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Review Article

The Role of Statistical Learning in Understanding and Treating Spoken Language Outcomes in Deaf Children With Cochlear Implants

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Purpose: Statistical learning—the ability to learn patterns in environmental input—is increasingly recognized as a foundational mechanism necessary for the successful acquisition of spoken language. Spoken language is a complex, serially presented signal that contains embedded statistical relations among linguistic units, such as phonemes, morphemes, and words, which represent the phonotactic and syntactic rules of language. In this review article, we first review recent work that demonstrates that, in typical language development, individuals who display better nonlinguistic statistical learning abilities also show better performance on different measures of language. We next review research findings that suggest that children who are deaf and use cochlear implants may have difficulties learning sequential input patterns, possibly due to auditory and/or linguistic deprivation early in development, and that the children who show better sequence learning abilities also display improved spoken language outcomes. Finally, we present recent findings suggesting that it may be possible to improve core statistical learning abilities with specialized training and interventions and that such improvements can potentially impact and facilitate the acquisition and processing of spoken language.

Method: We conducted a literature search through various online databases including PsychINFO and PubMed, as well as including relevant review articles gleaned from the reference sections of other review articles used in this review. Search terms included various combinations of the following: sequential learning, sequence learning, statistical learning, sequence processing, procedural learning, procedural memory, implicit learning, language, computerized training, working memory training, statistical learning training, deaf, deafness, hearing impairment, hearing impaired, DHH, hard of hearing, cochlear implant(s), hearing aid(s), and auditory deprivation. To keep this review concise and clear, we limited inclusion to the foundational and most recent (2005–2018) relevant studies that explicitly included research or theoretical perspectives on statistical or sequential learning. We here summarize and synthesize the most recent and relevant literature to understanding and treating language delays in children using cochlear implants through the lens of statistical learning.

Conclusions: We suggest that understanding how statistical learning contributes to spoken language development is important for understanding some of the difficulties that children who are deaf and use cochlear implants might face and argue that it may be beneficial to develop novel language interventions that focus specifically on improving core foundational statistical learning skills.

Over the past 20 years, a growing consensus has been emerging that spoken language development depends heavily upon auditory processing mechanisms that extract structural regularities, such as statistical based patterns, present in auditory linguistic input (Arciuli & Torkildsen, 2012; Aslin & Newport, 2014). These information-processing mechanisms allow for statistical learning (SL), which is the learning of frequency rules and probabilistic relationships between elements in sequential input. Thus, for example, in a series of items presented sequentially over time, such as words in spoken language,

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SL allows the learner (or in this case listener) to recognize the frequencies with which particular words occur together, allowing for the prediction of upcoming words or sounds based on the probability that a particular word will follow given what has already been spoken. For instance, there is a much higher probability that the word "ball" will follow the word "bouncy" than that the word "speak" will follow "bouncy" and a higher probability that, given the word "the," the word that follows will be a noun rather than a verb. Spoken language is a highly complex sequential signal, one that unfolds over time rather than being statically presented in a spatial array and that contains a rich underlying structure of frequency rules and probabilistic relationships among various linguistic units such as phonemes, morphemes, words, and phrases. SL enables parsing of this complex sequential signal into understandable units, such as syllables and words (e.g., Saffran, Aslin, & Newport, 1996); mapping of symbolic relationships between units, such as between words and their referents (e.g., Yu & Smith, 2007); and prediction of upcoming units, such as words and phrases within sentences (e.g., Conway, Karpicke, & Pisoni, 2007). Statistical sequential learning can occur through any sensory modality and appears essential in numerous domains of daily activity, such as language and communication, motor and skill learning, music perception and production, problem solving, and planning (Deocampo & Conway, 2014). However, SL may be particularly crucial within the auditory modality for the acquisition and development of spoken language due to the multiple levels of statistical sequential structure within spoken language (Erickson & Thiessen, 2015). Statistical structure governs how phonemes combine together to create syllables, how syllables combine together to create words, and how words combine together to create sentences. Statistical structure also dictates how word sounds map onto meanings and how grammar governs sentence structure (e.g., word order, which may determine meaning as in "the cat bit the dog" vs. "the dog bit the cat," and word placement, such as not splitting infinitives or dangling prepositions) to result in a meaningful utterance. Sensitivity to temporal patterns through SL appears essential for facilitating the enormous task of language learning (Saffran, 2003). This is exactly what is seen in typically developing human infants who are particularly attuned to auditory sequential patterns, such as rhythm and language, from birth (Deocampo & Conway, 2014). On the other hand, although other neural and cognitive mechanisms may also be involved in language acquisition and processing, disruption to SL ability could lead to widespread, compounding delays in language learning.

In this review article, we review recent research documenting an important role for SL in spoken language development. We first review behavioral and neural evidence linking SL to typical language development and then consider recent evidence that atypical SL could underlie some of the delays in spoken language development observed in some children with cochlear implants (CIs), as suggested by the auditory scaffolding hypothesis (ASH; Conway, Pisoni, & Kronenberger, 2009). We then highlight recent attempts to improve SL ability through computerized training and neurostimulation. Although additional research is still needed to identify what specific aspects of SL might underlie language learning difficulties and to what extent these abilities are modifiable and can generalize to improved language outcomes, we believe that there may be substantial value in developing novel interventions that target SL abilities as a way to improve language outcomes in children who are deaf or hard of hearing.

Overview of Foundational SL Research

In the midst of debate over whether language acquisition was innate or depended upon experience (e.g., Pinker, 1994, vs. Tomasello, 1995), Saffran, Aslin, and Newport (1996) chose a feature of language that they assumed must be learned, segmentation of continuous speech into separate words within the speech stream, to investigate core learning mechanisms that might be involved in language acquisition (Saffran, 2003). In fluent speech, pauses and other prosodic features are often not reliable cues to word boundaries that allow a naive listener to determine where one word ends and another begins in a phrase such as *Lookatthesillybunny!* However, the syllables within a word such as "bun" and "ny" in the word "bunny" occur together in a high proportion of utterances, whereas the syllables that span word boundaries, such as "ly" and "bun" from the words "silly" and "bunny," are likely to occur together less frequently because they are in separate words. Thus, given enough continuous speech as input, being sensitive to statistical co-occurrence probabilities (how likely particular syllables are to occur together one after the other) could give infants a mechanism by which to segment continuous speech (Jusczyk, 1993; Saffran, 2003; Saffran, Aslin, & Newport, 1996).

Saffran, Aslin, and Newport (1996) did, in fact, show that 8-month-old infants could use the statistical structure of a continuous auditory stream of nonsense syllables to recognize "word" boundaries and parse the stream into appropriate units ("pseudowords"). Infants listened to a continuous stream of four pseudowords, each composed of three syllables (e.g., pabiku, tibudo, golatu, daropi), with no pauses or other word boundary cues between pseudowords. The only way to discriminate "words" within the stream was to use the statistical properties of the sequence of syllables. Within words, the probability of one syllable following another was 100%. This is also known as a transitional probability of 1.0: Given the syllable "pa," there is a 100% chance or 1.0 transitional probability that the syllable "bi" will follow. That is, "bi" always follows "pa." However, between words, the transitional probability of one syllable following another was only .33. That is, any given final syllable of a pseudoword was followed 33% of the time by a given initial syllable of another pseudoword. For example, using the above-listed pseudowords, "ku" from "pabiku" was followed by "ti" from "tibudo" 33% of the time, "go" from "golatu" 33% of the time, and "da" from "daropi" 33% of the time. After listening to this continuous stream of syllables for only 2 min, 8-month-olds were able to discriminate between pseudowords, such as "daropi," and partial words that spanned word boundaries, such as "pigola" (made up of the last syllable of "daropi" and the first two syllables of "golabu"). Thus, although natural language learning likely involves multiple learning mechanisms, Saffran, Aslin, and Newport (1996) found that sensitivity to statistical cues in the speech stream was sufficient for infants to parse the stream into word-like units and coined the term "statistical learning" (SL) to describe these novel findings.

