimuli that could be easily verbalized; this was done in order to investigate the non-linguistic, perceptual learning mechanisms themselves. In all three tasks, participants who underwent the experimental condition were compared to participants in a control condition, who participated in the testing phase without the learning phase.

The results of the study showed that in all three modalities, participants who participated in the learning phase performed significantly better than the control group, correctly identifying grammatically consistent items significantly above chance. Importantly, when performance in the three domains were compared against each other, it was clear that participants performed

significantly better in the auditory task compared to vision or touch. There was no significant difference in task performance between the visual and tactile tasks.

This study, and several others (e.g., Conway & Christiansen, 2009; Emberson et al., 2011) indicate that audition appears to be a superior processing modality for ISL. On the other hand, when the task involves spatial arrangements, visual learning excels (Conway & Christiansen, 2009). Sensory modality appears to directly affect ISL, with audition highly tuned to learn sequential regularities and vision exceling at spatial patterns (see also Kubovy, 1988; Shamma, 2001). One consequence of this auditory-sequential / visual-spatial correspondence is that sound may act as a kind of “scaffolding” early in development, allowing children to learn to encode and represent serial order information in the environment (Conway et al., 2009). According to this “auditory scaffolding hypothesis” early experience with sound is essential not only for language development, but also for developing more domain-general sequencing abilities (in any modality). Consequently, early auditory deprivation may not only have a direct effect on language learning (as in the case of deaf children), but also has an indirect effect via domain-general sequence learning abilities, with deaf and hard-of-hearing children showing difficulties with visual and motor sequencing tasks (Conway, Karpicke et al., 2011; Conway, Pisoni et al., 2011) . Under this view, auditory deprivation prevents children from developing typical statistical-sequential learning abilities, and the deficit in these skills additionally hinders language development, even after hearing is restored in the case of a cochlear implant.

Further evidence of a distinction between auditory and visual ISL is provided by Walk and Conway (2011). Whereas before we examined ISL as it occurs in each modality separately, this study investigated the learning of dependencies across sensory modalities and perceptual categories. The stimuli were constructed using an artificial grammar consisting of six elements

that were mapped onto a combination of visual and auditory stimuli: three abstract black shapes and three pure tones. This meant that a single stimulus string consisted of both auditory and visual stimuli (e.g., A1-V2-V4-A5-V6-V2, where “A” and “V” denote particular auditory or visual stimuli respectively). As in other implicit learning studies, the experiment consisted of two phases: a learning phase, in which participants were asked to attend to an unbroken stream of “grammatical” stimuli, and a test phase, in which participants heard a six-item sequence and were asked to determine whether each item conformed to the same regularities as before. During the test phase, violations were introduced to half of the items. Of the items containing a violation, half were violations occurring at a boundary between elements of different modalities (i.e., a violation occurred between a shape and a tone) and half were violations occurring between elements of the same modality (i.e., a violation occurred between two shapes or two tones). When performance was compared to chance, it was found that participants performed significantly above chance on items in which a violation had occurred between elements of a single modality. However, learning was no greater than chance when the violation was placed between two items of two different sensory modalities, indicating that crossmodal learning (i.e., learning dependencies across sensory modalities) did not occur. In a subsequent experiment, we tested whether participants could identify pattern violations when they were between elements that were in the same modality, but belonged to a different perceptual category (e.g., between a tone and a nonsense syllable, which are two different perceptual categories within the same sensory modality). The results were similar; participants were unable to identify grammatical violations that crossed perceptual boundaries.

The findings from Walk and Conway (2011) suggest that ISL respects boundaries between perceptual modalities and categories. It is possible that the default learning mode is to

learn dependencies between items that are perceptually similar at the expense of learning associations across categories. Clearly then, ISL is not amodal, because if it were we would expect participants to learn the patterns across modalities and perceptual categories equally well. How these findings relate to the natural language learning situation is not currently clear. In natural language it is known that people do integrate cues across different perceptual modalities (e.g., using visual cues of a person's face to help interpret the auditory signal). However, our work might suggest that dependencies are learned primarily within each modality (e.g., speech vs. visual cues) separately, but that some additional process is used to link dependencies across the modalities. A similar proposal is found in Bernstein (2005), who proposes that modality-specific processing of speech occurs in early brain regions; subsequently, the predictable correspondences between auditory and visual information is learned (also see Conway & Pisoni, 2008 for further discussion on the relation between modality-specificity and domain-generality in both ISL and language acquisition).

