CURRENT DIRECTIONS IN PSYCHOLOGICAL SCIENCE

The Importance of Sound for Cognitive Sequencing Abilities

The Auditory Scaffolding Hypothesis

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ABSTRACT—*Sound is inherently a temporal and sequential signal. Experience with sound therefore may help bootstrap—that is, provide a kind of "scaffolding" for—the development of general cognitive abilities related to representing temporal or sequential patterns. Accordingly, the absence of sound early in development may result in disturbances to these sequencing skills. In support of this hypothesis, we present two types of findings. First, normal-hearing adults do best on sequencing tasks when the sense of hearing, rather than sight, can be used. Second, recent findings suggest that deaf children have disturbances on exactly these same kinds of tasks that involve learning and manipulation of serial-order information. We suggest that sound provides an "auditory scaffolding" for time and serial-order behavior, possibly mediated through neural connections between the temporal and frontal lobes of the brain. Under conditions of auditory deprivation, auditory scaffolding is absent, resulting in neural reorganization and a disturbance to cognitive sequencing abilities.*

KEYWORDS—*sound; deafness; sequence learning; language; prefrontal cortex*

It is customary to consider sound as being the province of auditory perception alone. However, recent findings and theories have emphasized the interactive nature of the sensory modalities as well as the ways in which sensory processing underlies higher cognition. For example, multisensory processing, in which multiple senses (vision, audition, touch) are used in concert, is beginning to be regarded as the norm in perception, not the exception. Furthermore, "embodied cognition" theories, which stress the close coupling of brain, body, and sensory systems, emphasize the importance of understanding how the dynamics of modality-specific constraints affect higher-level cognition such as learning and memory. To put it another way: Because the brain is an integrated functional system, sensory processing (and, by extension, the effects of sensory deprivation) are not completely independent from the rest of neurocognition and thus may have secondary effects on the brain and cognition as a whole.

Sound in particular is a temporal and sequential signal, one in which time and serial order are of primary importance (Hirsh, 1967). Because of this quality of sound, we argue that hearing provides vital exposure to serially ordered events, bootstrapping the development of sequential processing and behavior. Sound thus provides a "scaffolding"—a supporting framework—that organisms use to learn how to interpret and process sequential information. The auditory scaffolding hypothesis is backed by two lines of evidence: modality-specific constraints in hearing populations and non-auditory sequencing abilities in the congenitally deaf.

MODALITY CONSTRAINTS

Previous research has suggested that the sensory modality used in a particular task constrains cognitive functioning. Specifically, for any task that requires the perception, learning, or memory of events where their order or timing is important, people do best when they can rely on hearing. Consider sequences of light flashes or auditory tones that occur at varying rates of presentation. Adults can perceive and reproduce the auditory patterns more accurately than they can the visual patterns (Collier & Logan, 2000). Furthermore, it is a well-established phenomenon that short-term verbal memory is better with auditory presentation (i.e., spoken words) than with visual presentation (i.e., written words; Penney, 1989). To explain some of these findings, Glenberg and Jona (1991) argued that the coding of time is more accurate for auditory events than it is for visual events.

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Sequential Learning

More recently, an auditory-superiority effect was found with sequential learning (Conway & Christiansen, 2005). Three groups of participants were exposed to auditory, visual, or tactile sequential patterns (see Fig. 1). All stimuli were nonlinguistic and thus were not easy to verbalize.