Auditory SL of word boundaries has since been found under stricter circumstances (e.g., when word and nonword frequencies were equated; Aslin, Saffran, & Newport, 1998) in both children (e.g., Saffran, Newport, Aslin, Tunick, & Barrueco, 1997) and adults (e.g., Saffran, Newport, & Aslin, 1996). In addition, Perruchet and Vinter (1998) built a computer program (PARSER) that could segment words from a continuous stream under the same conditions as the infants as well as with words ranging from one to five syllables in length and with less input than given in Saffran, Aslin, and Newport (1996) despite having very limited computational abilities and memory capacity. SL can also accomplish other language-related milestones, such as discovering phonetic categories (e.g., Maye, Werker, & Gerken, 2002), word categories (e.g., parts of speech; Reeder, Newport, & Aslin, 2013), simple syntax (e.g., Saffran & Wilson, 2003), and word to referent mappings (Yu & Smith, 2007). In addition, SL has been found with other nonlinguistic stimuli, such as auditory tones (e.g., Saffran, Johnson, Aslin, & Newport, 1999) and visual stimuli (e.g., Shafto, Conway, Field, & Houston, 2012). This evidence that crucial aspects of language are at least capable of being learned under many different circumstances and therefore can be influenced by the environment rather than being largely innate provides support for the hypothesis that disturbances underlying language delays and language disorders may also be vulnerable to environmental influence and thus may be reversed through learning as well. This possibility will be discussed further below.

Overview of SL Theory

Despite the evidence for powerful learning mechanisms subserving language development, a classic nativist criticism is that language learning mechanisms cannot account fully for what appear to be strong similarities across world languages. Saffran (2003) countered this argument with a "constrained SL framework." Within this framework, language acquisition is accomplished through learning, but that learning is constrained, meaning that only some things can be learned and thus not everything available to be learned is learned. For example, infants can learn new phonemic regularities through SL if they are consistent with existing languages in the world but not if they do not fit with existing natural language structure (Saffran & Thiessen, 2003), and listeners can learn linguistic and nonlinguistic sequences better if they are arranged into predictive phrases similar to prepositional and noun phrases in language (Saffran, 2002). Additional constraints include attentional constraints (e.g., Turk-Browne, Jungé, & Scholl, 2005), perceptual constraints (e.g., Conway & Christiansen, 2005), preferences for certain types of elements as units of SL (e.g., Bonatti, Peña, Nespor, & Mehler, 2005), and consistency with prosodic (Johnson & Jusczyk, 2001) and gaze (Yu, Ballard, & Aslin, 2005) cues. These types of constraints, not innate knowledge, are the cause of cross-linguistic similarities in this framework. Only languages that could be learned within these constraints could evolve (also see Christiansen & Chater, 2008), making them more similar to each other than they would be without constraints. Thus, although SL seems to be a very strong mechanism allowing for rapid learning almost from birth (e.g., Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009), not every statistical relationship can necessarily be easily learned.

According to Aslin and Newport (2014), these constraints are also essential to avoid the "computational explosion" problem in language learning. The computational explosion problem describes the concept that, within any reasonably complex sequential input, including natural language or even the less complex pseudoword speech stream used by Saffran, Aslin, and Newport (1996), there are so many potential statistical relationships to be computed that the task of determining which relationships provide information meaningful for the learning task at hand is seemingly impossible. Thus, constraints that shape and limit the learning process are required to narrow down which statistical relationships will actually be learned.

Although much of the work on language-related SL has concentrated on transitional probabilities like those described by Saffran, Aslin, and Newport (1996) for word segmentation (and defined in the previous section), humans are highly sensitive to a much wider range of statistical structures, such as distributional frequencies (e.g., Maye et al., 2002). Aslin and Newport (2014) also suggested that SL, as described by Saffran, Aslin, and Newport (1996), was not in and of itself capable of accomplishing rule learning (such as an arbitrary rule that the AAB structure can form acceptable words, such as "babaga," but the ABB structure, such as "bagaga," cannot). However, they posited that distributional learning, in which language learners track frequencies of relevant language units (e.g., phonemes for learning word structure rules) rather than transitional probabilities, was a type of SL that could account for both transitional probability and rule learning. Thiessen, Kronstein, and Hufnagle (2013) developed the "extraction and integration framework" to account for other statistical sensitivities. According to this framework, language learners are sensitive to three types of statistical structure: *conditional statistical information* (such as the transitional probabilities used in word segmentation, where occurrence of one syllable is conditional upon or depends upon occurrence of the previous syllable; Saffran, Aslin, & Newport 1996); *distributional statistical information* (such as finding category boundaries based on the distribution of exemplars differing in frequency and variability; Maye et al., 2002); and *cue-based statistical information,* in which learners discover which perceptual attributes are correlated with attributes that cannot be directly

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perceived and which of those perceivable attributes are more reliable cues (e.g., using audible pauses and stressed syllables to define word boundaries that cannot be directly perceived in speech). Thiessen et al. (2013) use extraction and integration to explain how all three types of SL can be achieved. Extraction involves keeping two items in working memory (WM) and binding them together into one chunk so they no longer act like two items. Thus, if "bun" and "ny" occur together often, they may get chunked together into "bunny" achieving a form of conditional SL. Integration combines information across extracted chunks based on similarity resulting in frequencies, means, and common occurrences, which are required for distributional and cue SL. Together, extraction and integration can account for sensitivity to all three aspects of statistical structure (Erickson & Thiessen, 2015; Thiessen et al., 2013). Although these are thought to be separate processes with extraction relying on WM and attention and integration on long-term memory structures, they work together. Thus, learning of some statistical relationships may require more extraction and therefore more attention and WM, making them more explicitly, consciously learned, whereas others require more integration, which may actually be hurt by deployment of attention and WM, making them more implicit, unconscious processes. Extraction and integration used together to different extents for different learning situations can account for sensitivity to statistical structure, including conditional probabilities, distributional statistics, and cue-based statistics, using various aspects of the human memory system (activation, decay, interference, comparison, and abstraction) rather than relying on computation of transitional probabilities and other statistics per se.

Saffran (2003) also suggested that if human languages were shaped by basic human learning constraints, the learning mechanisms involved were likely not developed specifically for language but were mechanisms used elsewhere, and thus, learning in other areas should be subject to these same constraints. This implies that SL mechanisms may be domain-general, acting in multiple cognitive (e.g., linguistic, nonlinguistic, motor) and sensory (auditory, visual, tactile) domains, although there may be multiple subsystems accomplishing similar types of learning with different inputs in different sensory and cognitive domains. Conway and Pisoni (2008) suggested that there is behavioral and neural evidence for both domain-general (mechanisms that act in the same way across different cognitive and sensory domains) and modality-specific (mechanisms that are confined to a single cognitive or sensory domain) implicit sequence learning mechanisms of which SL is a component. They proposed that domain-general and modality-specific mechanisms and brain areas interact to produce successful learning and that those mechanisms and brain areas overlap with those involved in language processing. As discussed later, this proposal suggests that interventions specific to language as well as those targeted to closely related domain-general mechanisms may interact to provide successful treatment of language disorders.

