

## Chapter 15

# Two Distinct Sequence Learning Mechanisms for Syntax Acquisition and Word Learning

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### ABSTRACT

*The ability to acquire spoken language depends in part on a sensitivity to the sequential regularities contained within linguistic input. In this chapter, the authors propose that language learning operates via two distinct sequence-learning processes: probabilistic sequence learning, which supports the acquisition of syntax and other structured linguistic patterns, and repetition sequence learning, which supports word learning. First, the authors review work from our lab and others illustrating that performance on tasks that require participants to learn non-linguistic sequential patterns is empirically associated with different measures of language processing. Second, they present recent work from our lab specifically highlighting the role played by probabilistic sequence learning for acquiring syntax in a sample of deaf and hard-of-hearing children. Finally, the authors demonstrate that the learning of repeating sequences is related to vocabulary development in these children. These findings suggest that there may be at least two relatively distinct domain-general sequential processing skills, with each supporting a different aspect of language acquisition.*

### INTRODUCTION

How infants learn language is one of the great scientific questions of our time. While traditional nativist views of language development rely on predetermined, innate modules to explain the infant's ability to acquire complex language systems

in a short amount of time, learning perspectives have more recently turned to domain-general processes to explain this phenomenon. As it turns out, there is evidence that infants have an uncanny ability to encode structure in complex stimulus patterns through the use of domain-general, statistical learning mechanisms. Although the idea that statistical information could be used to help decode and segment speech is at least several

DOI: 10.4018/978-1-4666-2973-8.ch015

decades old (Harris, 1955), it was the pioneering study by Saffran, Aslin, and Newport (1996) that empirically demonstrated that, in fact, infants can use co-occurrence statistics to parse novel words from sequences of nonsense syllables. This finding has opened the door for more nuanced discussions of the nature of domain-general learning abilities and their role in language acquisition.

There is now considerable agreement that statistical learning processes (also known as distributional learning, implicit learning, sequential learning, procedural learning) are crucial to language acquisition (Conway & Pisoni, 2008; Kuhl, 2004; Reber, 1967; Saffran, 2003). However, most of the empirical work has focused on what could be referred to as “existence proofs”: Many organisms, including human infants, children, and adults (as well as some non-human animals and artificial neural networks) appear to have the capability for encoding the statistical structure contained within input sequences. However, it is an altogether separate question as to whether these organisms actually use these learning abilities in the service of language acquisition. A notable advance in this regard has been made by several recent studies that have empirically demonstrated that, in fact, such domain-general learning abilities are associated with aspects of language use (Arciuli & Simpson, 2012; Conway, Bauerschmit, Huang, & Pisoni, 2010; Misyak, Christiansen, & Tomblin, 2010). Despite (or perhaps, because of) these recent studies showing that domain-general learning mechanisms are associated with language processing, a second set of questions emerge. Are statistical/sequential learning mechanisms used for all aspects of language acquisition (i.e., phonology, syntax, word learning, etc.)? In addition, related to this question, might there perhaps be more than one learning mechanisms that the infant brings forth to learn different aspects of language?

In this chapter, we describe some initial evidence to suggest that the answer to these questions is “yes”; that there may be distinct, domain-general learning mechanisms that are used to learn dif-

ferent aspects of language. Below, we begin by presenting some theoretical considerations relating to these learning mechanisms. We then present three lines of empirical research exploring the connection between domain-general sequence learning and language skills: In the first line of research, we review behavioral and neurophysiological findings with healthy adults showing that sequential learning allows the learner to encode the structure inherent in language, which provides the means for making implicit predictions about what linguistic units will be spoken next. In the second line of research, we provide some evidence focusing on deaf and hard of hearing children, suggesting that syntax acquisition may be mediated by probabilistic (or statistical) sequence learning mechanisms. Finally, in the third line of research, we highlight recent work with this same population suggesting that word learning may be mediated by mechanisms related to repetition (or fixed or invariant) sequence learning. It should be noted that while the data presented in the chapter is cross-sectional in nature, we use the terms “language acquisition” and “language development” to express our theoretical viewpoint that these domain-general learning mechanisms causally affect language acquisition, rather than the two abilities merely co-existing independently.

## **BACKGROUND**

Any discussion of spoken language acquisition requires consideration of at least two cognitive processes: auditory processing and serial order processing. The importance of auditory exposure to spoken language is perhaps obvious. Children learn their native language through early exposure to the language stimuli presented in their environment. For example, a robust line of work demonstrates that children can discriminate between all phonemes at birth, but lose that capability around 3 months of age, around which time their vocalizations begin to take on the particular characteristics

of their native language (Kuhl, 2004). The role of auditory processing – or lack thereof—is also observed in the rare case studies in which a child is reared without spoken language input, as in the case of Genie (Curtiss, 1977; Gleitman & Newport, 1995); or in the case of children who are born deaf. It is a trivial fact that auditory input is needed in order to learn to comprehend auditory-vocal spoken language. What is less trivial is that for deaf children who receive a cochlear implant during childhood to partially provide the sense of sound, the age at which the implant is provided matters, with children who have access to sound earlier in life making greater gains in language acquisition than children who don't gain access to sound until later in childhood (after 14-18 months) (Houston, Stewart, Moberly, Hollich, & Miyamoto, 2012; Raeve, 2010; Tajudeen, Waltzmann, Jethanamest, & Svirsky, 2010).