Finally, an ongoing study in our lab (currently unpublished) offers further support that ISL operates differently in vision and audition. The aim of the study was to investigate whether participants treat reverse pairs differently than learned pairs in an implicit learning paradigm. Several previous studies have demonstrated that in addition to learning forward probabilities, participants can also track backward transitional probabilities. For instance, Jones and Pashler (2007) showed that after brief exposure to a visual statistical learning task using abstract shapes, participants were able to not only predict the second shape belonging to a pair of shapes that consistently co-occurred, but they could also “retrodict” the first shape based on a second given in a pair. Similarly, Turk-Browne and Scholl (2009) had participants undergo a visual statistical learning task with triplets rather than pairs of stimuli. During a testing phase, participants were

given two triplets and asked to choose which one was more familiar based on a familiarization period. As expected, participants were able to consistently choose triplets that they encountered during training over random foils. However, they also consistently chose backward triplets, which they never actually saw during training, over random foils.

While these studies indicate that participants can track backward probabilities embedded in structured environmental stimuli, they both only employed stimuli presented in the visual modality. It is therefore important to investigate these effects in other sensory modalities as well, especially given the evidence that the modalities may be better suited for different roles in learning. For example, Conway, Goldstone, and Christiansen (2007) demonstrated that in vision, participants' ability to learn the statistical associations of shape pairs was specific to the relative position of the shapes in space. This finding indicates that visual statistical learning is perceptually constrained by spatial grouping principles but unconstrained in terms of sequential order. In other words, in the spatial domain, participants' learning was specific to the exact spatial arrangement that they experienced during exposure, whereas in the sequential domain, participants were able to pick out familiar sequences even when the order was reversed (Turk-Browne & Scholl, 2009), suggesting more flexible learning abilities for sequences compared to spatial arrangements. In the present study, we sought to further investigate the serial order constraints of auditory and visual statistical learning using modality as a within subjects variable. The study incorporated visual abstract shapes and auditory pure tones. Participants were exposed to a continuous string of stimuli in which two pairs of shapes or tones were presented within a string of otherwise random stimuli. During the testing phase, participants were given a two alternative forced choice test and asked to identify pairs based on familiarity. Test items were constructed so that participants had to choose between two types of items, arranged in three

ways; participants always chose between a pair and a foil, a pair and reversed pair, or a reversed pair and a foil.

In the visual domain, participants consistently chose the pair over the foil, but for items where a forward pair was compared to a reversed pair, their responses were at chance levels. The opposite result was seen in the auditory modality. When pairs were compared to foils, performance was at chance. However, participants consistently chose the forward pair and the foil when either was compared to the backward pair. This result implies that in audition only, participants are very adverse to choosing the backward pair as familiar, even after being exposed to the dependencies between tones and comparing that to a random pairing. This is especially interesting in light of the Conway and Christiansen's (2005) study indicating that audition is a superior processing modality for sequence learning. This unpublished data in conjunction with Conway et al. (2007) lends further support to modality differences in statistical learning: auditory statistical learning is more sensitive to sequential order effects whereas visual statistical learning is constrained by spatial grouping. These findings are in contrast to an amodal view of statistical learning which would suggest that sequential patterns can be learned equally well through any modality.

In summary, the way in which statistical regularities are learned appears to differ depending on the sensory modality that is receiving the information. Sequential patterns are learned best by the sense of hearing and spatial patterns may be best learned by vision (also see Dye & Bavelier, 2010). Not only that, but dependencies across sensory modalities – and even perceptual categories within a modality – are not naturally or as easily learned. It appears then that ISL is heavily constrained by the perceptual modality and input category in question. Indeed, as we predicted earlier based on the available behavioral findings alone (Conway & Christiansen,

2005), there is now neural evidence suggesting that ISL may consist of multiple modality-specific mechanisms in the brain (Turk-Browne, Scholl, Chun, & Johnson, 2009; see also Goschke & Bolte, 2012). In addition to these domain-specific neural mechanisms, there may also be more domain-general neural processing regions that contribute to ISL (for discussion, see Conway & Pisoni, 2008). The manner in which these modality-specific and domain-general processing mechanisms interact is still currently underspecified. One possibility is that the separate, domain-specific neural mechanisms all rest on similar computational principles, and are linked or supervised in some manner through the involvement of more domain-general neural regions like the prefrontal cortex (Conway & Pisoni, 2008).