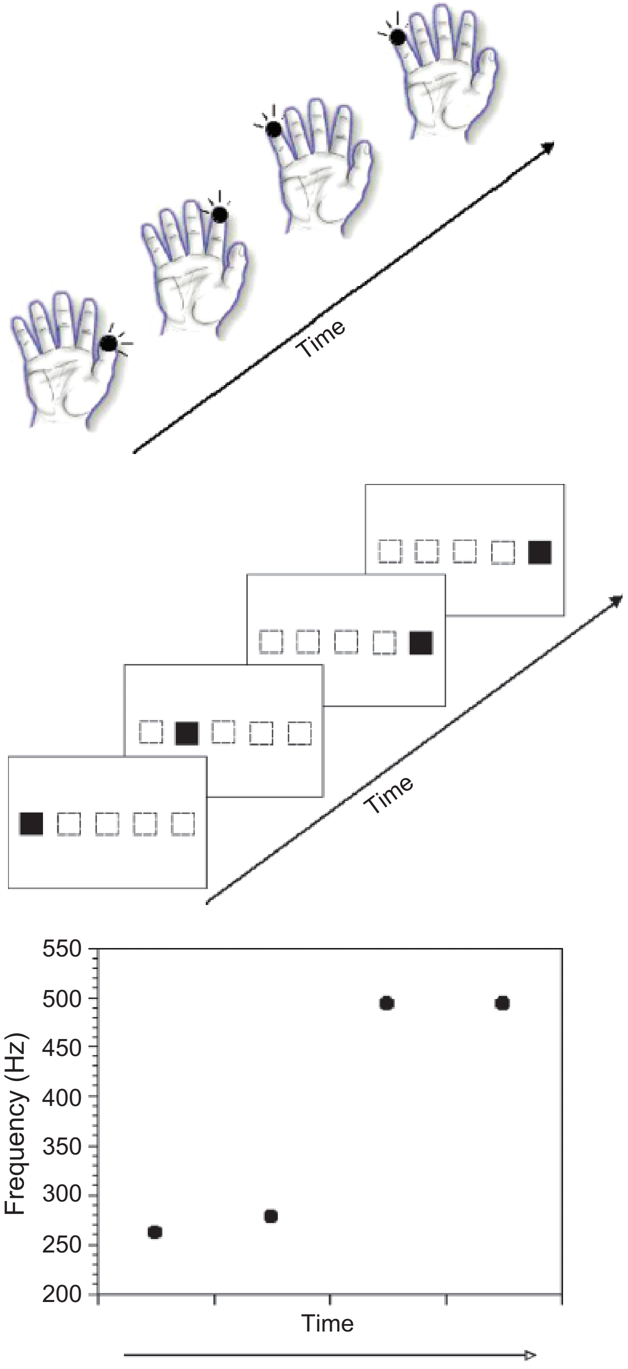

Fig. 1. Tactile, visual, and auditory sequences used by Conway and Christiansen (2005) to investigate possible modality differences in implicit sequential learning. Tactile stimulation was accomplished via vibrotactile pulses delivered to participants' five fingers of one hand. Visual sequences consisted of black squares appearing at different spatial locations, one at a time. Auditory sequences consisted of tone patterns.

Participants were not told that the sequences they were exposed to were generated by an artificial "grammar" that determined the order in which each stimulus could occur in a sequence. For example, a grammar might dictate that tone 1 can follow tone 2 and tone 3 each 50% of the time and can never come after tones 4 or 5. Following incidental exposure to the sequential patterns, participants were next exposed to novel patterns in the same sense modality as before, but this time half of the sequences were generated from the same grammar while the other half violated the rules of the grammar in some way. Participants were instructed to classify each sequence in terms of whether it was generated from the same grammar or not.

The results on the grammaticality-classification task revealed that the magnitude of auditory learning (75% items correct) was much greater than that of either tactile or visual learning (62% each). In fact, because in this task 50% is considered chance performance (no learning), a score of 75% (75 − 50 = 25) signifies twice as much learning as a score of 62% (62 − 50 = 12). Furthermore, additional research has shown that whereas visual sequence learning declines at fast rates of presentation (8 stimuli/second), auditory sequence learning is robust even in the face of fast presentation rates (Conway & Christiansen, 2009). Taken together with previous work showing modality-specific constraints in perception and memory, the sequence learning findings suggest that the auditory modality excels at encoding and processing temporal and sequential relations in the environment.

