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Corresponding Author	Family Name	**Conway**
	Particle	
	Given Name	**Christopher M.**
	Suffix	
	Division/Department	Department of Psychology
	Organization/University	222 Shannon Hall Saint Louis University
	Street	3511 Laclede Ave
	City	St. Louis
	State	MO
	Postcode	63103
	Country	USA
	Email	cconway6@slu.edu

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Sequential Learning

Christopher M. Conway
Department of Psychology, 222 Shannon Hall Saint Louis University, St. Louis, MO, USA

Synonyms

Sequential processing; Serial learning; Serial order behavior

Definition

For most higher organisms, the *order* in which events occur is of paramount importance (e.g., spoken language, music, animal communication, and motor skills). The cognitive and neural processes involved in learning about the proper ordering of events and stimuli are called sequential learning. Sequential learning can be applied toward encoding a specific sequence in its entirety (e.g., A-C-E-F) as well as learning the distributional properties among multiple sequences, in which the learner induces the fragments or underlying regularities common to all exemplars (e.g., noticing that the fragment *A-B* occurs in the following three sequences: *A-B*-D-E, C-*A-B*-A, D-*A-B*-C). Hierarchical sequential patterns can also be acquired, a type of learning that may be crucial for much of human cognition and behavior, especially language processing. Sequential learning can occur implicitly or explicitly, under supervised or unsupervised conditions, or through any combination thereof.

Theoretical Background

Although research exploring serial order behavior has a long tradition, beginning with the early work of Ebbinghaus, it was Lashley (1951) seminal paper that elevated the importance of sequential processing in the psychological sciences. Lashley was one of the first to fully recognize and appreciate the ubiquity of sequencing in human behavior, thought, and language. For example, the sentence "please pass me the *bottle* that is near the *glass*," has a vastly different meaning from "please pass me the *glass* that is near the *bottle*," despite the fact that the only difference between the two sentences is the order in which the words *bottle* and *glass* occur. To take one of Lashley's own examples, in English, an adjective generally precedes the noun. "*I see the red ball*" is grammatical but "*I see the ball red*" is not. In French, the opposite is true.

In addition to language and communication, other domains in which sequential order is important include motor and skill learning, music perception and production, problem solving, and planning. Clearly, however, not all serial order behaviors are *learned*. Many sequential behaviors in humans and other species appear to be largely pre-wired, such as grooming movements, simple locomotion, and respiration. Thus, sequential learning encompasses the cognitive and neural mechanisms involved in the process of *acquisition* itself, which may be independent from other issues relevant to serial order behavior more generally, such as how serial patterns are perceived (but not necessarily learned), represented in the mind and brain (whether they were originally pre-wired or learned sequences), or produced.

There are at least three different modes of sequential learning, each corresponding to a different type of sequence pattern (Conway and Christiansen 2001): fixed, statistical or probabilistic, and hierarchical.

Fixed sequential learning is perhaps the simplest type, involving learning of any arbitrary serial pattern or list (e.g., A-E-G-K), such as a phone number. In language, the use of fixed sequences can be found at different levels, including idioms and stock phrases (e.g., "once upon a time") or even words themselves, which can be construed as fixed sequences of phonemes. This type of sequential learning is informed by a vast amount of previous research in areas such as list learning, Hebb repetition effects, short-term memory, and working memory (e.g., Marshuetz 2005).

Many situations facing humans and other higher organisms involve more complex patterns that consist of statistical patterns of co-occurring elements within multiple exemplars. For example, if one were to consider the entire corpus of English speech that a listener may perceive over the course of a year, the sound sequences "fun-ny" and "ro-bot" are each likely to occur more frequently than "ny-rob." This is true because *funny* and *robot* are English

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words, whereas *nyrob* would generally only be heard across a word boundary (e.g., "I see the fun*ny ro*bot"). Being sufficiently sensitive to the frequently co-occurring sounds in continuous speech, a process known as word segmentation, allows a language learner to induce which speech sounds constitute a word versus which sounds just happen to co-occur because they are the final and initial sounds of two separate words that were spoken consecutively.

Word segmentation is an example of the more general phenomenon of *statistical* or *probabilistic* sequential learning, which involves inducing the common underlying distributional patterns from among multiple exemplars. In language, learners can use the statistical or probabilistic properties of linguistic input to discover the structure not just of words, but also of other properties such as phonology (sound patterns) and syntax (Saffran 2003). Although language provides a wealth of examples of statistical sequential learning, many nonlanguage domains also have probabilistic structure, in which a given element of a sequence does not perfectly predict the next element, but rather may predict it in a probabilistic fashion. Thus, statistical learning is likely used in many aspects of perceptual and motor processes, such as learning to imitate the complex movements of a dancer, or learning the melodic, rhythmic, and harmonic structures of different styles of music.