The importance of serial order processing for language acquisition is perhaps less obvious but no less important. In a sentence, a phrase, or a single word, one cannot extract meaning if the individual sound units are not ordered in a meaningful way. Thus, young infants must become sensitive to serial order in order to develop adequate receptive and expressive language abilities. Furthermore, it is possible that there may be different types or modes of serial order learning, each corresponding to a different type of input pattern (Conway & Christiansen, 2001; Conway, 2012). What we refer to as fixed or repetition sequential learning is perhaps the simplest type, involving learning any arbitrary but invariant serial list (e.g., A-E-G-K), such as a phone number. In language, fixed sequences are observed in frequently-used phrases (e.g., "It's about time") as well as in words, which are fixed sequences of phonemes. This type of sequential learning is informed by a vast amount of previous research in areas such as list learning, Hebb repetition effects, and immediate serial recall (e.g., Marshuetz, 2005). On the other hand, probabilistic sequential learning involves inducing the common underlying distributional

patterns from amongst multiple exemplars. For example, the sound combinations fun-ny and ro-bot appear together in English much more often than the combination ny-rob, though ny-rob may appear occasionally, as in the phrase "funny robot" (Conway & Christiansen, 2001). Much of language, in fact, is characterized by these types of statistical or distributional patterns that define the structure of phonology or of syntax (Redington & Chater, 1997; Saffran, 2003).

How these two sequence-learning mechanisms develop in childhood is still an open question. One possibility, as argued by Conway, Pisoni, and Kronenberger (2009), is that auditory input is necessary for developing sufficient sequencing skills, which in turn are used to acquire language. Because sound is a natural carrier of temporal information, the auditory modality appears to be more efficient for encoding structured sequential patterns (Glenberg & Jona, 1991). For example, adult participants performed significantly better on a sequential pattern learning task when it was presented in the auditory modality compared to similar patterns presented visually or tactually (Conway & Christiansen, 2005), which in turn are more effective at encoding spatial information (Thinus-Blanc & Gaunet, 1997). One possible consequence of this phenomenon is that individuals who receive no or reduced early exposure to sound input may have difficulties developing such finely tuned sequencing abilities (Conway, Karpicke, Anaya, Henning, Kronenberger, & Pisoni, 2011; Conway, Pisoni, Anaya, Karpicke, & Henning, 2011; Dawson, Busby, McKay, & Clark, 2002). Using a battery of tactile, motor, and visual tasks, Conway, Karpicke, Anaya, Henning, Kronenberger, and Pisoni (2011) demonstrated that deaf children with cochlear implants performed significantly worse only on a motor task that required participants to exploit simple sequences, whereas their performance was not significantly different from children with typical hearing on other tasks that did not require sequence processing. Interestingly, performance on the sequencing

task was significantly correlated with performance on several subtests of the Clinical Evaluation of Language Fundamentals (CELF-4; Semel, Wiig, & Secord, 2003).

Working from the assumption that sequence-learning abilities underlie language acquisition, it is a logical extension to suggest that some language disorders may be a cognitive consequence of a disturbance to domain-general sequential learning, or at the very least, that variations in sequence learning may make some contribution to language difficulties. In fact, a number of studies have shown an association between language disorders and sequence learning. For instance, using an artificial grammar constructed of novel words, Gomez, Gerkin, and Plante (2002) demonstrated that language impaired adults were significantly worse at implicitly learning the rules governing word order. In addition, children diagnosed with Specific Language Impairment (SLI) show significantly delayed sequence learning abilities compared to children with normal language (Tomblin, Mainela-Arnold, & Zhang, 2007; Saffran & Robe-Torres, 2009). Finally, Van Weerdenburg, Verhoeven, Bosman, and van Balkom (2011) used a series of structural equation models to investigate the relationships among linguistic and domain-general learning assessments, word reading, and spelling abilities in children with SLI. The models revealed that the only significant predictor of word reading, and later spelling abilities, was a factor related to verbal-sequential learning.

In sum, the existence of domain-general learning abilities, such as repetition and probabilistic sequential learning, may be able to help explain both typical and atypical language development. In fact, what have been traditionally labeled as “language universals” may be the result of constraints on the human ability to parse, interpret, and learn patterns embedded in complex environmental stimuli (Christiansen & Chater, 2008). However, the nature of how language bootstraps onto sequential learning abilities is a question yet open for investigation (see Kuhl, 2004, for a review).

Our proposal in the current chapter is that different domains of sequence processing require the extrapolation of different types of dependencies that in turn lead to the development of different types of language skills. Specifically, we argue that probabilistic sequencing is directly related to the acquisition of syntax (and perhaps phonology as well), whereas repetition sequence learning is associated with word learning. Before directly examining this proposal in a target population of deaf and hard of hearing children, we first describe a set of studies with healthy adults that examined the role of sequence learning and prediction in language processing.

## **SEQUENCE LEARNING AND LANGUAGE**

### **Issues, Controversies, Problems**

#### **Sequence Learning and Language in Adults: The Role of Prediction**

Before exploring the distinction between repetition and probabilistic sequence learning in deaf and hard of hearing children, we first explore a more general account of how sequence-learning mechanisms might underlie the acquisition and processing of language in healthy adults. 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, sequence learning (Cleeremans, 1993). We suggest that the crucial commonality between sequence learning and language learning and processing is the ability to encode and represent sequential input, using preceding context to implicitly predict upcoming units.