The Link Between SL and Language: Recent Behavioral Findings

After the initial discovery of human SL ability (Saffran, Aslin, & Newport, 1996) in a pseudolinguistic context, predictions followed that if SL is important for language learning, individual differences in SL ability should be related to individual differences in several diverse language abilities. One of the first studies to test this prediction in typically developing adults compared performance on two laboratory tasks: a probabilistic artificial grammar learning task called the Simon task (a type of complex SL task; see Cleary, Pisoni, & Geers, 2001; Reber, 1967) and a sentence prediction task (Conway et al., 2007). In the SL Simon task, adults reproduced a series of color sequences and spatial sequences. The order of elements in the sequences during an exposure phase was dictated by a "hidden," probabilistic grammar (artificial grammar) that consisted of a set of rules that defined the probability of each color (color sequences) or location (spatial sequences) following each other color or location. Thus, for example, for a particular participant, the grammar might be such that if green is displayed first, there is a 50% chance that red would come next, a 50% chance that blue would come next, a 0% chance that yellow would come next, and a 0% chance that green would be presented again. There would be another set of probabilities for which color would follow the next item in the sequence, and so forth. Participants' ability to incidentally learn the regularities of the grammar during an exposure phase led to better ability to reproduce new sequences during a test phase that followed the grammar better than those that did not. For the language processing task, participants listened to spoken sentences that had been spectrally degraded using a vocoder and were asked to write down the final word in each sentence. The final words were either highly predictable due to high semantic context of the sentence, difficult to predict due to low semantic context that allowed for multiple potential words at the end of the sentence, or unpredictable due to anomalous (meaningless) semantic context (Kalikow, Stevens, & Elliott, 1977). Performance on the color sequence task (color Simon task) was found to be positively correlated with performance on the high- and low-predictability sentences, but not on the anomalous sentences. Performance on the spatial sequence task (spatial Simon task), a less verbalizable task, was not significantly correlated with language processing performance. Conway et al. (2007) suggested that these data indicate that implicit SL, particularly in the verbal domain, may underlie language processing ability in adults.

Continued research in the same vein has replicated these initial findings and extended them to an auditory probabilistic grammar task, which was found to be correlated with an audiovisual sentence prediction task (Conway, Bauernschmidt, Huang, & Pisoni, 2010). General linguistic knowledge, global intelligence, short-term sequence memory, WM, nonverbal intelligence, and attention and inhibition were ruled out as possible factors that could account for the positive correlations between the SL tasks and sentence

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prediction tasks. In addition, Misyak and Christiansen (2012) also found individual differences in SL. They reported that the ability to learn adjacent statistical relationships, in which one item dictates the directly following item in a sequence, positively predicted language processing ability for adjacent relationships (such as “an” being directly followed by a noun beginning with a vowel, such as “apple” rather than “grape”), whereas the ability to learn nonadjacent statistical relationships (those in which an item in a sequence predicts another item that follows at a distance rather than immediately) predicted language processing ability for tracking long-distance relationships, such as the pronoun “he” agreeing with “boy” in the sentence, “The boy was about to fall when he caught himself.” These relationships between SL and language abilities were independent of other cognitive, experience, and motivational factors. Conway et al. (2010) postulated that sensitivity to the underlying statistical structure of sequences was the information-processing mechanism allowing for success on both the implicit sequence learning task and the language processing sentence prediction task and that better implicit sequence learning ability permitted more detailed representations of word order probabilities allowing for more efficient language processing and prediction of upcoming units.

In another study, Misyak, Christiansen, and Tomblin (2010) found that an SL task with nonadjacent dependencies requiring long-distance prediction was also positively correlated to a natural language processing task involving comprehension of object-relative clauses, which require tracking changes in meaning and therefore predictive outcome across an entire sentence. In addition, Misyak et al. (2010) were able to model their participants’ performance on the SL prediction task using a computer model with a very limited WM capacity. The authors concluded that their results coupled with previous findings confirmed that prediction-based processes supported by SL mechanisms are critically important in language processing and that SL ability is a better predictor of language processing than verbal WM capacity.

Research with infants and children has produced additional evidence for a positive link between SL and language development as well. For example, using a longitudinal design, Shafto et al. (2012) presented three-item visual sequences in a visual SL (VSL) task to 8.5-month-olds. Each item was presented either in front of the infant or to the left or right of the infant with the order of locations consistent across sequences. Infants who learned the order of locations could more quickly correctly turn their heads toward the next item in the sequence. Shafto et al. (2012) found that response time for a head turn toward the next shape in the visual sequence was positively correlated with infants’ receptive vocabulary at the time. In addition, 5 months later when infants were 13.5 months old, their VSL performance at 8.5 months predicted their communicative gesture comprehension at 13.5 months, suggesting a possible causal link in which better SL leads to better language development. In another longitudinal study, Ellis, Gonzalez, and Deák (2014) found that 6-month-olds’ response speed to a predictable visual target was highly positively predictive of both their receptive and productive vocabularies at 22 months, regardless of mother’s speech quality and general cognitive development level. These findings provide additional converging support that sensitivity to sequential or statistical dependencies contributes to individual differences in language learning and processing.

In a different type of word learning experiment, 22-month-olds were first exposed to an artificial language using an auditory speech stream that contained two word categories distinguished by probabilistic distributional and phonological properties. After exposure to these materials, the children were presented with pictures mapping meaning to the words in which meaning correlated to the phonological and distributional properties of the words (Lany, 2014). Only children with higher levels of grammar development were able to map the meanings to the words; however, their vocabulary size was not related to their ability to map the words and referents. Lany (2014) suggested that this finding may mean that infants’ ability to probabilistically match sound and meaning may contribute to both word learning and grammatical development, implying that SL is important for both vocabulary and grammar acquisition.

Research with older children has also established a positive relationship between SL and grammar ability. Four- to 6-year-olds implicitly learned a new grammatical construction (passive form) through a technique called syntactic priming, in which an experimenter described a picture using the target construction (passive form) and then considered children to have learned through syntactic priming if they subsequently used the passive form in describing a different picture (Kidd, 2012). Children also participated in an implicit VSL task as well as an explicit test of word pair learning. Kidd (2012) found that performance on the VSL task, but not the explicit word pair learning task, predicted children’s ability to maintain use of the passive form after syntactic priming had ended. In another study, 6- to 8-year-olds were tested for their comprehension of four grammatical constructions and completed a VSL task that assessed sensitivity to adjacent dependencies (Kidd & Arciuli, 2016). Performance on the two most difficult and least frequent grammatical constructions, passives and object relative clauses, was positively predicted by VSL performance. Together, these studies, along with Lany (2014), suggest that a domain-general SL mechanism may also underlie grammatical development, particularly for low-frequency constructions.

Finally, there is also evidence for the important role of SL in reading ability. Arciuli and Simpson (2012) found that, for both adults and children, individual differences in performance on a VSL task positively predicted reading ability once they controlled for age and attention. Spencer, Kaschak, Jones, and Lonigan (2015) also found a positive relationship between two measures of SL (a visual artificial grammar task and an auditory word segmentation task) and literacy skills and, in particular, with three components of early literacy: oral language skill, vocabulary knowledge, and phonological processing. According to Arciuli and

Simpson (2012), high SL ability may boost reading ability both directly by helping in detection of statistical regularities between letters and phonemes and indirectly by contributing to performance in a number of other areas in language, such as vocabulary and syntax (as discussed above; Ellis et al., 2014; Kidd, 2012; Kidd & Arciuli, 2016; Lany, 2014; Shafto et al., 2012), that are critically important for building reading skills.