Developmental Constraints on Implicit Statistical Learning

Most research has demonstrated that ISL abilities are present in some form very early in development (Fiser & Aslin, 2002; Jusczyk, Houston, & Newsome, 1999; Kirkham, Slemmer, & Johnson, 2002; Saffran, Aslin, & Newport, 1996; Saffran, Johnson, Aslin, & Newport, 1999). These findings are relatively consistent with Reber's (1993) claim of developmental invariance in implicit learning skills. On the other hand, there is some evidence that there are developmental differences in implicit learning, with adults or older children out-performing younger children (e.g., Mecklenbräuker, Hupbach, & Wippich, 2003; Thomas, Hunt, Vizueta, Sommer, Durston, Yang, & Worden, 2004). To make matters even more confusing, there is some evidence that cognitive limitations that may be present early in development might actually lead to a computational advantage for certain learning situations (Elman, 1993; Newport, 1990; Poletiek, Conway, Ellefson, Lai, & Christiansen, under review).

Recently, our lab has begun a series of studies using a brain based measure, event related potentials (ERPs), to disentangle the developmental progression of ISL in both typical and atypical populations. Our initial results suggest that there may be dramatic developmental changes in ISL over the course of childhood, and that certain special populations have altered ISL mechanisms that may be affecting their development of language and other skills.

In order to probe the development of ISL in adults and children of different ages and ability, we designed a simple visual probabilistic learning task (Jost, Conway, Purdy, and Hendricks, 2011; under review) . In the task, participants were seated in front of a computer in which they saw a series of different colored large circles flash in the center of the screen one at a time. The participants' task was to press a button as quickly as possible in response to a target color, that was told to them at the beginning of the experiment. What participants were not told is that the appearance of the target circle was not random but was partly predictable based on what color preceded it. One of the predictor colors was the "high predictor", which was followed by the target 90% of the time and a filler 10% of the time; a second predictor color was the "low predictor", which was followed by the target only 20% of the time and a filler 80% of the time; the final predictor color was the "zero predictor", which was never followed by the target (and was followed by a filler 100% of the time). Our expectation was that if participants learned that the high predictor was a better predictor for the occurrence of the target, then this should be reflected in differences in the ERP waveforms for the high versus the low or zero predictors. That is, when the participant observes the high predictor color, their brain should (implicitly) "recognize" that this particular color signifies a good chance that the target is to follow. Even though this paradigm is simpler in terms of input complexity than other typical tasks often used to study statistical learning, pilot testing has shown that the task is effective with child

participants and other special populations (i.e., the children find the task engaging and do not show frustration with the task demands)..

We have collected ERP data from college-aged adults, older children (ages 9-12), and younger children (ages 6-9). We examined ERP results separately for the first half of the experiment compared with the second half, in order to assess learning effects that may have taken place over the course of the experiment. For all three age groups, a late positivity superficially similar to a P300 component emerged in the latter half of the experiment in response to the high predictor. Although the P300 component is generally not considered to be a language-related component in the same way that the P600 is, it is possible that the P300 is essentially an “earlier” P600 (Coulson, King, & Kutas, 1998), which would provide further links between the brain bases of statistical learning and language processing (see also Christiansen, Conway, & Onnis, 2012).

In addition to the P300, the younger children also showed an N2 response for the high predictor. The combination of N2/P300 components elicited in this learning task perhaps is not surprising, as the N2 and P300 have been observed together in previous studies examining basic learning processes such as context updating and chunking (Russeler & Roesler, 2000; Schlaghecken, Stuermer & Eimer, 2000). What is more surprising is that the N2 and P300 emerged in the children in the first part of the experiment, whereas for the adults the P300 did not emerge until the last part of the experiment. That the children showed learning-related neural components after much less exposure to the statistical probabilities than did the adults suggests a heightened sensitivity to predictive statistical dependencies. Thus, unlike previous studies suggesting developmental invariance or a steady progression of ISL, these neural findings suggest that children’s brains are “primed” to learn statistical patterns in the environment. A

similar finding was also recently uncovered by Janacsek, Fiser, and Nemeth (2012), with performance in an implicit probabilistic sequence learning showing a developmental decline at around age 12.

Although there may be a number of factors that could explain the heightened learning abilities in the children, one possibility is that, cognitive limitations early in development (e.g., smaller working memory capacity) might actually be beneficial in that they allow children to focus on the smaller and simpler aspects of a complex stimulus domain first, which promotes more effective and efficient learning abilities (Elman, 1993). These findings are also consistent with an experience-dependent framework for ISL: initially, a child's brain is highly plastic and very adept at learning environmental regularities. As a child's brain becomes "entrenched" with the statistical regularities of a particular input domain (such as language), learning for that particular input domain improves; on the other hand, for other types of regularities that are inconsistent with that same domain, learning suffers (Elman et al., 1996; Goldberg, 1993; Kuhl, 2004).