To directly test this hypothesis, we recently explored whether individual differences in sequence learning abilities were related to how well college students could use sentence context to guide spoken language perception under degraded listening conditions (Conway, et al., 2010). The study was based on the premise that language skills depend in part upon a person's implicit knowledge of sentence structure as evidenced by his/her ability to predict words downstream in a sentence that is perceptually difficult to distinguish. We predicted that implicit sequence learning as measured on a non-linguistic learning task would be related to the ability to use predictive knowledge of language to interpret auditorily degraded sentences.

For the sequence learning task, we designed a task based on the Milton Bradley game "Simon," that consists of four colored panels on a touch-sensitive screen that light up in a sequence of a particular order (Figure 1) (see also Karpicke & Pisoni, 2004). After viewing a sequence, participants were required to replicate the sequence by tapping the squares on the touch screen monitor.

Unbeknownst to the participants, an artificial grammar was built into the task, so that initially all of the sequences presented conformed to an underlying probabilistic structure as defined by the grammar (Figure 2). That is, the grammar creates a set of sequences that contain probabilistic regularities: as an example, there may be a 50% likelihood that the color green will follow the color red when red is the first item in the sequence. Participants viewed and replicated a subset of grammatical patterns in the "learning phase" of the task. Next, the task moved seamlessly into a "testing phase," in which sequences with grammatical violations were introduced.

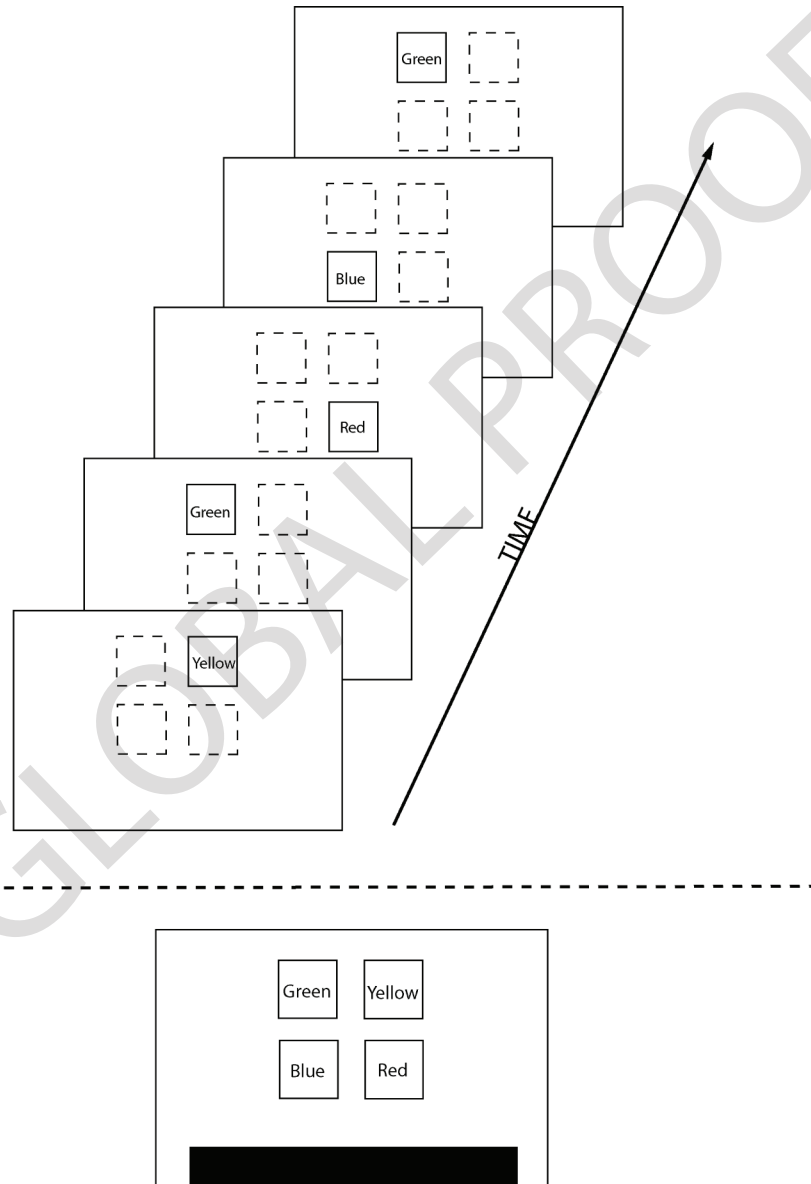
Learning of the probabilistic regularities was assessed by comparing sequence replication accuracy for grammatical sequences to those with grammatical violations. Behaviorally, greater replication accuracy for grammatical sequences compared to sequences containing violations is indicative of implicitly learning the underlying probabilistic patterns. One important characteristic of this task is that it is completely visual, and therefore provides a non-auditory comparison to spoken language processing.

The language task was designed to exploit sentence predictability. Participants listened to auditorily presented sentences and were required to identify the last word of the sentence. All sentences were acoustically degraded with a sine-wave vocoder, the aim of which was to perceptually degrade them, causing participants to rely on context in addition to auditory perception. Two types of sentences were used (Kalikow, et al., 1977): One consisting of target words that were highly predictable based on the context of the preceding words in the sentence, and the other consisting of target words that were not predictable based on the preceding words in the sentence. Thus, this word predictability task was designed to capitalize on the natural serial order information inherent in the structure of spoken language.

