language experience, attention allocation, and working memory resources influence lower-level auditory processing at the level of the brainstem and even at the level of the cochlea.

These are known as top-down influences because a higher level of processing—higher in the sense of being further from the periphery of the central nervous system and also in the sense of being more cognitive—influences a level that is lower, or earlier, in the process. For example, phonological awareness may influence backward masking performance; auditory brainstem responses can be affected by musical training or by a person's choice of what stimulus to attend to. Thus, the causal direction of auditory processing deficits is not clear. Although perceptual deficits could cause problems in spoken and written language, as well as verbal working memory, attention, and other cognitive functions, problems with these higher functions could also influence perception.

In summary, the relationship between auditory processing and language impairments is difficult to characterize. There is a large body of evidence showing that auditory processing deficits are common in children with SLI or SRD. However, it seems unlikely that these deficits play causal roles in spoken and written language impairments. The auditory processing deficits are diverse in nature, and no single type of auditory processing difficulty has been found consistently across studies. Regardless of the auditory processing task, group differences are not always found, and even when they are, not all individuals with SLI or SRD demonstrate deficits. Furthermore, alternative explanations of the observed deficits are plausible. Interventions that aim to improve auditory processing have little effect on language or reading, and auditory processing is not consistently predictive of language and academic outcomes.

There remain, however, avenues of research that may reveal the nature of the relationships between auditory processing and language, causal or otherwise. Our understanding of the exceedingly complex auditory system, and its interactive relationship with the language processing system, continues to grow. At the applied level of ameliorating SLI and SRD, most auditory training interventions investigated so far have been based on a temporal processing deficit account. Other hypotheses that focus on brainstem timing or cortical oscillations may lead to different intervention techniques that are more effective. Explaining the entire neurodevelopmental pathway from the perception of the speech signal to the representation of phonological, lexical, and syntactic aspects of language is an ambitious goal but one that is worth pursuing.

Carol A. Miller
Pennsylvania State University

See Also: Developmental Dyslexia; Intervention for Child Language Impairments; Phonological Awareness; Processing Deficits in Children With Language Impairments; Specific Language Impairment (Overview); Speech Processing.

Further Readings

Banai, K. and N. Kraus. "Neurobiology of (Central) Auditory Processing Disorder and Language-Based Learning Disability." In *Handbook of (Central) Auditory Processing Disorder.* Volume I, F. E. Musiek and G. D. Chermak, eds. San Diego, CA: Plural Publishing, 2007.

Banai, K. and N. Kraus. "The Dynamic Brainstem." In *Controversies in Central Auditory Processing Disorder*, A.T. Cacace and D. J. McFarland, eds. San Diego, CA: Plural Publishing, 2009.

Fey, M., et al. "Auditory Processing Disorders and Auditory/Language Interventions." *Language, Speech, and Hearing Services in Schools*, v.42 (2011).

Marler, J. A. and C. A. Champlin. "Sensory Processing of Backward-Masking Signals in Children With Language-Learning Impairment as Assessed With the Auditory Brainstem Response." *Journal of Speech, Language, and Hearing Research*, v.48 (2005).

Miller, C. A. and D. A. Wagstaff. "Behavioral Profiles Associated With Auditory Processing Disorder and Specific Language Impairment." *Journal of Communication Disorders*, v.44 (2011).

Rees, N. S. "Auditory Processing Factors in Language Disorders: The View From Procrustes' Bed." *Journal of Speech and Hearing Disorders*, v.38 (1973).

Rosen, S. "Auditory Processing in Dyslexia and Specific Language Impairment" *Journal of Phonetics*, v.31 (2003).

Auditory Sequence/ Artificial Grammar Learning

Spoken language development depends upon basic auditory processing mechanisms that encode structural regularities in the input. These mechanisms, studied under the guise of sequence/sequential learning and often using the artificial grammar learning paradigm, represent midlevel cognitive processes that could be construed as being "above" auditory sensory and perceptual mechanisms but "below" true language processes. Research has suggested that these auditory learning mechanisms are specifically attuned to time-varying, sequential signals (like spoken language), are an important aspect of the development of language, and may be compromised in children with impoverished experience with sound.

Sequential learning refers to general abilities that most higher organisms possess for learning about structured patterns of information in the environment that unfold over time. Sequential learning can take place through any sensory modality and in multiple domains, including language and communication, motor and skill learning, music perception and production, problem solving, and planning. It is essential for learning both patterns of stimuli and patterns of responses, such as those required in classical and instrumental conditioning, skill learning, and high-level problem solving and reasoning. Such learning is particularly important for organisms early in development; in fact, human infants are very sensitive to temporal patterns from birth, especially auditory patterns such as rhythm and language.