If early in development, the child's brain is especially well-attuned to encoding environmental regularities linguistic or otherwise, is it possible that in some cases of atypical language development, impaired ISL may be to blame? This is the next question we have begun to explore using ERP methodology. Behavioral evidence has suggested that certain special populations have more difficulty with ISL than typically developing children. This has been shown in deaf children with cochlear implants (Conway et al., 2011) as well as in children with dyslexia (Eden, Stein, Wood, & Wood, 1995; Howard, Howard, Japiske, & Eden, 2006). However, very little work has used brain based measures to investigate the neural mechanisms of ISL in such populations.

We are currently using the same predictive learning task as that described above (Jost et al., 2011) with a new group of typically developing children, deaf children with cochlear implants ($n=3$), and children who have been diagnosed with dyslexia ($n=4$). Our previous work with deaf children with cochlear implants suggests that their language outcomes may be due to variations in underlying domain-general (i.e., non-auditory) ISL abilities (Conway et al., 2011). We added the group of children with dyslexia to see if a very different type of language impairment may have at its root cause a similar underlying neural deficit as the hearing-impaired children. ERPs were recorded in all three groups to compare the neural mechanisms underlying ISL. Like our results described above, the typically developing children showed a late positivity in response to the high predictor. Somewhat surprisingly, a very similar pattern of results was seen in the deaf children with cochlear implants. In contrast, no late positivity was seen in the children diagnosed with dyslexia. Instead, for the children with dyslexia, there was some evidence of a late positivity in response to the low predictor condition.

Although these results are still preliminary and due to the low sample size must be treated with caution, they are illustrative of the kind of approach that is possible when one takes the theoretical stance that variations in domain-general ISL abilities causally relate to language outcomes. In this particular case, the preliminary results suggest that children with dyslexia have difficulties not only with decoding written language, but also with learning the statistical regularities of non-linguistic visual stimuli. It is perhaps this impairment to fundamental statistical learning abilities (or to processes that constrain ISL) that contributes to problems with reading. Like spoken language, written language is also characterized by statistical structure that governs the pairings between letters as well as the mappings between letters and sounds. Interestingly enough, recent evidence suggests that variations in statistical learning are associated

with reading ability in both typically developing children and adults (Arciuli & Simpson, 2012). Whereas it is too early to tell whether dyslexia is in fact caused by impairments to ISL, rather than impairments to other processes such as phonological short-term memory (Hulme & Snowling, 1992), we believe the current findings are at least suggestive of such a link and deserve further research.

In contrast to the children with dyslexia, our initial results with the deaf children with cochlear implants showed intact ERP correlates of statistical learning, similar to the typically developing children. Based on our earlier work suggesting that this clinical group may show behavioral impairments to ISL (Conway et al., 2011), we expected these children to show altered neural waveforms. The reason for this finding is currently unclear but there are at least two possibilities. The first is simply that the power in this group was low ($N=3$), and it may be that these three particular children are on the high end of language and cognition. Indeed, subjective observations revealed that these particular children were quite adept at spoken language, and thus it would be consistent with our theoretical framework that their ISL abilities are also strong. The second possibility is that this clinical population in fact does have typical neural mechanisms for encoding statistical structure, but that there exist behavioral (e.g., perceptual-motor) deficits in expressing such knowledge. Such a finding is intriguing and could help pinpoint where the apparent difficulty with language learning might occur: specifically, it would mean that the children's brain mechanisms involved with encoding environmental and language statistical structure is intact; but their cognitive or behavioral manifestation of such learning is altered. If this is in fact true, then it suggests that interventions focusing on the output of learning and on accessing one's knowledge of language may be more important for this clinical population than interventions designed to help with perception and acquisition of the input itself.

Discussion

We have presented several key findings. First, individual differences in ISL are associated with how well one is able to use knowledge of statistical regularities to predict and better perceive units of spoken language (Conway et al., 2010). Such individual differences may help explain variations related to atypical spoken language processing, such as in the case of deaf or hard of hearing children (Conway et al., 2011; Conway et al., under review). Second, ISL is heavily constrained by the sense modality used to perceive the information. Whereas audition excels at sequential statistical learning, vision appears best at spatial statistical learning (Conway & Christiansen, 2005; 2009). Furthermore, the learning of cross-modal or cross-category associations does not appear to occur as easily or as readily as within-modal or within-category dependencies (Walk & Conway, 2011). Third, there also appear to be developmental constraints affecting ISL. Children showed neural evidence of visual statistical learning much quicker than did adults, possibly suggesting that at least in typically developing children, their brains are highly adept at learning environmental regularities (Jost et al., 2011). Such an exquisitely-tuned mechanism for encoding statistical regularities might explain the presence of sensitive periods in language acquisition, with children able to learn a new language generally better than adults. Some preliminary evidence was also presented showing that deficits to visual statistical learning are also associated with children who have been diagnosed with dyslexia. Thus, an atypical developmental trajectory in ISL, leading to ISL impairments, may be a contributing factor to the presence of certain language and communication disorders.