SEQUENCING SKILLS IN THE DEAF

Although it is common to consider deafness as affecting the sense of hearing alone, we argue that because sound is the primary gateway to understanding temporal and sequential events, auditory deprivation may result in significant disturbances on a wide range of other tasks (Conway, Karpicke, & Pisoni, 2007). For instance, Bavelier, Dye, and Hauser (2006) have argued that deafness results in a reorganization of cortical function. Therefore, losing the sense of audition early in development may set up a cascade of complex effects that alter a child's entire suite of perceptual and cognitive abilities, not just those directly related to hearing and the processing of acoustic signals.

According to the auditory scaffolding hypothesis, deafness may especially affect cognitive abilities related to learning, recalling, and producing sequential information. A delay or disorder in domain-general sequencing skills, triggered by lack of auditory stimulation at an early age, could provide a significant impediment to normal development. Indeed, previous work suggests that the profoundly deaf show disturbances in (nonauditory) functions related to time and serial order, including immediate serial recall (Marschark, 2006).

Some Recent Findings

Recent findings from our research group tested sequencing skills in two groups of children aged 5 to 10 years old: deaf children with cochlear implants (CIs) and an age-matched hearing group. A CI is an electronic device that directly stimulates the auditory nerve to create the percept of hearing. Children's motor sequencing abilities were assessed using a fingertip tapping task from a neuropsychological assessment called the NEPSY (Korkman, Kirk, & Kemp, 1998). One version of the task required the child to repetitively tap together his or her thumb and index finger as fast as possible. Another version required the child to tap the tip of his or her thumb to the index, middle, ring and pinky finger, in that order, as quickly as possible. Overall, the deaf children with CIs performed worse than the control group and were also atypical relative to the published normative data (Conway et al., 2009). It is important to note that the deaf children were *not* impaired on several other nonsequencing tasks, such as visual-spatial memory and tactile perception.

We also tested the children with a visual sequential learning task similar to the methodology discussed previously with adults (Conway, Pisoni, Anaya, Karpicke, & Henning, in press). In this task, the children were exposed to sequences of colored squares displayed on a touch-sensitive screen. The children were required to remember the sequence of colors on the screen and then reproduce each one by pressing the touch-screen panels in the correct order. Note that because each color is uniquely associated with a particular location on the screen, a child may be remembering a sequence of colors, a sequence of locations, or both.

Unbeknownst to the children, all of the sequences initially were generated from an artificial grammar. After completing the reproduction task for a subset of visual sequences, the experiment seamlessly transitioned to a test phase, which consisted of new sequences generated from the same grammar and new sequences generated from a novel grammar. For each subject, a learning score was calculated; this score represented the extent to which sequence memory spans improved for sequences generated from the same grammar compared to those generated by the novel grammar.

The results showed that the normal-hearing children's sequence learning score was significantly greater than that of deaf children, who on average showed no learning. Furthermore, whereas 53% of the normal-hearing sample showed some effect of implicit sequence learning, only 34% of deaf children did.

The results from the fingertip tapping and sequential learning tasks demonstrate that deaf children show atypical motor and visual sequence learning compared to age-matched normal-hearing children. What both tasks have in common is that they require facility with encoding or producing sequential patterns. Taken together, these findings suggest that a period of deafness early in development may cause secondary disturbances to non-auditory sequencing skills.

Implications for Language Development

Figure 2 presents a general framework for the interactive relationship between sound, sequencing skills, and spoken language development. Clearly, a lack of sound hinders the development of spoken language. However, this framework depicts an additional effect of auditory deprivation: delays in non-auditory sequencing functions. Even for those deaf children who have a CI surgically implanted and therefore receive sound via electrical stimulation, cognitive and perceptual sequencing skills appear to be delayed and/or reorganized. Delays in sequence learning likely contribute to problems learning the complex grammatical patterns of spoken language (Ullman, 2004). That is, a deaf child with a CI may be able to accurately *hear* (i.e., detect and discriminate) individual sounds occurring in sequence (i.e., words), but may have difficulties performing higher-level cognitive operations on those sounds (i.e., learning the sequential regularities of words in spoken language) that form the basis of grammatical knowledge.