The previous two forms of sequential learning – fixed and statistical – are both similar in that they involve learning the relationships between adjacent elements, a process sometimes referred to as "chaining." However, as Lashley (1951) made clear, even though a sequence may appear as a chain of linear elements, there may exist an underlying hierarchical structure. For example, in the repeating sequence "1-3-2-3-1-2-1-3-2-3-1-2. . .," each item can be followed by one of two possible items (e.g., "1" is followed by either "3" or "2" with equal probability). Only by taking into account the previous context in which an item occurs can one accurately predict the subsequent item (e.g., knowing that the "1" is preceded by "2" allows one to accurately predict "3"). With these more complex patterns, it is necessary to encode not just the preceding element in a sequence, but the previous two or more elements. Such a strategy of encoding long-distance or nonadjacent relationships among items in a sequence might provide the basis for *hierarchical* sequential learning, in which primitive units are combined to create more complex units (forming a "chunk"), which in turn can be combined to create even more complex units in a recursive fashion. Learning hierarchical structure has several advantages over merely learning the "flat" linear structure, including it being easier to self-repair in the event of failure and providing easier and more efficient access to subroutines of sequences (Bapi et al. 2005).

In human language, hierarchical structure is especially evident in the realm of syntax. In the sentence,"*The cat chased the mouse*," there are two phrases, a noun phrase ("*the cat*") and a verb phrase ("*chased the mouse*"), with the latter containing a secondary noun phrase within it ("*the mouse*"). Once one has learned that a particular phrase is a noun phrase (e.g., "*the mouse*") and assuming one has also learned the basic structure of English syntax, the phrase forms a single unit that can then be inserted into other situations that require a noun phrase ("*The mouse ate the cheese*" or "*I see the mouse*"). In addition to language, other domains such as complex motor skills and problem solving can have hierarchical structure.

Important Scientific Research and Open Questions

A key question is to what extent other animal species, such as nonhuman primates, demonstrate equivalent sequential learning abilities to humans. By exploring the abilities and limitations that other primates have for processing sequential information, we can begin to understand the evolutionary origins of such capabilities in humans as well as the unique aspects of human sequential learning.

Unfortunately, few studies have provided direct comparisons between nonhuman primates and humans. The evidence that is available suggests a number of commonalities as well as crucial differences between the species (Conway and Christiansen 2001). In terms of fixed sequential learning, primates appear to be capable of encoding, storing, and recalling arbitrary fixed sequences consisting of motor actions as well as visual stimuli, with proficiency comparable to that of human preschoolers. In terms of statistical sequential learning, one particular species of primate, the cotton-top tamarin, appears to have some of the same basic capabilities, at least on a par with human infants. However, in the case of hierarchical learning, there is growing consensus that nonhuman primates lack human-like proficiency. Most studies have demonstrated that apes and monkeys rarely use hierarchical routines in their spontaneous and learned actions. Whether this suggests a genuine cognitive limitation for learning hierarchical sequential patterns or is due to other methodological or contextual discrepancies is not entirely clear. Even so, the apparent species differences especially in hierarchical learning may be one crucial reason that nonhuman primates are generally incapable of acquiring human-like language.

In general, the pattern of performance differences across species suggests that some aspects of human

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sequential learning (fixed and statistical) derives from evolutionarily old cognitive substrates, whereas hierarchical sequential learning may be a more recent development. A related key issue, then, is to understand the neural bases of sequential learning. In humans, findings from neuroimaging studies indicate that the frontal cortex (e.g., prefrontal cortex, premotor cortex, supplementary motor areas, etc.), subcortical areas (e.g., basal ganglia), and the cerebellum play essential roles in sequence learning and representation (Bapi et al. 2005). The ways in which these different brain areas interact appear to be complex and may partly depend on the nature of the task demands. For example, in some cases, the prefrontal cortex appears necessary for learning new sequences while the basal ganglia only become active once the sequences become well-practiced. In other cases, learning appears to occur first in the basal ganglia, which then guides learning in prefrontal cortex. A third possibility is that the basal ganglia contribute to reinforcement learning while the cortex is specialized to handle unsupervised learning situations.

One issue that neuroscience studies can help resolve is to what extent the three types of sequential learning (fixed, statistical, and hierarchical) are in fact distinct mechanisms. Consistent with the behavioral findings with nonhuman primates, some evidence does suggest that hierarchical processing in humans relies on an evolutionarily newer brain region, Broca's area (Friederici et al. 2006). A second issue that neuroimaging studies can help illuminate is whether different domains such as language, music, and skill learning are mediated by a common pool of neural regions or whether domain-specificity exists. The evidence here is mixed; on the one hand, there is evidence suggesting that Broca's area is used across multiple domains including both music and language and therefore may act as a kind of "supramodal" sequence processor; on the other hand, a handful of studies have shown that sensory-specific brain regions (e.g., occipital cortex) are involved in the acquisition of sequential patterns in a modality-specific manner.

Because the majority of sequential learning research has been devoted to a handful of domains (spoken language acquisition, motor skill learning, and music), there is a need to explore connections to other areas of cognition and behavior. Very few studies have also investigated how these three types of sequential learning skills develop in humans. One possibility is that there is a progression of developmental stages, with fixed sequential learning developing first, then statistical learning, and finally hierarchical learning. Another possibility is that the different facets of sequential learning develop more or less in parallel, or in an interactive fashion. In the realm of education, there is a need to further explore how sequential learning is used in areas such as mathematics, reading, and writing, and whether individual differences in sequential learning may relate to various aspects of cognitive, linguistic, and educational outcomes.

Cross-References

► Animal Learning and Intelligence
► Implicit Learning
► Implicit Sequence Learning
► Sequence Learning
► Statistical Learning

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