These findings stand in contrast to earlier characterizations of implicit learning as having little variation across individuals, being amodal in nature, and being developmentally invariant.

In fact, we believe our findings point to the rich diversity of ISL abilities both within and across individuals. Such differences in ISL appear to have direct consequences for the acquisition and processing of language, and possibly even other cognitive and perceptual domains. One question that presents itself is whether a given individual possesses multiple ISL mechanisms of varying ability, each possibly impacting a different type of cognitive, motor, or perceptual skill domain. A study done by Feldman, Kerr, and Streissguth (1995) may speak to this issue, in which participants completed a host of procedural and declarative learning and memory tasks. Interestingly, whereas the declarative learning tasks correlated strongly with one another, the procedural learning tasks not only did not correlate with the declarative learning tasks, but they also did not correlate with each other. Thus, implicit learning may consist of multiple relatively encapsulated learning systems. A related finding comes from Goschke and Bolte (2012) who observed independent simultaneous sequence learning of different stimulus types, suggesting a relatively modular framework for ISL (c.f., Conway & Christiansen, 2006).

Another issue that presents itself is that the findings we have presented here have been primarily correlational in nature. That is, individual differences in ISL are associated with certain aspects of language ability, in both typical and atypically-developing populations. Clearly there is a need to demonstrate whether such an association between ISL and language performance is causal in nature, and if so, its direction. There are at least two ways to demonstrate causality. As we have suggested previously (Conway et al., 2011), a longitudinal design would be useful for establishing whether ISL abilities at a particular age predict language abilities later. This type of design has been used successfully to determine for instance that variations in working memory predict vocabulary development in children (Gathercole & Baddeley, 1989). It would seem feasible to take the same approach with ISL.

Another way to demonstrate causality is through the use of interventions designed to improve ISL. We are currently taking this approach by designing computerized tasks that target ISL abilities in adults and children as a way to improve not only ISL itself but also language abilities. Our preliminary work suggests that it does in fact appear that not only can ISL be improved through repetitive training, but that such improvements carry over to non-trained learning and language tasks in both typically developing adults and in a clinical group of children with a language delay (Conway, Grep, Walk, Bauernschmidt, & Pisoni, 2012). A similar approach has been taken in the realm of working memory training (e.g., Klingberg, 2010). We believe that like working memory and perhaps other aspects of cognition, ISL also can be improved within an individual, and that such improvements could have important health-related and educational benefits especially to individuals whose learning abilities are at the core root of their disability.

One specific area that is in need of further research is the role played by ISL in second language acquisition (SLA), a topic that has seen some debate (Krashen & Terrell, 1983). As we have seen, it is widely accepted that knowledge of an individual's native language (L1) is acquired in an implicit manner, with the rules that govern the language being acquired automatically, and without awareness or intention. The acquisition of a second language (L2), however, is often done in a classroom setting, with explicit rules and feedback (Hulstijn, 2010). While it may be assumed that the most effective L2 learning would emulate L1, evidence suggests that certain aspects of explicit learning are necessary for adult L2 acquisition (DeKeyser, 1995; Robinson, 1997). A widely cited example is the important role of attention, or noticing (Schmidt, 1990), which empirical evidence suggests is necessary, if not sufficient for the acquisition of L2 (e.g. Eckerth & Tavakoli, 2012; Lam, 2009). However, the specific role of

sequence processing and statistical learning in SLA is largely unexplored and may be a fruitful area of future research.

In sum, there is increasing evidence suggesting that ISL is variable across and within individuals, that such variation has real-life implications to cognitive functioning and language outcomes, and that these abilities in part appear to be modifiable, plastic, and experience-dependent. Implicit learning is a crucial skill for development. It allows children to develop important cognitive skills such as event processing, memory, and language acquisition via mechanisms that allow them to track patterns in the environment, extract underlying regularities, and apply this knowledge to novel situations. It may be one of the primary ways that children make sense out of otherwise incredibly complex and chaotic stimuli. By understanding the experience-driven and developmental constraints that govern ISL in both typical and atypical situations, we gain insights into foundational learning mechanisms that support language, cognition, and communication.

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