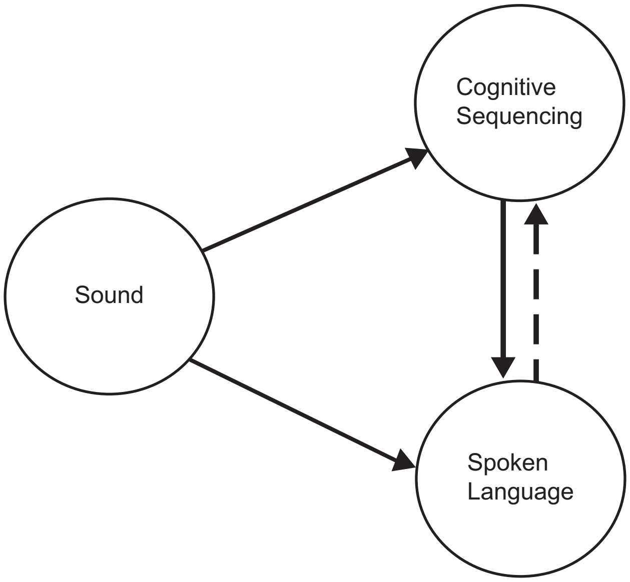

Fig. 2. Proposed framework for understanding the relations among sound, cognitive sequencing, and spoken language development. The solid lines represent effects among these factors that are consistent with the present findings. The dotted line represents the possibility of an additional but as-yet unspecified influence: spoken language skills affecting the development of general cognitive sequencing abilities.

This implies that deaf children who receive new auditory input via a CI and who appear to be well on the path to developing spoken language abilities may in fact also have delays in sequencing functions that contribute to difficulties with certain aspects of language development. This association between sequence learning skill and language has been observed empirically (Conway et al., 2007; Conway et al., 2009; Conway et al., in press).

POSSIBLE MECHANISMS

We consider here two possible ways in which these effects may be instantiated. One possibility is that listening to sounds, especially those that are easy to verbalize, provides an opportunity to automatically imitate (i.e., vocally rehearse) what is heard, either out loud or covertly. Imitating what is heard gives a discrete verbal label to a continuous auditory signal, providing anchor points for learning associations among the discrete symbols (i.e., words). Under this "embodied" account, hearing thus recruits vocal rehearsal processes that presumably strengthen the development of domain-general implicit sequence learning abilities. A second possible mechanism relies on the fact that all environmental input likely includes "modality-neutral" information in addition to the modality-specific signal itself (cf. Rosenblum, 2008). Sound, unlike vision, may specifically carry higher-level patterns of information related to temporal change and serial order. Under this view, hearing is the primary gateway for perceiving high-level sequential patterns of input that change over time (rather than over space). The development of fundamental sequence learning mechanisms would thus be delayed when this type of input is unavailable, as is the case in deafness.

Both the embodied and the modality-neutral accounts, which are not necessarily mutually exclusive, are consistent with neurobiological data suggesting cortical reorganization in the deaf, especially in the prefrontal cortex. This region of the frontal lobe plays a critical role in learning, planning, and executing sequences of thoughts and actions (Fuster, 2001). Electrophysiological data suggest that deaf children show decreased cerebral maturation in left fronto-temporal regions and bilateral frontal regions compared to hearing peers (Wolff & Thatcher, 1990). A lack of auditory input due to deafness may reduce auditory–frontal connectivity (Emmorey, Allen, Bruss, Schenker, & Damasio, 2003), fundamentally altering the neural organization of the frontal lobe and, crucially, the prefrontal cortex. Delayed cortical maturation in this region could have significant effects on the development of cognitive and motor sequencing skills used in language and other aspects of cognitive processing.