In an initial experiment and two subsequent replications (Conway, et al., 2010), performance on the visual sequential learning task was shown to be significantly correlated with performance on the sentence completion task, despite the two tasks occurring across different sensory modalities. Thus, the ability to learn and exploit non-linguistic (and non-auditory) sequential patterns appears to be associated with the ability to use sentence context to implicitly predict—and thus better perceive—the final word in a spoken sentence. Even when other relevant cognitive factors were statistically accounted for, such as general intelligence, nonverbal intelligence, receptive language, inhibition, and short-term memory, the relationship between the two tasks remained

## Two Distinct Sequence Learning Mechanisms for Syntax Acquisition and Word Learning

Figure 1. Depiction of the visual sequential statistical learning task used in Conway et al. (2010), similar to that used in previous work (Karpicke & Pisoni, 2004). Participants view a sequence of colored squares (700-msec duration, 500-msec ISI) appearing on the computer screen (top) and then, 2000-msec after sequence presentation, they must attempt to reproduce the sequence by pressing the touch-panels in correct order (bottom). The next sequence occurs 2000-msec following their response.

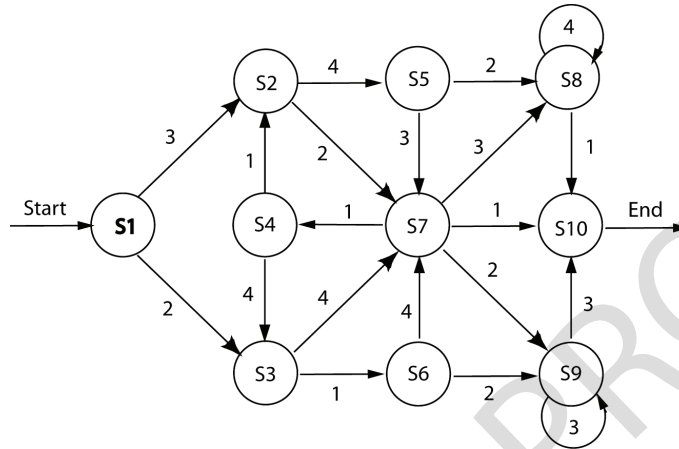


strong (Conway, et al., 2010). Finally, using a step-wise multiple regression in which performance on the visual sequence learning task, nonverbal intelligence, short-term memory, and inhibition were predictors, only sequence learning was a

significant predictor of performance on the word predictability task.

Thus, in typically developing college students, visual (probabilistic) sequence learning abilities account for a significant amount of variance in

Figure 2. Example of the type of artificial grammar used in Conway et al. (2010). For each subject, the numbers (1-4) are randomly mapped to the four possible locations and colors, such that the sequence 3-4-2-4-1 might be instantiated as the sequence Red-Green-Blue-Green-Yellow appearing at different locations on the screen.



one's ability to use the predictive patterns of structure to interpret words when the perceptual auditory input is inadequate. Thus, just like the neural networks described by Elman (1990), people appear to be sensitive to the sequential probabilities of language, which once learned, allow one to implicitly predict and more effectively perceive and process the next linguistic units in an utterance.

To further strengthen the connection between domain-general sequence learning mechanisms and language learning and processing, these behavioral findings have been complemented with Event-Related Brain Potentials (ERPs). ERP recordings are sensitive to neural changes in brain voltages over time and therefore can be used to observe information processing occurring by the millisecond. Because of this sensitivity, it is an excellent candidate for assessing language and sequence processing, in which information is transmitted temporally.

In ERP experiments, a sensor net is placed on the participants' head while he/she performs a cognitive task. The task stimuli are time-locked, allowing computer software to parcel out and

average stimuli of different types. Later, the experimenters can create a set of averaged waveforms illustrating neural changes in voltage over time for different locations on the scalp. Some waveforms appear consistently in response to certain tasks and are thought to be neural signatures signifying a specific cognitive process. For instance, a relevant component prominent in the language literature is the P600, which is consistently shown in response to syntactic anomalies such as violations of noun/verb agreement (Nevins, Dillon, Malhotra, & Phillips, 2007), word order agreement (Hagoort, Brown, & Groothusen, 1993) and article-noun gender agreement (Gutner, Friederici, & Schriefers, 2000). In addition, it has been shown to reflect complex syntactic processing, such as integration of complex syntactic properties (Kaan, Harris, Gibson, & Holcomb, 2000) or in situations of syntactic ambiguity (Frisch, Schlewsky, Saddy, & Alpermann, 2002). Christiansen, Conway, and Onnis (2012) argued that the P600 may not be related to syntactic processing per se, but rather may be a reflection of any violation in a learned sequential structure, be it linguistic or non-linguistic.

To test this hypothesis, Christiansen, Conway, and Onnis (2012) measured the ERPs of typically developing adults while they performed a computerized visual sequence learning task in which participants were presented with categories of visual stimuli of various levels of complexity. For the sake of illustration, let us assume that there are three categories (A, B, and C). The A category can consist of a single stimulus, whereas B and C can consist of three stimuli (B1, B2, B3, and C1, C2, and C3). Simple artificial rules were created that defined which categories could occur in a sequence together; for instance, if the grammatical structure was  $A \rightarrow B \rightarrow C$  then A, B2, C3 would be a grammatical item as would A, B3, C1, and A, B1, C2. Therefore, participants could not learn the grammatical dependencies based only on transitional probabilities between stimuli. It was necessary for them to use hierarchical dependencies and abstract knowledge of a categorical structure that was predictive of stimuli, as in spoken language. The visual stimuli consisted of complex shapes and appeared in different colors and locations on the screen. Note that the example given above is meant for illustration's sake only. The actual task consisted of more categories and used a more complex grammatical structure (see Christiansen, Conway, & Onnis, 2012, for further details). As in previous studies, participants were trained on the task before taking part in a testing phase where they were exposed to grammatical and ungrammatical items.