Taken together, these studies (and others) of the links between various forms of SL and language processing, vocabulary, syntax, and reading in infants, children, and adults suggest that there is a strong association between SL and language abilities and that individuals' performance in one is positively correlated with their performance in the other. Longitudinal studies, such as that by Shafto et al. (2012), even point toward a causal link in which better SL leads to better language development in infants. These studies begin to lend support to the suggestion that finding a way to improve SL as part of a language intervention may, in turn, lead to improved language outcomes. Further support for this idea can be found in the neuropsychological research, as discussed below.

The Link Between SL and Language: Neural Findings

Abundant behavioral research shows links between SL and multiple aspects of language processing, including word segmentation and category formation, vocabulary, syntax, and semantic predictability. A logical next step in fleshing out the relationship between SL and language is to determine whether there are any links between the neural underpinnings to the two sets of processes, which would give additional direct evidence of the nature of the association and at what level it occurs. A small handful of event-related potential (ERP), functional magnetic resonance (fMRI), and other brain imaging studies have begun to address this foundational question.

ERP Research

In the first study to directly compare neural mechanisms of SL and language within the same set of participants, Christiansen, Conway, and Onnis (2012) measured ERPs (electrical changes in the brain elicited by cognitive, sensory, or emotional processing of an event) from adults who completed both a complex VSL task and a visual natural language processing (reading) task. In both tasks, when a violation of the sequence or sentence grammar was encountered, there was a positive change in voltage recorded from the scalp 600 ms after the violation, known as a P600 component. This component is considered to be an index of syntactic processing of natural language. In addition, the P600 was observed in the same scalp region for both tasks, suggesting that they may be evoking activity in the same part of the brain. Thus, Christiansen et al. (2012) concluded that it was likely that the same brain mechanisms were being recruited for both syntactic processing of language and more general VSL and that these brain mechanisms might function to make predictions about upcoming items in a sequence regardless of the form of the sequence (e.g., linguistic or nonlinguistic). Using a similar design with a Spanish-speaking sample, Tabullo, Sevilla, Segura, Zanutto, and Wainselboim (2013) found similar results with the added result of an additional ERP component, the N400 (a negative change in voltage of 400 ms after the violation), in common between tasks.

Daltrozzo et al. (2017) used a different method in which they measured SL by comparing ERPs to two stimuli that predicted a target with either high or low probability within a visual sequence. They showed that neural measures of SL ability in adults were positively related to performance on standardized measures of both grammar and receptive vocabulary. In addition, although the relationship between neural measures of SL and grammatical ability was independent of the level of selective attention displayed by the participant, the relationship between SL and vocabulary held only for those participants who displayed high levels of selective attention. These recent findings lend additional support to the hypothesis that SL mechanisms are at least partially domain-general, in that a VSL measure was positively related to two auditory language measures, and yet they are also somewhat modality-specific, in that one of those relationships was attention-dependent whereas the other was not.

Finally, Smith, Valdez, Walk, Purdy, and Conway (2016) used a technique that allowed them to extrapolate the region of the brain from which the ERPs originated. They found that violations to a visual task with an artificial grammar (a black and white version of the Simon task) elicited a larger P300 ERP component whereas grammar violations in a visual natural language task elicited a larger P600 ERP component. Further analyses (Smith, Valdez, Walk, Purdy, & Conway, 2017) showed that both originated in the left anterior superior temporal gyrus (STG) brain region. The left anterior STG is known to be part of a left-lateralized language processing network that includes Broca's area. Smith, Valdez, et al. (2016; Smith et al., 2017) concluded that the anterior STG may be part of a domain-general, general-purpose sequence processing network (Smith et al., 2017), rather than a language-specific network, and that this brain network underlies both SL and syntactic processing of natural language.

Brain Imaging Research

Brain imaging studies have also found evidence that SL and language activate the same brain regions. As mentioned, Broca's area, in the left inferior frontal cortex, has long been associated with language processing, especially the processing of syntax (Embick, Marantz, Miyashita, O'Neil, & Sakai, 2000). A number of recent neuroimaging studies have found that Broca's area is also activated during various SL tasks, including fMRI of an auditory statistical word segmentation task (Karuza et al., 2013), fMRI of visual simple artificial grammar learning and classification (Forkstam, Hagoort, Fernández, Ingvar, & Petersson, 2006), fMRI of visual hierarchical artificial grammar learning (Bahlmann,

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Schubotz, & Friederici, 2008), and near-infrared spectroscopy of auditory statistical tone sequence segmentation (Abla & Okanoya, 2008). Thus, it appears that multiple kinds of SL tasks activate a classic language processing area of the brain, suggesting that SL and language processing operations rely upon some of the same underlying mechanisms and brain networks.

In summary, the ERP research demonstrates similar electrical signals for various aspects of SL and language as well as correlations between the ERPs elicited in both SL tasks and language assessments. The brain imaging research further shows overlap in the brain areas activated by both SL and language tasks. Taken together, there is strong converging evidence that SL and language processing may share some of the same underlying brain mechanisms.

SL in Children Who Are Deaf and Use CIs

The Original Findings

Early research on deafness has shown that early onset deafness may have implications beyond hearing that lead to disruption of temporal and serial order processing and related abilities (e.g., Myklebust & Brutten, 1953; Rileigh & Odom, 1972). In addition, children who are prelingually deaf and later gain access to sound through cochlear implantation show widely variable language outcomes (Markman et al., 2011), not all of which are accounted for by conventional demographics such as age of implantation and length of deafness (Tomblin, Barker, & Hubbs, 2007). Conway, Pisoni, Anaya, Karpicke, and Henning (2011) hypothesized that children who are prelingually deaf and use CIs (henceforth, “children with CIs”) might show variability in or atypical SL, which in turn could perhaps explain some of the observed variability in language outcomes after implantation.

Conway, Pisoni, et al. (2011) tested this proposal with 5- to 10-year-old typically hearing (TH) children and prelingually deaf children with CIs who had received their implants before the age of 4 years and used them for at least 3 years, reported no other disorders, and were living in an American English language predominantly speech-based environment and attending oral schools for the deaf. Both sets of children completed a VSL task (Simon task described earlier) similar to that used in previous research with TH adults (e.g., Conway et al., 2007, 2010). In the task, children were asked to reproduce sequences of colors using a touch screen. Unbeknown to the children, the visual sequences obeyed the rules from a probabilistic grammar, which dictated the order that each color could occur. After a period of exposure, the sequences seamlessly changed, such that only half followed the grammar but were novel and half were novel ungrammatical sequences. Greater accuracy on the grammatical than ungrammatical sequences indicated SL, and the magnitude of the difference indicated the level of SL. Although the TH group as a whole showed evidence of SL, the children with CIs as a group did not. In addition, individually, SL levels of the children with CIs were significantly positively correlated with two standardized measures of language, both involving syntax, as well as other language skills, even after controlling for verbal short-term memory capacity and vocabulary. Conway, Pisoni, et al. (2011) concluded that a period of sound deprivation early in life was detrimental to SL development and that, for children with CIs, that impoverished domain-general SL was closely linked to language development outcomes. They also suggested that individual differences in SL ability could account for the wide variation in language outcomes for children with CIs. In addition, further research indicated that an early period of sound deprivation also led to poorer motor sequencing skills (speeded sequential finger tapping) in children with CIs than their TH peers and that motor sequencing ability was also positively correlated with a global clinical language measure (Conway, Karpicke, et al., 2011; also Fagan, Pisoni, Horn, & Dillon, 2007; Horn, Fagan, Dillon, Pisoni, & Miyamoto, 2007).