One additional implication of delayed maturation in the frontal lobe is that deaf children may also display difficulties with some types of abilities known as "executive functions," which include domain-general control processes such as working memory, response inhibition, self-regulation, and goal-oriented behavior (Hauser, Lukomski, & Hillman, 2008). Thus, it may be possible that a period of profound deafness results in widespread disturbances to frontal-lobe-related executive functions more generally, with sequence learning being just one behavioral indication.

SUMMARY AND OUTSTANDING QUESTIONS

Sound appears to provide a perceptual and cognitive scaffolding for the development of functions related to time and serial-order behavior. Experience with perceiving and producing sound helps organisms learn how to encode and manipulate sequential information, while a lack of auditory stimulation hinders the development of these skills.

Although we believe that the auditory scaffolding hypothesis currently best explains the findings presented, much work remains to be done in order to rule out alternative explanations. One possibility is that the disturbances in sequencing functions that have been observed in the deaf are due not to auditory deprivation per se but, rather, to differences in the social environments of deaf and hearing children. A deaf child's sociocultural environment may be very different from that of a hearing child, due to differences in educational opportunities, parenting styles, and other social, communicative, and emotional factors (Marschark & Hauser, 2008). It is currently underspecified how such social-environmental factors may affect cognitive development and, specifically, sequence learning abilities. Another possibility is that lack of experience and skill with spoken language specifically—not with hearing more generally—affects cognitive sequencing abilities. For instance, it is known that deaf children have particular difficulties with sequence learning and memory when the input is verbal or easily coded in verbal form (Dawson, Busby, McKay, & Clark, 2002). However, as we have reviewed, deafness also appears to affect even non-auditory and non-verbal sequencing skills, suggesting that impaired performance by deaf individuals on sequence learning tasks is not merely due to difficulties with processing verbal information.

To help disambiguate the multiple factors that may be at play in cognitive development in both hearing and hearing-impaired populations, there is a need to carefully study specific aspects of cognitive and neural development in hearing, hearing-impaired, and deaf children with and without CIs. Additional ways of investigating the impact of sensory deprivation on brain and cognition include animal studies (through destruction of the peripheral sensory pathways), brain imaging and electrophysiological techniques to study cortical reorganization in the deaf, and even the use of neural networks to model the development of sequence learning in the face of reduced sequential input.

In summary, we believe that when all findings are taken together, the auditory scaffolding hypothesis is useful because it integrates findings in both hearing and hearing-impaired populations, providing novel and testable predictions. The findings and theory reviewed suggest that the role of sound in cognition goes far beyond domain-specific auditory perception. Sound bootstraps the development of cognitive processes that rely on the encoding, learning, and manipulation of information and behaviors occurring in sequence. Because sequencing abilities directly affect many aspects of cognition, including perception, sensory–motor control, language, and higher-level functions, these findings have profound implications for understanding a wide range of issues related to neurocognitive development and plasticity in normal-hearing, hearing-impaired, and language-disturbed populations.

Recommended Reading

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Marschark, M., & Hauser, P. (2008). (See References). An edited volume that highlights recent findings in cognitive abilities of the deaf, including language development, learning and memory, attention, numerical cognition, and executive functions.

Myklebust, H.R., & Brutten, M. (1953). A study of the visual perception of deaf children. *Acta Oto-Laryngologica Supplementum*, *105*, 1–126. An early study reporting that deaf children differ on a variety of measures of visual perception, concluding that sensory deprivation affects the development of the entire organism, not just modality-specific processing.

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Acknowledgments—This work was supported by the following grants from the National Institutes of Health: R03DC009485, T32DC00012, 5R01DC00111, and 2R01DC000064. We wish to thank Arthur Glenberg for suggesting the embodied account as a possible mechanism underlying the auditory scaffolding effects.

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