The language task was adapted from that used in Osterhout and Mobley (1995) and consisted of a set of 120 sentences, 30 of which were grammatically correct, and the rest of which contained a grammatical violation which was either a subject/verb number agreement violation, an antecedent-reflexive number agreement violation, or a gender agreement violation. The sentences containing a subject/verb number agreement violation were used as experimental items, and the remaining two types of sentences were used as fillers. Participants' task was to indicate whether the visual

sequences and sentences were grammatical with a button press. ERP recordings from the test phase of the sequence-learning task and from the sentence task were analyzed and compared.

Behaviorally, participants performed very well on both tasks, correctly classifying approximately 94% of both the sentences and the visual sequences. Neurally, the ERP components elicited by each task were also similar. A late positive deflection (P600) was seen in response to grammatical violations in both the language and sequence-learning task. An analysis of variance indicated that the P600s seen in the two tasks were not statistically different from each other. Furthermore, a regression analysis showed that there was a significant association between the magnitudes of the P600 in the two tasks: the larger the P600 in the sequential learning task, the larger it was in the natural language task.

dropping out of editor mode: very cool finding!

These findings indicate that the same neurocognitive mechanisms are likely at play in the two tasks, offering further supporting evidence that domain-general sequence learning mechanisms are tied to language processing.

### **Probabilistic Sequence Learning and Syntax Acquisition in Deaf and Hard of Hearing Children**

The acquisition of syntax is perhaps the most complicated component of language learning. Most characteristics of syntax are fundamentally linked to serial order processing. Young children must learn to encode the meaning of ordered units of sound in order to learn phrase structure rules, and ultimately construct sentences. Recent work from our lab has provided evidence that there is indeed an association between syntax acquisition and probabilistic sequence learning.

As we have seen, it appears that domain-general sequence learning mechanisms are used in service of language acquisition and processing, at least in healthy adults. In addition, as



we discussed earlier, exposure to sound early in development may be necessary for developing adequate sequencing abilities (Conway, et al., 2009). A question of importance, then, is how these sequence-learning processes may operate in populations that have language deficits or delays due to auditory deprivation. Deaf children with Cochlear Implants (CIs) offer a unique opportunity for studying these questions. Children with cochlear implants are profoundly deaf (often congenitally) who have residual hearing restored via a device surgically implanted in the ear that bypasses the ear drum and electrically stimulates the cochlea in response to sound (Colletti, et al., 2005). While their restored hearing is not perfect, it is an improvement; however, these children still often have difficulty learning language that is not fully explained by the quality of their hearing alone (Niparko, et al., 2010).

Children with CIs have been shown to perform lower on a variety of sequencing tasks when compared to normal hearing peers including the Continuous Performance Task (CPT) (Mitchell & Quittner, 1994) and serial short term memory (Conrad & Rush, 1965; Jutras & Gagne, 1999; Wallace & Corballis, 1973). The CPT requires participants to analyze a pattern of serially presented numerals by pressing a button in response to a two-numeral target. Thus, participants must employ both attention and inhibition to successfully complete the task. Studies have shown that children with CIs perform below normal hearing peers on this task (Mitchell & Quittner, 1994) although there is evidence that deaf children may “catch up” with their peers later in childhood (Quittner, Smith, Osberger, Mitchell, & Katz, 1994; Smith, Quittner, Osberger, & Miyamoto, 1998). Deaf children have also been shown to perform lower than typically hearing children when judging duration (Kowalska & Szlag, 2006), indicating that their impairment may be present in multiple forms of temporal and sequential processing.

Similarly, deaf children with CIs perform worse on tasks of speech perception (Waltzmann, et al.,

1997) though most children show increasing gains with longer cochlear implant use. Eisenberg, Martinez, Holowecky, and Polgorelsy (2002) further demonstrated that CI children were significantly better recognizing sentences containing lexically easy words, which are frequently used but acoustically different, compared to lexically difficult words, which are less familiar and more acoustically similar. Furthermore, our recent work suggests that children with CIs may not be as efficient at using preceding sentence context to predict and perceive words in a sentence (see Conway, Walk, Anaya, & Pisoni, 2012). This finding is just what we would expect given the apparent disturbances to domain-general sequencing abilities.

Our lab group recently attempted to systematically examine sequential processing and language functioning in deaf children with CIs by using the Simon visual sequence learning task described above and a battery of standardized assessments (Conway, Pisoni, Anaya, Karpicke, & Henning, 2011). The deaf children in the study had an average age of 7.5 years ( $SD = 1.65$  years) and were all raised in environments in which spoken English was their primary method of communication. The Simon task was similar to that used in Conway et al. (2010), a measure of probabilistic sequence learning. As a measure of language ability, three subtests of the CELF-4 were used: Concepts and Following Directions, in which children must follow increasingly complex set of directions by pointing to different pictures in the testing manual; Formulating Sentences, in which the children were required to use a set of target words to formulate full, meaningful sentences that referenced a visual scene; and Recalling Sentences, in which children were to imitate increasingly long and complex sentences. These three subtests reflect both receptive and expressive language skills, with an emphasis on knowledge of syntax. In addition, the forward and backward digit span tests of the Wechsler Intelligence Scales for Children (WISC-3; Wechsler, 1991) and the Peabody Picture Vocabulary Test (PPVT-4; Dunn & Dunn, 1997) were used to as-

sess verbal short-term memory and vocabulary knowledge, and the Dot Location subtest of the Children's Memory Scale (CMS; Cohen, 1997) was used to assess nonverbal ability.