Although these were the first studies to specifically address SL in children with CIs, they are consistent with a number of previous studies showing deficits in other nonverbal serial tasks. For example, Todman and Seedhouse (1994) found that children who were profoundly prelingually deaf (some signing experience and some speech training) performed better than TH children at free recall of action–visual stimulus pairs (e.g., open your mouth when you see a square), but they did much worse than TH peers when they were required to recall the pairs in the correct serial order, suggesting specific difficulty with the sequential nature of the task. In addition, Schlumberger, Narbona, and Manrique (2004) found that children who are deaf (both with and without CIs) showed evidence of delays in the development of complex motor sequence production. Thus, it appears that children who are deaf may have a specific impairment to learning sequential patterns, such as those exploited in some types of SL.

Proposed Explanation: The ASH

Conway et al. (2009) proposed the ASH to explain the relationship between sound and cognitive abilities related to sequencing. This hypothesis provides an explanation for the findings of Conway, Pisoni, et al. (2011) and Conway, Karpicke, et al. (2011) with regard to SL and other sequencing abilities of children with CI as well as their relationship to language outcomes. According to the ASH, sound itself, unlike other sensory signals, is by its nature a sequential, temporally ordered signal (e.g., Hirsh, 1967). Thus, access to sound early in life provides a “scaffolding” that supports the development of sequential processing and sequential behavior by providing access to salient, easily ordered stimuli (see Luria, 1973). Therefore, the absence of sound early in life is likely to cause developmental delays to sequence-related skills such as SL and language, as found by Conway, Pisoni, et al. (2011) and Conway, Karpicke, et al. (2011). Conway et al. (2009) cite two lines of research supporting the ASH: the superiority of hearing over other senses for SL (e.g., TH adults perform better with auditory compared to visual or tactile SL tasks; Conway & Christiansen, 2005)

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and the deficits displayed on SL and other sequence-related tasks shown by those who have experienced sound deprivation through deafness (e.g., Conway, Karpicke, et al., 2011; Conway, Pisoni, et al., 2011; Myklebust & Brutten, 1953; Rileigh & Odom, 1972).

Conway et al. (2009) suggested two potential mechanisms through which the ASH could work. First, auditory signals may provide an opportunity to imitate and rehearse sounds in a continuous sequence, thus strengthening attention to sequences as well as to domain-general SL abilities. Second, sounds, unlike other environmental signals, may provide higher-level, domain-general information regarding temporal change and serial order, and hearing is the gateway to gain access to this source of information. Both mechanisms would recruit learning and planning mechanisms originating in the frontal lobe of the brain, and their absence due to lack of access to sound could lead to brain changes in the form of the cortical reorganization and atypicalities in the frontotemporal regions seen in children who are deaf (e.g., Luria, 1973; Wolff & Thatcher, 1990).

Recent Studies of SL in Individuals With Hearing Impairment

A number of recent studies have reported results that are consistent with the original findings by Conway, Pisoni, et al. (2011) and Conway, Karpicke, et al. (2011), although results from other studies do not appear consistent. Gremp (2011) conducted a similar study to Conway, Pisoni, et al. (2011) with two groups of 5- to 12-year-old children: one of TH children and one of prelingually deaf children with CIs and/or hearing aids who had been diagnosed with hearing loss prior to 3.5 years and fitted with hearing aids or CIs by 4 years and were living in an American English language predominantly speech-based environment and attending oral schools for the deaf, the most receiving early intervention. No additional impairments were reported other than a handful of children with attention-deficit/hyperactivity disorder. Gremp (2011) presented children with four versions of the Simon SL task used in Conway, Pisoni, et al. (2011): a simple Simon SL task with easily nameable color stimuli and repeating sequences that built on each other to reproduce, a similar Simon SL task with less easily nameable black and white stimuli differentiated only by location on the screen, a Simon sequence memory task with easily nameable color stimuli in which each sequence to be reproduced was different and thus a pattern could not be learned, and a Simon sequence memory task with less easily nameable black and white stimuli. Children with hearing impairment performed worse than TH children on all versions of the task, but they performed particularly poorly on the easily nameable color SL version. This suggests that children with hearing impairment had particular difficulty with SL (as compared to sequence memory) of stimuli in which a strategy of verbally labeling stimuli could be useful. In addition, the easily nameable Simon task positively predicted children's receptive vocabulary for children with hearing impairment only, not for TH children.

In another study, Ulanet, Carson, Mellon, Niparko, and Ouellette (2014) tested 4- to 8-year-old children who were prelingually deaf and implanted with CIs between 13 and 74 months of age and who attended school in a fully integrated classroom alongside TH peers and were being raised in an American English–speaking environment. They found that those who had lower than expected language development had lower sequential processing scores than peers with CIs who were performing at or above expected language levels. Simultaneous processing (i.e., nonsequential) scores, however, did not differ across CI groups. In addition, Bharadwaj and Mehta (2016) found both behavioral and ERP evidence that children with CIs (5–11 years, prelingually deaf, implanted before age 4, English-speaking, using spoken language or sign-supported speech, no other reported delays or impairments) performed worse on visual sequential memory and visuomotor sequencing tasks than TH peers (6–12 years, English-speaking, no reported delays or impairments). Furthermore, children with CIs appeared to have slower ERP responses and reaction times in a visual sequential matching task, suggesting slower processing of visual sequential stimuli.

More broadly, another study by Bharadwaj, Matzke, and Daniel (2012) showed that 5- to 9-year-old prelingually deaf children with CIs implanted before the age of 5 (all receiving auditory verbal therapy and using spoken language as their primary communication mode and residing in Texas) performed as well as or better than standardized norms on visual, tactile, and proprioceptive spatial assessments. However, when temporal, sequential assessments of tactile and proprioceptive performance (visual was not measured) were compared to norms, children with CIs scored below average, suggesting a deficit specifically in processing and/or responding to sequential stimuli. Deaf adults (20–65 years, both pre- and postlingually deaf participants, half with a CI and the rest with either hearing aids or no hearing device used) also showed learning impairments compared to TH adults (age-matched) in a study using a visual–motor sequence learning task (Lévesque, Théoret, & Champoux, 2014). When participants were given sequences of stimuli and asked to press corresponding buttons for each stimulus, although both groups responded faster in blocks that contained a repeating sequence versus blocks that contained random sequences, TH adults benefitted significantly more from repeating sequences (a very simple form of SL) than did deaf adults. Thus, even adults with hearing impairment appear to show deficits specific to statistical, sequential information.

Interestingly, Guo, McGregor, and Spencer (2015) determined that toddlers with bilateral CIs showed sensitivity to the statistical structure in spoken language similar to TH children at the same stage of lexical development, but toddlers with unilateral CIs did not show the same level of sensitivity, suggesting that increased exposure to sound through bilateral implants may boost SL abilities, consistent with the ASH. Toddlers in this study were approximately 28 months of age at the time of testing and had received their implants before 24 months; none showed evidence of

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other delays or impairments, and all spoke American English and received either oral communication or total communication early intervention. In another study of an SL-related real-world skill, Faes, Gillis, and Gillis (2017) used the longitudinal video data to determine whether word frequency influenced phonemic accuracy for both TH children and children with CIs. Children with CIs were prelingually deaf monolingual Dutch speakers living in Flanders with no other health or developmental problems reported and were followed from device activation (all before 2 years) through 7 years. All children used primarily oral communication with some signs and received speech and language therapy and auditory training. For both TH children and children with CIs, word production accuracy was higher for words that were encountered more frequently in natural language. However, the effect of word frequency on production accuracy was stronger for TH children, suggesting that, although both sets of children were sensitive to language statistics in the form of word frequency, children with CIs were less sensitive—another example of impairment to a real-world form of auditory SL for children with CIs. Finally, Studer-Eichenberger, Studer-Eichenberger, and Koenig (2016) used ERPs to determine that 4- to 7.5-year-old children with hearing impairment (not CIs but > 30 dB hearing loss in at least one ear, no other impairments or delays, mainstreamed in Swiss schools and spoke German or Swiss German) had reduced auditory SL compared to age-matched TH peers even if they showed no deficit in speech production. Studer-Eichenberger et al. (2016) suggest that this reduced auditory SL may explain impaired phonological short-term memory, phonological discrimination, and articulation rate, which has been linked to verbal short-term memory.

