THE MISSING PIECE IN WORD LEARNING

Ever get stuck on a puzzle only to discover you do not have all pieces? This book is our attempt to gather in one place all of the groundbreaking evidence, theories, and models of word learning that have arisen in the past decade. The chapters in this edited volume are from around the world and from two domains, developmental psychology and artificial intelligence. We believe that these two domains have much to offer each other, with each domain possessing critical information for the other. Many of the problems encountered in one domain have already been solved by the other, and it is only in putting these pieces together that we will make progress in the next decade. In short, solving the puzzle of word learning becomes easier when we have more of the pieces of the puzzle from multiple domains.

OBJECTIVE OF THE BOOK

The primary purpose of this edited volume is to advance cross-disciplinary understanding between developmental psychologists and artificial intelligence researchers regarding the development of word comprehension and the multiple levels that influence its development. Our intent is to make a wide range of approaches to language comprehension and learning in both fields accessible in a single, comprehensive volume. Our hope is to cross-pollinate research in developmental psychology and artificial intelligence, connecting word learning in infancy and childhood and insights into human language development with computational models of language development and learning. The chapters in this edited volume are written with the general intent of explaining the dynamic process of word learning and elucidating the complex processes by which humans and artificial systems develop an understanding of words from their ambient language. This book, we hope, will serve as a repository for the state-of-the-art theoretical and computational models that elucidate the various mechanisms for word learning and the multiple levels of interaction involved.

WHAT LEAD TO THIS BOOK?

In the process of writing our theoretical review of language development, titled *Invariance Detection within an Interactive System: A Perceptual Gateway to Language Development*, it became clear that two disparate fields are on complementary courses that, until now, have had little overlap: on one side, developmental researchers have been studying the natural process of word learning with a host of em-
empirical studies on young children. On the other side, researchers in the field of artificial intelligence and robotics (in particular, epigenetic robotics) have been designing agents that learn and interact—effectively programming and reprogramming themselves based on environmental input. These scientists solve the difficult task of programming a robot to effectively learn words by having that agent learn in the same manner and environment as a human child.

Clearly, these two domains have much to offer each other. The developmental field is more than 50 years old with a long history of theories on language development that encapsulate the complexity and subtlety of organismic and environmental factors, including complex social interactions. The robotics field, while new to this type of problem, has an extraordinary appreciation for the complexities that can arise from the implementation of theories. It also recognizes, better than most, the remarkable feats possible through iteration of a few simple learning mechanisms, laying out an epigenetic basis for the study of language development in general and word learning in particular.

We became convinced of the importance of cross-disciplinary examinations of language development. Only by combining experimental and observational techniques with sensory-oriented computational modeling will the field make progress in explaining the complex interactions and processes that result in fully developed language. Such cross-disciplinary examinations are, in part, an effort to address questions about the underlying perceptual mechanisms that facilitate language development. They are also an effort to place language development in the context of other cognitive skills and abilities. For example, in the field of developmental psychology, infant word learning has been shown to emerge from simpler general purpose sensory mechanisms that span across language and non-language domains. Likewise, the field of artificial intelligence is designing artificial systems that are receptive to sensory input and adapt to their dynamic environment to simulate a range of complex behaviors. The combination of these two lines of research would represent a powerful new interdisciplinary domain for study in the future.

Thus, an edited volume that provides a comprehensive overview of the state-of-the-art might bridge the two fields of developmental psychology and artificial intelligence and would be useful to advance the field at this time. This would encourage discussion about the general principles involved in the development of adaptive systems and explain how complex forms emerge from simpler forms. By combining insights from both fields, this volume could elucidate the multi-level influences (e.g., phonology, syntax, or social cues) on word learning to show how the complex process of word learning might emerge as a result of these influences. This volume represents the combination of the best and most current theoretical and computational approaches and research findings across these disciplines.

In support of combining research, each of these disciplines has independently discovered several organizing principles that overlap enormously: a) development within natural as well as artificial systems happens across multiple levels; b) learning occurs as a result of ongoing embodied experience or the interaction between the organism and its environment; and c) simpler forms give rise to more complex forms of development in a process called ongoing emergence. We will expand on these organizing principles in the next three paragraphs.

- **Multiple Levels:** A comprehensive analysis of the developmental process of word learning must consider multiple levels of influence. From basic perception of auditory-visual information in the ambient communication of caregivers to the use of more complex social cues to glean word-referent relations, all of these factors interact in the process of word learning. These interactions are extremely difficult to predict, a priori. The chapters in this edited volume are written with the goal
to elucidate these multiple levels of influence on word learning and to advance state-of-the-art psychological and computational models that represent these multiple levels in ever-more specific and detailed ways. Some of the ways these levels can interact are considered in section 1 (Chapter 3) and in other chapters (Chapter 7, Chapter 12).

- **Embodied Systems:** From the interaction of organism and environment, properties develop that are not evident in either alone. Word learning does not occur in a vacuum. Caregivers respond to their children, and children respond to their caregivers and the environment around them in a never-ending dance of development. While researchers have long acknowledged the futility of a nature/nurture debate, modern theories have gone beyond acknowledgement into implementation and empirical research—looking at exactly how these complex interrelationships between organism and environment play out—even including how the embodied nature of a child can constrain development. Some of these emergent properties are examined in sections 1 and 2. In particular, section 2 elucidates the power of examining the development of word learning as an ongoing interaction between organism and environment: the embodied experience.