Behaviorally, the typically hearing children and the deaf children with CIs performed equally in the learning phase of the sequence-learning task; however, the typically hearing children showed differentiation between grammatical and ungrammatical sequences in the testing phase, whereas the CI children did not. The typically hearing children performed significantly better on the grammatical items when compared to the ungrammatical items, whereas the performance of the CI children was the same between item types. This finding suggests that the difference in learning between the hearing and deaf children was related to learning the underlying sequential structure of the patterns, rather than a general difference in short-term memory capacity. Furthermore, a set of partial correlations, controlling for chronological age, indicated that age of implantation and length of cochlear implant use were both significantly associated with their performance. Age of implantation was negatively correlated with performance on the sequencing task, indicating that children who received an implant at an earlier age were more likely to have a higher score on the sequencing task. Length of CI use, on the other hand, was positively correlated, suggesting that children who had more hearing experience were also more likely to have a higher score on the sequencing task.

Importantly, the scores on the probabilistic sequence-learning task were significantly predictive of both the Formulating Sentences and Recalling Sentences subtests of the CELF-4 (Conway, et al., 2011). Sequencing scores were also marginally significantly correlated with the Concepts and Following Directions subtest. The pattern of correlations was unchanged when the variance in sequencing performance due to age of cochlear implantation, length of experience with an implant, PPVT scores, and forward and backward digit span performance were controlled. The

correlation between sequencing performance and the Formulating Sentences subtest was especially strong, suggesting that sequence processing may be particularly important for the development of expressive language abilities. On the other hand, sequence learning was not correlated with vocabulary knowledge, as measured by the PPVT.

An important implication of these findings is the apparent importance of probabilistic sequence learning to language development. Probabilistic sequence learning is different from simple serial recall because it requires participants to extract the underlying regularities from a pattern, recognize them in a variety of stimuli, and in the case of language, apply them to novel stimuli. Serial recall, on the other hand, is a memory exercise requiring participants to repeat patterns only. An important assumption of the sequence-learning task is that in the training phase, participants are practicing serial recall, whereas they have had a chance to learn the underlying patterns by the time they enter the test phase. This distinction is evident because the CI children and typically hearing children performed equally well on the training phase of the experiment. Similarly, only sequence learning performance on the test phase was correlated with the language measures. Thus, it appears that probabilistic sequence learning, rather than immediate memory for a fixed serial order, is important for the development of receptive and expressive language skills that place an emphasis on the proper use of syntactic relations.

### **Repetition Sequence Learning and Lexical Development in Deaf and Hard of Hearing Children**

If probabilistic sequence learning is associated with syntax acquisition, what processes underlie vocabulary acquisition? A potential candidate is repetition sequence learning. There are compelling empirical and theoretical reasons to consider repetition learning as a potential predictor of word learning ability. First of all, repetition learning

does not appear to be a precursor for syntax. Recall that Conway et al. (2011) found no difference in language delayed children with CIs and typically developing children on the learning phase of a sequencing task. The learning phase of this task effectively acts as a repetition-sequencing task. Though the structure is present, presumably it has not been learned. Therefore, participants are repeating stimuli that have no structural meaning to them, as in a repetition-learning task. Because the CI and typically hearing children showed no performance difference on this part of the task, it appears this process was not significantly impaired in the samples examined. Thus, it appears we can rule out repetition learning as a predictor for syntax acquisition. It is important to note that this assumption is based on null results, and should therefore be interpreted with caution. However, we do believe that it is noteworthy that measures of syntax and repetition learning appear to be unrelated.

Second of all, probabilistic sequence learning does not appear to be empirically associated with vocabulary learning. In the Conway et al. (2011) study, performance on the probabilistic sequential learning task was not correlated with performance on the PPVT, a measure of vocabulary development, in deaf children with CIs.

Theoretically speaking, a presumed link between memory-based cognitive mechanisms, such as associative learning, and vocabulary development is suggested even in the terms used to describe these stores, such as the “mental lexicon.” As the name suggests, the mental lexicon is thought to operate like a cognitive dictionary, storing words and their meanings for retrieval from long-term memory. Unlike a written dictionary, the mental lexicon is thought to be organized based on word meanings, which makes word retrieval more efficient (Aitchison, 2003). However, the presumed reliance on memory processes for lexical storage and retrieval suggests that a memory-based process, such as repetition learning, may be related to semantic processing. This has empirically been

shown to be the case. Interestingly, serial order repetition memory—rather than item short-term memory—appears to be important for lexical knowledge (Leclercq & Majerus, 2010).

Previous research has suggested that phonological working memory abilities are associated with vocabulary development in typically developing children (Gathercole, Willis, Emslie, & Baddeley, 1992). These findings suggest that the ability to repeat a sequence of items on one occasion—which can be measured with the non-word repetition task—lies at the heart of word learning. However, we think it is more useful to think of word learning as not just repeating a sequence of items one time, but doing so over multiple instances. Thus, word learning might be best thought of as a type of repetition sequence learning, rather than a type of immediate serial recall. This type of learning is embodied by the Hebb repetition effect (Hebb, 1961), in which memory recall for a list of items improves with repeated exposures.