Thus, consistent with the ASH (Conway et al., 2009), research reported thus far has shown that, across a variety of tasks and conditions, it appears that children and adults with hearing impairments show atypical SL and sequencing abilities and that SL performance for this population is positively related to their spoken language ability. In addition, deficits appear to be specific to SL, sequencing, and language with other cognitive mechanisms left intact or even possibly enhanced.

On the other hand, two recent studies appear to be contrary to the findings discussed thus far and inconsistent with the ASH. Hall, Eigsti, Bortfeld, and Lillo-Martin (2017) tested three groups of 7- to 12-year-old children: one group with CIs (severely to profoundly prelingually deaf, implanted by 3 years, raised in an American English–speaking environment with an oral/aural approach) who had a period of both sound and language deprivation, one group of native signers (severely to profoundly prelingually deaf, some used hearing aids or CIs sometimes, bilingual in American Sign Language and written English, being raised in the United States) who continued to have sound deprivation but had never experienced language deprivation, and one group with typical hearing (American English–speaking monolinguals and multilinguals) who had neither sound nor language deprivation. Children completed both an artificial grammar task designed to be the same as the Simon SL task used by Conway, Pisoni, et al. (2011) and a serial reaction time (SRT) task in which a 10-item sequence repeated 12 times interleaved with random sequences and children pressed the appropriate response key for each item presented within each sequence (Nissen & Bullemer, 1987). There were no differences in learning across the three groups on either task; none of the groups showed learning on the Simon task, whereas all of them demonstrated learning on the SRT task. Hall et al. (2017) concluded that SL is not affected by sound deprivation and that their results did not support the ASH.

Hall et al.'s (2017) study is well motivated in that previous studies have not been able to discriminate between the effects of auditory deprivation versus language deprivation per se as groups with hearing impairment have typically either endured an early prelingual period without both sound and language exposure or the group included a mixture of hearing histories, which may or may not have included language deprivation. Research is needed to discriminate between these possibilities to determine the viability of the ASH, which hinges on effects of auditory deprivation leading to disruption of SL but does not exclude the possibility that language deprivation may also contribute to such disruption. Hall et al.'s (2017) study attempts to fill this gap by providing separate groups that had either sound deprivation only (native signers), sound and language deprivation (children with CIs), or neither sound nor language deprivation (TH children). However, there are several reasons to carefully examine the recent findings and conclusions of Hall et al. (2017).

Considering the Simon task first, it is puzzling that none of the participant groups demonstrated evidence of sequence learning on the task. The Simon task has been used across multiple studies both by our research group and others (e.g., Conway et al., 2010, 2007; Conway, Pisoni, et al., 2011; Karpicke & Pisoni, 2004; Spencer et al., 2015), providing ample demonstration of its usefulness for measuring SL ability. That Hall et al. (2017) did not replicate the SL effect in any of the groups they tested, even in the TH children, suggests that the task may have been implemented differently from that used in previous studies. One difference is that Hall et al. (2017) allowed the participants to make self-corrections, which likely invalidates the task as a measure of implicit (unconscious) learning. Second, a number of features of the SRT task make it a much simpler form of SL than the Simon task. The SRT task involves simply responding to a repeated pattern through motor learning and requires no recall, whereas the Simon task involves recall of sequences that follow a complex grammar (see Cleary & Pisoni, 2003). Finally, there are important differences between the participant samples used in Hall et al. (2017) compared to our original study (Conway, Pisoni, et al., 2011). Children in the Hall et al. (2017) study were both older and had received their implants earlier than the participants in Conway, Pisoni, et al. (2011), leading in turn to about 3 more years of implant use. Greater amounts of exposure to sound and spoken language likely make the

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Hall et al. (2017) sample more proficient at SL. Other limitations in the Hall et al. (2017) study methodology and interpretation may also limit its relevance for comparing effects of auditory and language experience and for testing the ASH (Kronenberger & Pisoni, in press).

Another important study to consider is by Torkildsen, Arciuli, Haukedal, and Wie (2018). Children with CIs and TH children were presented with a VSL task involving a continuous stream of images that were arranged into triplets in which three individual items were always presented in the same sequential order during an exposure period. After the exposure period, they were tested on triplets from the exposure and triplets not shown during exposure and asked which they had seen. Torkildsen et al. (2018) found that children in both groups learned the triplets, and there was no difference in performance between children with CIs and TH children. In addition, there was no correlation between VSL and the age at which children received their implants or speech perception ability. Torkildsen et al. (2018) suggest that the ASH is too broad in its claim of domain-general deficits due to an early period of sound deprivation and that the differences between their results and those of previous studies are likely due to the fact that their stimuli did not lend themselves to verbal rehearsal to the extent that others did.

On the one hand, we agree that it is likely that children with CIs may have an especially difficult time encoding and representing stimuli that lend themselves well to verbal rehearsal (Cleary et al., 2001; Gremp, 2011; Nittrouer, Caldwell-Tarr, Low, & Lowenstein, 2017), and so perhaps this is where the greatest group differences on SL tasks are likely to be found. On the other hand, there is some evidence that children with CIs show difficulty even with nonverbal sequencing tasks (e.g., Conway, Karpicke, et al., 2011). In addition, similar to our discussion related to the Hall et al. (2017) study, there are important differences both in the task used by Torkildsen et al. (2018) and possibly with the participant sample. For instance, their VSL task could be considered to be a simpler form of SL compared to the demands of the Simon task because the VSL task does not involve encoding, storing, and retrieving sequences generated by a complex artificial grammar that requires generalization to novel stimuli. Likewise, the participant sample used by Torkildsen et al. (2018) seems less representative of the typical populations of TH children and children with CIs (e.g., both groups scored 0.33 *SD*s above the normative mean on the Leiter International Performance Scale–Revised [Roid & Miller, 1997] memory subtests and both groups scored on average 0.5 *SD*s below the normative mean on the Leiter Attention Sustained subtest).

Based on these two recent studies, it is clear that more research is needed to fully understand which aspects of SL might be compromised in deaf children with CIs and what factors can explain variability in performance on different tasks. The studies reviewed in this section are important for offering additional tests of the ASH and help delineate under what conditions children may or may not struggle on tasks involving SL. It is our belief that, even with some of the evidence providing what could be construed as inconsistent findings, the majority of research to date has been consistent with the idea that certain aspects of SL are atypical in children with CIs and that such delays in basic learning skills have a detrimental impact on their ability to acquire spoken language. The studies that purport to contradict the ASH are important for contributing additional findings that may promote a refinement of our understanding but should be understood in the general context of all findings. Although beyond the scope of the current review, it is also important to situate the SL studies reviewed here in the context of other research examining cognitive effects associated with deafness and cochlear implantation. For instance, Nittrouer, Caldwell-Tarr, and Lowenstein (2013) showed impairment to WM storage related to poor sensitivity to phonological structure but no detriment to WM processing in children with CIs. It is likely that deficits to aspects of WM in conjunction with impairments to SL may have detrimental bidirectional effects that combine to lead to poor language outcomes.

Can SL Be Improved?