As a form of implicit learning, sequential learning can occur regardless of whether the individual intends to learn the pattern and does not require explicit recall or recognition. For instance, sequential learning is preserved in amnesic patients who have no explicit memory of the sequences. The implicit nature of (visual) sequence learning has traditionally been investigated through Mary Jo Nissen and Peter Bullemer's serial reaction time (SRT) task. In the original task, a single visual stimulus is presented in three or four spatially distinct locations. Each location has a response key associated with it. As the sequence is presented at each location, the participant presses the corresponding key. Unbeknownst to the participant, the stimuli can be presented at the various locations according to a repeating sequence. Learning is demonstrated by a reduction in reaction times as the task progresses; when a new sequence is presented, reaction times increase again. Sequence learning occurs even when the participant is unable to explicitly predict the next location in the sequence and, for this reason, is thought to be a form of implicit learning.

Artificial Grammar Learning (AGL) Paradigm

Another paradigm often used to examine implicit sequence learning is Arthur Reber's artificial grammar learning (AGL) paradigm. The original task involved presenting subjects with a string of printed letters, but the task has also been presented as a sequential auditory task using nonsense syllables. In Reber's original AGL study, adults were presented with "sentences" made from various combinations of five different letters, six to eight letters in length. Subjects were asked to memorize the sentences but were not told that they had been given either randomly produced sequences of letters or sequences that had been generated based on a complex set of grammatical rules. Subjects who had "grammatical sentences" learned them faster than those with randomly generated strings of letters. In addition, after learning grammatical sentences, subjects were told that the sentences followed a set of rules and were asked to categorize new sentences according to whether or not they followed the rules. Despite being unable to verbalize what the rules were, subjects categorized strings of letters according to those rules at above-chance levels. Like the SRT paradigm, learning in AGL is thought to be implicit. This ability to extract rules based on patterns in the environment is assumed to be an important component of how children learn language in a mostly incidental manner.

Infants and Young Children

Another form of the AGL task that is even more akin to language learning has shown infants as young as 5 months to be sensitive to statistically derived patterns of auditory stimuli. In this case, participants hear sequences of nonsense syllables. The order in which the syllables are presented is governed by a grammar that statistically determines the probability of what syllable will follow another, given the preceding syllables. Infants, like adults, are capable of categorizing novel grammatical and ungrammatical sequences after listening to grammatical sequences for just a few minutes. Human infants appear to be quite adept at this type of sequential-statistical learning. Impressively, the learning takes place even after very limited exposure to the input and also occurs at very early ages, with little or no development across the life span. For these reasons, it is likely that these learning mechanisms are used in the service of language learning.

In fact, infants and young children have been shown to be capable of a whole host of skills requiring some level of understanding of sequential patterns. These range from categorizing novel versus familiar sequences presented in a single sensory modality, to matching sequences across different modalities, to sequencing their own motor actions in naturalistic settings. However, relatively little is known about the development of sequential learning skills. For sequence learning with visual stimuli, findings are somewhat ambiguous. The ability to discriminate simple, familiar, statistically determined sequences from unfamiliar sequences appears to be present by 2 months and to remain stable with no development across infancy. However, not all methods of testing have found clear evidence of visual sequence learning in all infants. It may be that the complexity of the task or mode of response is relevant. In contrast, studies of older children and adults have found age-related improvement in visual sequence learning. Although both adults and children ages 7 to 11 years learn visually presented sequences, adults have been shown to do so with greater speed and magnitude.

Development of Auditory Sequence Learning

Findings on the development of auditory sequence learning are less ambiguous. Infants appear to be sensitive to auditory sequence information in the form of rhythm, tones, and nonsense syllables by 5 months or earlier. By 8 months, they can learn complex transitional probabilities such as are present in the AGL task, and this ability remains stable across the life span with little or no development. The discrepancy in the development of visual and auditory forms of sequential learning (i.e., that visual sequence learning appears to remain static across infancy and then improves from childhood to adulthood, while auditory sequence learning as measured by the AGL task does not appear to develop at all) may be explained by two sound-related phenomena.

First, some research has suggested that there is an auditory dominance in memory, which may include implicit memory, in early childhood that shifts to a visual dominance in later childhood and adulthood. For example, when visual and auditory stimuli are paired and participants are subsequently tested for recognition of original pairs with correct pairings, repairings of original stimuli, or pairings that include either new visual or new auditory stimuli, children around the age of 4 years recognize when the auditory stimulus is new more reliably than do adults. On the other hand, adults and older children perform better on the visual stimuli. Thus, it is possible that this auditory bias might explain the different developmental patterns observed for auditory versus visual sequential learning.

The second sound-related phenomenon is that there appear to be modality constraints for the learning of sequential and spatial patterns: an overall auditory superiority for temporal tasks, such as sequence learning, but a visual superiority for spatial tasks. When adults are exposed to stimuli that are auditory (sequences of tones of varying frequency), visual (black squares presented sequentially at different locations), or tactile (sequences of vibrotactile pulses delivered to different fingers) that are generated by an artificial grammar, they show twice as much learning for auditory sequences than for visual or tactile sequences. In addition, with faster rates of sequence presentation, visual learning declines, whereas auditory learning is not affected. It is likely that the auditory superiority effect seen in sequential learning is related to the fact that sound itself is inherently a temporally arrayed, sequential signal in which elements are defined specifically by the timing or serial order in which they are presented.