To further investigate the possible association between repetition sequence learning and vocabulary development, Grep, Walk, and Conway (2012) explored repetition sequence learning in deaf and hearing children. The Deaf/Hard of Hearing (D/HH) children examined in the study used a combination of cochlear implants and hearing aids but all children used spoken language as their primary means of communication. All children were tested on a visual sequence-learning task adapted from Conway et al. (2010). As if the other Simon tasks described above, this task consisted of four squares placed on a touch screen computer monitor, participants observed a series of squares that lit up in succession and then repeated the sequences by touching the squares on the screen. The difference, however, was that instead of an artificial grammar governing the patterns probabilistically, the task generated fixed repeating sequences. Children began with a sequence of two (e.g., 3-1). If the child correctly replicated the two item sequence, the program repeated the

initial two items, adding a third (e.g., 3-1-2). If this was correctly replicated, a fourth would be added (e.g., 3-1-2-1), and so on. In this way, the sequence incrementally built upon itself, giving participants increased exposure to the sequence. Children were also given the PPVT-4 to measure their vocabulary skills.

An ANOVA assessing group differences showed that the typically hearing children performed significantly higher on both the repetition sequence-learning task and the PPVT compared to the D/HH children. Better performance on the PPVT for the typical-hearing children is perhaps not surprising, since other studies have indicated that D/HH children may have, on average, smaller vocabularies compared to hearing children (Blamey, et al., 2001). The difference in performance on the repetition learning task, however, is important because it indicates that the D/HH children may be impaired not only on the more complex form of probabilistic sequence learning (Conway, et al., 2011), but also on a relatively “simple” form of repetition sequence learning. The D/HH children showed impaired ability to exploit the repeating nature of these items, a very basic and fundamental type of learning ability.

In addition, a series of correlations were run on the D/HH sample of children, revealing that the repetition sequence-learning task was significantly correlated with PPVT scores, after controlling for chronological age. For the subset of children with a CI, this relationship remained significant even after controlling for age of implantation. These initial results suggest that repetition sequence learning appears to be related to vocabulary learning, whereas the previous findings suggested that probabilistic sequence learning was associated with aspects of syntactic development.

A second version of the repetition sequence-learning task was also used, incorporating black and white squares rather than colored ones. The rationale was to eliminate some of the reliance on verbal processing. It has been theorized that

D/HH children may have a tendency to encode stimuli visually rather than verbally (Conrad & Rush, 1965; Wallace & Corballis, 1973) and may therefore show artificially deflated scores on cognitive tasks that contain stimuli that are naturally encoded verbally. Colors provide salient verbal labels for children, giving the D/HH children a disadvantage. Thus, this black and white version of the task was meant to be a nonverbal version of the repetition sequence-learning task. While we realize that children can still attach verbal labels to black and white stimuli, it is our experience that children are less likely to attach spatial labels (e.g., “top right corner”) than they are to attach colored labels, especially when the stimuli are presented at a relatively fast pace. Overall, there were no significant group differences between the hearing children and the D/HH on the nonverbal repetition task; however, when PPVT was included as a covariate in the ANCOVA, group differences did emerge, with the D/HH again showing lower performance. Therefore, the difficulties that deaf and hard of hearing children have on visual sequence learning appears to extend to nonverbal stimuli, when differences in vocabulary development between the two groups was accounted for statistically.

## **Solutions and Recommendations**

The evidence provided in this chapter suggests that domain-general sequential learning mechanisms are associated with language processing. It appears that an individual’s ability to make sense of structured sequences directly predicts language competencies in both typically developing adults (Christiansen, et al., 2012; Conway, et al., 2010) and hearing-impaired children (Conway, et al., 2011; Gremp, et al., 2012). The evidence furthermore suggests that sequential processing is impaired in deaf children with CIs leading to poorer language outcomes (Conway, et al., 2011). Experience with naturally occurring sound stimuli

in the environment appears to provide unique opportunities to develop sequence-processing abilities (Conway, et al., 2009).

While serial order processing appears to be important for the acquisition of both syntax and the lexicon, we propose that these two processes are instantiated by two different types of serial order mechanisms: probabilistic and repetition sequencing. We propose, based on the work outlined above, that probabilistic sequence learning underlies syntax acquisition (Conway, et al., 2011), whereas repetition sequence learning underlies lexical development (Gemp, et al., 2012).

This idea is also reflected in other theories, such as that of Ullman's (2004) declarative/procedural model of memory and language. Like our sequence-learning hypothesis, the model proposes that domain-general memory and learning abilities are recruited for language acquisition. Under his view, syntax is subserved by procedural memory processes, which operate via implicit cognitive mechanisms involving the basal ganglia, portions of the parietal and superior temporal cortex, and cerebellar structures. The mental lexicon, on the other hand, is subserved by declarative memory, whose function is to store associative (i.e., semantic and episodic) information, involving the medial temporal lobe neural structures. Ullman proposes that the procedural, grammar-serving system is especially sensitive to sequential structures, though sequencing is not a dominant aspect of his theoretical view as it is with ours. Whereas both our and Ullman's (2004) theory emphasizes the role played by two distinct learning mechanisms for syntax and vocabulary development, they differ in how the two learning mechanisms are characterized. Rather than the learning systems being categorized in terms of procedural/implicit and declarative/explicit memory, we believe the learning mechanisms differ in terms of the types of input that are processed (probabilistic versus repeating or invariant sequences). Thus, the issue of explicitness or conscious awareness does not

play a role in our theory. Indeed, we see it likely that both probabilistic and repetition sequence learning might be equally characterized as being a form of implicit learning; similarly, explicit learning could be brought to bear with both types of inputs, as well.