If proficiency in SL ability is positively associated with successful development of spoken language and if some children with CIs show atypical SL as the research findings appear to suggest, then it may be beneficial to improve spoken language outcomes by enhancing SL. One approach is to use computerized neurocognitive training regimens to improve SL, similar to the way this technique has been used to enhance other aspects of cognition, such as WM. Another approach could be to stimulate the neural regions recruited for SL, which can be done noninvasively with electrical or electrical magnetic current. These two approaches to neurocognitive enhancement could signify avenues for capitalizing on the neural potential for plasticity (the brain's capability of being modulated and reorganized throughout the life span; Kleim & Jones, 2008; van Praag, Kempermann, & Gage, 2000) to develop contemporary, implementable language interventions that focus specifically on improving SL skills.

Computerized Training

WM Training

Computerized training has been used in an effort to improve certain facets of cognitive processing, a technique that has been investigated expansively in the domain of WM. The general aim of the initial computerized WM training (CWMT) studies was to assess whether engaging in a battery of WM training tasks over a period of weeks would boost WM capacity and show transfer to other nontrained tasks of WM (near transfer) as well as transfer to different cognitive functions that were not directly related to the trained task, such as fluid intelligence or mathematical reasoning (far transfer; see Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002, for examples of the core CWMT battery and seminal findings). Overall findings from these early CWMT studies showed that, at

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follow-up sessions, up to 3 months posttraining, participants in the WM training condition showed significant improvement compared to the control group for nontrained WM tasks and improvement for some nontrained executive functioning tasks, including the Stroop task and Raven's matrices. Of particular note for the current discussion, a recent pilot study (Kronenberger & Pisoni, 2016) provided evidence of the efficacy of CWMT for children with CIs. They found improvements in measures of both WM and sentence repetition following training. Although the magnitude of improvement for most measures declined after 6 months, the improved level of sentence repetition performance was preserved.

Several critiques have been directed against the effectiveness of WM training, particularly those questioning mixed ability to replicate the far-transfer findings that suggest that enhancement of WM capacity leads to improvements in other nontrained abilities beyond WM (e.g., Melby-Lervåg & Hulme, 2013; Morrison & Chein, 2011; Shipstead, Redick, & Engle, 2010, 2012). One important premise of computerized training is that the success of any given regimen hinges on whether the cognitive skill being trained and the nontrained cognitive skill targeted for far transfer must recruit the same neural regions (e.g., Hoen et al., 2003; Klingberg, 2010; Morrison & Chein, 2011; Olesen, Westerberg, & Klingberg, 2004). In the case of WM training, evidence suggests that activity in prefrontal and parietal brain regions is associated with training-related gains to WM (e.g., Klingberg, 2010). This suggests that some amount of far transfer should be possible, given that this frontal/parietal network is associated broadly with myriad cognitive skills related to attention, learning, memory, executive control, intelligence, and language (Kobayashi, Schultz, & Sakagami, 2010; Siddiqui, Chatterjee, Kumar, Siddiqui, & Goyal, 2008). However, it is possible that computerized training will be most effective when the shared neural mechanisms are recruited in a more targeted manner or when the entire network, including its projections, can be better defined in terms of how it supports the cognitive skills being trained. For example, by specifically targeting training efforts toward achieving neural changes in Broca's area, a brain area known to be involved in both language processing and SL, it is possible that this could lead to improvements to both SL and language functions. Still, the CWMT literature continues to grow with over a hundred published studies using versions of the CogMed training regimen alone and has ushered in the possibility that computerized training can be used to modify other aspects of cognition, such as SL.

SL Training

A few studies have revealed early promise that SL can be modified by computerized training, with some of the findings linking enhancement of SL to improvement in language processing. For example, using auditory speech streams of artificial words obeying two different artificial grammars with healthy adults, Onnis, Lou-Magnuson, Yun, and Thiessen (2015) demonstrated that participants could be induced to use either forward or backward transitional probabilities to parse strings of phonemes into pseudowords through training. They did this by giving one or the other type of transitional probability higher probabilities, making them more reliable sources of information. Although this study did not investigate the potential for far-transfer effects of SL training extending to language abilities, these findings do suggest that the ability to extract statistical information useful for processing grammatical structure can be enhanced through experience.

Hoen et al. (2003) directly investigated whether SL training would improve both SL and syntactic language processing for patients with agrammatic (Broca's) aphasia. Following 10 days of nonlinguistic SL training, significant improvement to performance on a nontrained artificial grammar-based SL task occurred (near transfer). In addition, this enhancement of SL transferred to significant improvement on a nontrained natural language syntactic comprehension task (far transfer), but only for sentences with a certain type of syntactic structure. Training-related gains were only observed for sentences with a relative clause structure (e.g., sentences similar to *It was the mouse that the cat hugged*), but not for active sentences without a relative clause (e.g., sentences similar to *The cat hugged the mouse*) or for passive sentence types without a relative clause (e.g., sentences similar to *The mouse was hugged by the cat*). The authors argued that the common neurocognitive component shared by both the SL task and the sentence comprehension task was the ability to extract basic structure out of complex patterns to make sense of the information being presented.

In a recent line of research, Smith, Conway, Bauernschmidt, and Pisoni (2015) used a mediation analysis to better understand the process by which computerized SL training might impact language outcomes. Healthy young adults were first assessed on baseline measures of SL and speech perception in noise. They then participated in 4 days of SL training, which involved tracking visual–spatial patterns embedded with statistical regularities and reproducing sequences built on those regularities. Although posttest findings using the same baseline measures did not result in training-related changes relative to two types of control groups who did not receive the SL training, they did indicate moderate training-related improvements to the nontrained SL task and the nontrained speech perception in the noise task. However, the results of the mediation analysis showed that the SL training had both direct and indirect effects on the measure of language, with enhancement of SL significantly mediating the improvements observed on the speech perception task. This study was an initial step toward understanding the processes by which SL and language abilities interact with each other and may be one of the first to show that improvement to SL can lead to improvement to language processing ability.

To the extent that SL training would be expected to directly impact language processing, we would expect SL and language to recruit the same or similar neural regions or networks. Smith, Galvis, Rickles, Valdez, and Conway (2016) reported a proof of concept study with healthy adults

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to explore the computerized training-related changes in electrophysiological activity recruited during both SL and natural syntactic language processing. ERPs were used to assess any changes in electrical activity following training. Findings indicated that SL training resulted in modulation of the P300 ERP component elicited by a measure of SL and of the P600 component elicited by a measure of natural syntactic language processing, with both effects observed in the same frontal scalp locations. Furthermore, SL training led to a significant increase in behavioral accuracy on the nontrained measure of SL only in the group that received the training. None of these neural or behavioral training-related effects were observed in control groups. In a preliminary follow-up nontraining ERP study using versions of the same SL task and the natural syntactic language task from the previously mentioned study, source localization of electrical activity (a method of determining from where in the brain the electrical signals originate) showed marked overlap of the neural mechanisms recruited for both types of tasks in the anterior STG (Smith et al., 2017). As part of the so-called language network, STG connects with Broca's area encompassing BA 44/BA 45 and deep frontal operculum via the ventral pathway (Anwander, Tittgemeyer, von Cramon, Friederici, & Knösche, 2007; Friederici, 2011, 2012). Overall, the findings from these two recent studies suggest that improvements for SL and natural syntactic language processing following computerized training occur via modulation of neural mechanisms that may share a common neural origin and thus reflect the basis for successful training outcomes for these two aspects of cognition.