Despite these modality constraints, sequential learning also appears to be a domain-general cognitive mechanism that is used across a number of domains. The link between sequential learning and language development specifically is supported by evidence that infants' visual sequence learning ability is correlated with both their receptive language ability and their ability to communicate using gesture. These findings are in agreement with those showing that visual sequence learning ability is correlated with language processing ability in adults and in children with hearing impairment. Language learning is generally viewed to be an unconscious process, with people often using and understanding language without an explicit understanding of the grammatical rules that govern it. Thus, it is likely that language is acquired through implicit learning mechanisms, such as sequence learning.

As mentioned earlier, the temporal and sequential nature of sound and the superiority of audition for processing sequentially presented information may make sound and hearing the primary means for understanding temporal and sequential events. Thus, hearing may provide critical exposure to sequentially presented information, which may help scaffold the development of sequential learning mechanisms. As such, early sound deprivation may result in domain-general disturbances to sequence learning across all sensory modalities. Because so much daily information is presented sequentially and so many behaviors depend upon one's ability to interpret and produce sequential behaviors, impairments to sequence learning abilities could have far-reaching consequences, particularly for language learning. Research, in fact, corroborates these extrapolations.

Not only do deaf adults show disturbances to non-auditory functions related to time and serial order, but children born deaf who later gain some level of hearing through cochlear implants show greatly depressed ability to complete both motor learning tasks and visual sequential learning tasks compared to normal-hearing peers. In addition, deaf children who gain hearing through cochlear implants vary greatly in their ability to develop spoken language after implantation. While some catch up to their normal-hearing peers, others continue to display language-learning deficits that cannot easily be explained by early lack of language exposure alone. It is possible that individual differences in natural sequence learning abilities and the extent to which they were disturbed by early sound deprivation could lead to profound differences in the ability to learn spoken language after implantation. This notion is supported by research showing that implicit sequence learning abilities are correlated with standardized measures of language outcomes for children with cochlear implants.

Finally, there is also evidence that variations in sequential learning skill may contribute to the deficits observed in certain language and communication disorders such as specific language impairment (SLI), dyslexia, and autism. For example, children with SLI learned the pattern of a visual SRT task slower than typically developing (TD) peers. Once the pattern was learned, children with SLI who had grammatical deficits continued to have slower reaction times than TD peers, while children with SLI who had vocabulary deficits did not, suggesting a specific link between sequence learning and grammar skills.

In addition, children with SLI need twice as much exposure to learn transitional probabilities in an auditory AGL task as TD peers, and they show even more difficulty learning sequences of tones. Research on SRT tasks with dyslexic individuals has been mixed, but they seem to show impaired sequence learning and increased spatial context learning compared to TD peers. In addition, dyslexic students' reading abilities are positively correlated with their sequence learning abilities and negatively correlated with their spatial context learning. Thus, it is not a general cognitive or even implicit learning deficit but a specific deficit in implicit sequence learning that appears to be related to poor reading in individuals with dyslexia.

Joanne A. Deocampo
Christopher M. Conway
Georgia State University

See Also: Distributional Knowledge and Language Learning; Interrelationship of Language and Cognitive Development (Overview); Language Development in Children With Cochlear Implants; Prediction in Language Learning, Role of; Statistical Learning.

Further Readings

Conway, C. M. and M. H. Christiansen. "Modality-Constrained Statistical Learning of Tactile, Visual, and Auditory Sequences." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, v.31 (2005).

Conway, C. M., D. B. Pisoni, and W. G. Kronenberger. "The Importance of Sound for Cognitive Sequencing Abilities." *Current Directions in Psychological Science*, v.18/5 (2009).

Nissen, Mary Jo and Peter Bullemer. "Attentional Requirements of Learning: Evidence From Performance Measures." *Cognitive Psychology*, v.19 (1987).

Reber, Arthur S. "Implicit Learning of Artificial Grammars." *Journal of Verbal Learning and Verbal Behavior*, v.6 (1967).

Robinson, Christopher W. and Vladimir M. Sloutsky. "Auditory Dominance and Its Change in the Course of Development." *Child Development*, v.75/5 (2004).

Autism and Language Development

Communication impairments have been recognized as one of the core features of Autism Spectrum Disorders (ASD) along with social deficits and restricted and repetitive behaviors. Approximately 20 percent of the ASD population does not acquire any functional expressive language. Communication deficits in ASD include a variety of impairments such as use of stereotyped speech or delayed echolalia (e.g., repeating lines from a favorite cartoon) and difficulties initiating and