## **FUTURE RESEARCH DIRECTIONS**

Though the literature reviewed in the present chapter lays a theoretical foundation, it is by no means exhaustive. Future work is needed in several areas. Much of our work thus far has concentrated on deaf children with cochlear implants as a means of investigating language processes. While this sample has certain advantages, it is unable to account for other types of language, such as manual signed languages. It has been shown that deaf signers have a reduced short-term memory capacity for signs compared to a hearing person's general capacity for sounds (Geraci, Gozzi, Pagno, & Cecchetto, 2008). O'Connor and Hermelin (1973) showed that hearing subjects had a preference for auditory information when they were trying to complete a sequential task, but deaf individuals had no modality preference. However, general working memory span was no different between the two populations (Boutla, Supalla, Newport, & Bavelier, 2004). Thus, it appears that some of the differences in sequential memory may be due not to differences in the capacity of general short-term memory, but to how stimuli in different modalities are processed in working memory. These issues are important to determine whether the theoretical position outlined here is appropriate to apply to all languages, or to spoken languages only. It is possible that manual languages may be less reliant on sequence processing, since manual languages depend upon visual input and spatial localization is more important than in spoken language.

More work from a developmental perspective would greatly enhance our understanding

of these learning processes. Longitudinal and cross-sectional designs are needed to explore the operation of these mechanisms over time. Several studies have suggested that auditory deprivation may cause short-term deficits in sequence processing, but that individuals can experience recovery over time. Bross and Sauerwein (1980) subjected typically hearing adults to 24 hours of complete auditory deprivation during which participants performed a visual flicker task, which is a differentiation task designed to assess sensitivity to visual stimuli presented over time. Though participants showed initial deficits, after about 12 hours of auditory deprivation their performance returned to normal. Similarly, a study with deaf children showed that 10 year olds were significantly impaired on a rhythm imitation task, whereas 15 year olds performed equivalently to same-aged peers (Rileigh & Odom, 1972). These studies suggest the possibility that auditory deprivation (either induced temporally via an experimental manipulation or in the natural case of deafness) may lead to initial difficulty with temporally based tasks but that these difficulties can recover over time. It would be important to examine these effects of auditory deprivation using the kinds of probabilistic and repetition-based sequential learning tasks described in this chapter. Ideally, longitudinal paradigms could be combined to exhaustively study this problem. Measures of probabilistic sequence learning, repetition learning, syntax knowledge, and vocabulary could all be taken at different points in time over the course of an individual's development. Using this paradigm, one could observe the relationships between sequence learning and language and the changes that occur in those relationships throughout childhood. Importantly, such a longitudinal design also addresses the issue of causality and would go beyond merely reporting associations between the measures.

Future work is also needed to ascertain the underlying neurobiological mechanisms for probabilistic and repetition learning. If as we propose these

are two distinct neurocognitive mechanisms, and then they ought to reflect the operation of different neural regions (as measured using fMRI) and/or processes (as measured using ERP). Findings from neuroimaging studies indicate that frontal cortex (e.g., prefrontal cortex, premotor cortex, supplementary motor areas, etc.), subcortical areas (e.g., basal ganglia), and the cerebellum play important roles in sequence learning and representation (Bapi, et al., 2005). To our knowledge, no studies have as yet investigated and directly compared the neural mechanisms involved in probabilistic versus repetition sequence learning.

Lastly, a fruitful avenue of study is to investigate other potential mediators of the reported effects. It is possible that the results presented above can be explained by a mediational variable that we have not adequately measured in our extant data. For example, a potential candidate may be attention, in which the divergence of syntax and vocabulary processing may be explained by children with different experiences being drawn to attend to different types of stimuli, explaining why children may learn various aspects of language at different rates and experience different levels of expertise with language.

## **CONCLUSION**

It is an astounding feat to learn the complex nuances of a language from the apparently messy input that infants receive from their auditory environment. The work presented here shows compelling evidence that language learning depends on general learning abilities that allow infants to track invariant and probabilistic patterns that exist in their linguistic environments. Ongoing work in our lab is currently investigating whether it is possible to train and selectively enhance these sequential learning abilities, and whether improvement to these underlying processes of probabilistic and repetition sequencing may improve language function in language impaired populations such

as deafness and autism. Understanding the neurocognitive bases of domain-general learning mechanisms and their relation to different aspects of language acquisition thus has important theoretical implications as well as clinical applications.

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## KEY TERMS AND DEFINITIONS

**Cochlear Implantation:** A surgical procedure by which profoundly deaf individuals can receive access to residual sound via an electrical pulse to the cochlea in response to auditory stimulation.

**Cognition:** Mental processes including but not limited to perception, attention, memory, language, decision making, and creativity.

**Deafness:** Partial or full loss of hearing.

**Implicit Learning:** The ability to extract patterns from a structured environment in which learning is generally automatic and results in knowledge that is below the level of awareness.

**Repetition Learning:** Gradual learning of a fixed, invariant stimulus pattern through multiple exposures.

**Sequence Learning:** Pattern learning of sequences of stimuli in which the serial order is essential to the meaning of the stimulus stream.

**Statistical Learning:** Acquiring knowledge of the distributional or probabilistic regularities existing between stimuli.