Neural Stimulation

As previously described, evidence from behavioral lesion studies and from neuroimaging studies suggests that activity in Broca's area, which has traditionally been associated specifically with syntactic linguistic processing (Friederici, 2004) as part of the previously mentioned language network, may be recruited in a more global manner for SL (e.g., Forkstam et al., 2006; Petersson, Folia, & Hagoort, 2012; Ullman 2001, 2008). The delineated overlap of neural circuitry that is thought to be recruited for SL and for language processing seems to make Broca's area a good focus for using neural stimulation approaches for enhancement. Neural stimulation is a noninvasive technique to modulate activity in the brain via electrical current administered either through electrodes positioned on the scalp (transcranial direct current stimulation) or by using a magnetic coil to generate a magnetic field that induces an electrical current inside the brain (transcranial magnetic stimulation [TMS]). Neural stimulation can result in enhancement of neurocognitive function by either increasing or decreasing neuronal excitability. It is also possible that neural stimulation can result in disruption of neurocognitive functioning, which also may have beneficial effects in certain clinical cases. Investigations using neural stimulation have the capacity to identify causal relations among constructs of interest and also hold promise as a potential treatment for individuals with a language delay or disorder.

Neural stimulation has been used to investigate the role of Broca's area in a number of studies focusing on SL of motor sequences (e.g., Alamia et al., 2016; Clerget, Andres, & Olivier, 2013; Clerget, Badets, Duqué, & Olivier, 2011; Clerget, Winderickx, Fadiga, & Olivier, 2009). Here we focus mainly on a few of the investigations that have specifically targeted Broca's area as a way to modulate SL. Uddén et al. (2008) examined the putative causal relation between activity in Broca's area and performance on an SL task based on the classic version of the artificial grammar learning (e.g., Reber, 1967) paradigm in which, during a learning phase, participants are exposed to sequences of stimuli that follow the rules of an artificial grammar and then, in a test phase, are presented with new sequences and are asked to classify them as either grammatical or ungrammatical. Their findings suggested that offline repetitive TMS of left Broca's area at BA 44/BA 45 enhanced grammaticality classification in the artificial grammar learning–based SL task by increasing the rejection rate of ungrammatical items and by reducing reaction time of correct rejections. This study was one of the first to establish a causal role of Broca's area in the enhancement of SL. In a subsequent study (Uddén, Ingvar, Hagoort, & Petersson, 2017), findings suggested that Broca's area is particularly important for learning long-distance dependencies between elements, which is the hallmark structure of hierarchical, syntactic language.

Alamia et al. (2016) found that disruption by TMS to the left Broca's area at BA 44 resulted in an increase to the processing speed of higher-order chunking during SL of a motor sequence, allowing the participants to quickly group items together into a unit to enhance processing efficiency. Interestingly, these findings have some parallel to the Hoen et al. (2003) earlier findings from the computerized training study previously discussed in which they concluded that their SL training regimen specifically enhanced the ability to extract a simpler structure out of complex structure, which is likely necessary for the successful understanding of spoken language.

Implications for Rehabilitation of Spoken Language for Children Who Are Deaf With CI

Emerging findings of computerized training and neural stimulation studies, some of which have been highlighted briefly here, indicate that it may be beneficial to attempt improvement of spoken language outcomes by enhancing SL. Could this approach lead to effective rehabilitation of spoken language for children who are deaf using CIs? Although it is yet too early to answer this question conclusively, we offer some points to consider.

The research reviewed earlier suggests that not only is SL modifiable by computerized training (e.g., Hoen et al., 2003; Onnis et al., 2015; Smith et al., 2015, 2017) and/or neurostimulation (e.g., Alamia et al., 2016; Uddén

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et al., 2008) but that such improvements to SL can, in some cases, result in far-transfer effects to improve language processing (Hoen et al., 2003; Smith et al., 2015). This work with healthy adults is complemented by recent demonstrations that cognitive and perceptual training, including WM, music, and other types of training, for children with CIs is also not only feasible but also potentially effective for improving spoken language performance and related cognitive skills (e.g., Bedoin et al., 2017; Ingvalson, Young, & Wong, 2014; Kronenberger, Pisoni, Henning, Colson, & Hazzard, 2011; Mishra & Boddupally, 2018; Roman, Rochette, Triglia, Schön, & Bigand, 2016). Recently, we have adapted the Smith et al. (2015) computerized SL training regimen for use with young children with CIs (e.g., Gremp, 2011). After 10 days of SL training, children with CIs showed improvements in performance on a test of nonword repetition (Gathercole, Willis, Baddeley, & Emslie, 1994), which is known to be strongly correlated with multiple measures of spoken language performance (Casserly & Pisoni, 2013). Furthermore, these gains persisted to a second session 4–6 weeks after the training, demonstrating that the training-related effects are not entirely transient (Gremp, 2011).

Thus, although there are still, as of yet, only a handful of studies that have attempted to target sequence memory and SL through computerized training, the existing evidence to date is promising, and additional research is needed to specify the extent of the training effects. Some questions that remain are whether the best form of training consists of VSL paradigms, auditory paradigms, or a combination of both, and what form and amount of training will result in the best gains to language outcomes that will persist over time. The type of SL training discussed in which children gain SL experience by reproducing sequences with an underlying structure that increase in length with each success (e.g., Gremp, 2011; Smith et al., 2015), although potentially requiring daily sessions, may be amenable to implementation in a relatively short daily period through an easy-to-administer, standardized computer program that can be completed at home, in schools, or in practitioners' offices. In addition, it may offer the advantage of being presented in a familiar game-like computer-based format that is at least somewhat entertaining, even for children who may have difficulty with social interactions. This can potentially lead to increased efficacy through high levels of compliance and motivation. In addition, tapping into SL as an underlying mechanism of language acquisition may lend additional efficacy, allowing for treatment of not only the symptom of language delay but also the underlying cause. Furthermore, training in visual and/or SL as well as language-based therapies, including specific training in syntax, semantics, and phonology to increase sensitivity to phonological structure leading to increased WM storage as suggested by Nittrouer et al. (2013), allows for multiple pathways for brain reorganization. Lasting brain, cognitive, and behavioral changes, in turn, may lead to long-term improvement in academic, social, and other important outcomes for children with CIs and potentially other hearing and language impairments who might otherwise endure life-long struggles to catch up to peers in various language-related skills.

A final question is whether neurostimulation, either alone or in conjunction with computerized training, might also offer tangible benefits to children with CIs. Neurostimulation research with young children is still in its infancy, and there are still basic questions about not only its efficacy but also its safety and whether it can have detrimental consequences to a child's developing brain (e.g., Amatachaya et al., 2014; Krause & Kadosh, 2013). There may also be complications surrounding the use of certain types of neurostimulation in affecting a child's CI functionality. However, despite these challenges, the potential benefits that could accrue through such novel intervention approaches appear to merit further investigation.

Conclusions

Despite advances in CI technology and in the scientific understanding of neurocognitive factors contributing to spoken language development in children with CIs, many children with CIs still struggle to learn spoken language effectively. We contend that fundamental learning and memory processes, especially those related to encoding and extracting regularities from environmental input, may represent the "missing piece of the puzzle" and provide the key to not only understanding but also improving language outcomes in this population (Pisoni, Kronenberger, Chandramouli, & Conway, 2016). Emerging research findings from cognitive science and cognitive neuroscience suggest that robust language development depends heavily upon fundamental SL mechanisms and that these learning mechanisms might develop atypically in some children who do not have adequate exposure to sound. Fortunately, experience via sound provided by a CI may help children bootstrap their learning and attention abilities to be able to adequately extract the regularities they are exposed to in speech and other input. The development of interventions using cognitive training and/or neural stimulation holds great promise for children who continue to exhibit delays in basic learning mechanisms to help promote and facilitate the successful acquisition of spoken language and ensure that all deaf children obtain optimal benefits from their hearing aids and CIs.

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