- **The Principle of Ongoing Emergence:** Simple mechanisms iterated across developmental time scales can produce complex outcomes. Generalized organismic mechanisms can emerge into more complex forms as a result of ongoing interaction with and adaptation to the environment. Such change is only possible through the fluid interaction and reorganization of the organism or the environment, or both, across different timescales. Some of the power of these emerging mechanisms can be seen in several chapters throughout this volume (Chapter 1, Chapter 2, Chapter 7). Similarly, generalized algorithms, when provided with sensory input and iterated across time, can yield more complex ones by which artificial systems adapt to an ever-changing and more complex environment.

While virtually all of the chapters ascribe to these three principles, each chapter has a different emphasis. In this volume, we have organized each chapter loosely according to this emphasis (see organization of chapters below).

As we put this volume together, we also recognized that within the domain of language development, its study has historically been fragmented into several sub-domains. While some researchers have focused on how infants learn word meaning (semantics), others have focused on the sounds of language (phonology), and many others have focused on grammatical development. Whereas this approach, focusing on individual sub-domains, worked optimally in the past to chart the details of a phenomenon as complex as language development, a negative outcome of this approach is that few have examined the inter-relatedness between the domains of word learning and phonology (Chapter 11) or word learning and syntax (Chapter 15).

**THE ORGANIZATION OF CHAPTERS**

This volume is divided broadly into three sections. Below, we provide a roadmap to the three sections of this volume and their relation to the organizing principles discussed in the previous section.

The first section takes a broad approach to the puzzle of word learning with a collection of chapters, each discussing a different approach to the development of word learning and the complex interplay of the factors involved. Each of the chapters in this section examines word learning from a perspective that
emphasizes, and in some cases explicitly considers how the interactions of multiple factors can lead to
the complex phenomenon that is word learning. In Chapter 1, Samuelson, Spencer, and Jenkins provide
a Dynamic Neural Field Model of word learning. Their model captures processes both at the second-to-
second and developmental timescales and provides a comprehensive view of how individual behaviors
accumulate to create development. In Chapter 2, we propose a novel dynamic view of sensitive periods,
as periods of heightened organismic-environmental interaction, and show how changes in the timing of
these interactions can result in changes in developmental outcomes. In Chapter 3, McMurray et al. take
a long view of the power of associative learning, demonstrating that by combining multiple levels of rep-
resentation with real time competition, an associative model actually can account for many complexities
and principles of word learning. In Chapter 4, Houston-Price and Law expand on this theme of building
complex word learning from simple associative mechanisms. They provide a complete theoretical model
for how early experience might enable young children not only to learn words but also to develop ever
more complex word learning strategies. In the final chapter of this section (Chapter 5), Henderson and
Sabbagh further explore the notion that environmental differences can influence individual differences
in children’s language learning. They conclude aptly that an integration of environmental and organismic
factors would provide a valuable framework for designing word learning experiments.

The second section considers the Embodied Experience and looks at how specific pieces within the
interplay of environment and organism have effects on word learning. Yu and Smith provide a micro-
genetic perspective of the child’s visual field in word learning contexts as observed during parent-child
interaction (Chapter 6). Bortfeld et al. elucidate the neurophysiological correlates of in utero speech
perception in the organism as it interacts with an ambient environment, eventually leading to reciprocal
communication in infancy (Chapter 7). In Chapter 8, Twomey et al. provide a robotic implementation of
categorization and word learning via attention to regularities in the environment. In Chapter 9, Arsenio
describes the usefulness of scaffolding in human-robot interactions, detailing how certain word learning
problems are solved simply by having a human caregiver teach the robot in the same manner one might
teach a child. In the final chapter of this section (Chapter 10), Wrede et al. provide a detailed account
of how mothers acoustically package and synchronize their use of color terms to actions when moving
objects that they name to their children.

The third section looks at how specific organismic factors contribute to the process of word learning,
with particular focus on the power of specific learning mechanisms and algorithms within domains. Mulak and Best (Chapter 11) present a detailed account of current research on how phonology affects
word recognition in infancy. They show how infants come to discern variation within speakers and
within accents and recognize words. Veale (Chapter 12) provides a neurorobotics approach to looking
behavior and habituation learning during word mapping. The bottom-up model, from single neuron to
overt behavior, aims to understand how neural circuits and bodily constraints combine to produce spe-
cific behaviors. This chapter provides an excellent example of how empirical data can be used to inform
modeling. First, evidence is gathered about the maturity and function of neural circuits in an organism.
Next, this evidence is used to construct artificial neural circuits that drive robotic bodies to produce the
same behavior as the original organism. Cederborg and Oudeyer (Chapter 13) propose that a single imitation
algorithm can learn linguistic and nonlinguistic tasks without being told to respond to it. Sato et al.
(Chapter 14) present two models that also address the process of word discovery. Learning is based on
repetition in an acoustically oriented perceptual model and interaction in their interactive model. They
simulate in human-robot interaction the specialized interaction between the child and the caregiver, where
child-directed speech (word) is induced in the caregiver (adult) as a result of the learner’s phonological perception and approximation of word-like forms. Finally, Walk and Conway (Chapter 15) present two different general purpose mechanisms for learning language, a repetition sequence learning mechanism for word learning, and a probabilistic sequence learning mechanism for the learning of syntactic structure.

TARGET AUDIENCE

This book is intended for an audience that is interested in and certainly those who conduct interdisciplinary research on language learning and development, particularly research in developmental psychology and computational models of language development from artificial intelligence. The book is also intended for researchers that adopt general principles of development to create artificial systems that can develop an understanding of spoken language. This book would make an excellent supplementary reader for courses in artificial intelligence or language development/learning.

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