Connectionism, Artificial Neural Networks and Reading

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APA: Toprak, T. E. (2018). Connectionism, Artificial Neural Networks and Reading. *RumeliDE Dil ve Edebiyat Araştırmaları Dergisi*, (12), 276-283. DOI: 10.29000/rumelide.472778

Abstract

Connectionism, which is a novel approach to human intellectual abilities, has challenged the basic assumptions and tenets of top-down and interactive approaches of the 1960s and 1970s to human cognitive processing and reading. Connectionism has specifically dealt with reading in order to understand and model the cognitive processes and intellectual properties underlying this significant skill. It has also embraced a more bottom-up approach to reading, an orientation which attaches great importance to pattern recognition governed by parameters, weights, connections and constraints in lieu of rules and symbols. Although the great majority of studies which applied connectionism have concentrated on how words are recognized, a considerable amount of scholarly work also has targeted at understanding syntactic parsing and pronouncing words. To date, connectionism has contributed to the understanding and modeling human reading and attracted the attention of researchers working in various fields such as linguistics, psychology, and artificial intelligence to a considerable extent. This paper aims to provide fundamental information about the connectionist approaches and neural network modeling that suggest an alternative to the classical theory of the mind while accounting for the cognitive processes that underlie human reading. The paper also compares the connectionist approaches to traditional approaches to reading, such as bottom-up, top-down and interactive approaches. Finally, it reviews several connectionist models that have proved to be highly influential in the relevant literature.

Key words*:* Connectionism, artificial neural networks, linguistics, cognitive psychology, reading.

Bağlantıcılık, Yapay Sinir Ağları ve Okuma

Öz

Bağlantıcılık (connectionism) insanın bilişsel becerilerini anlamaya ve modellemeye yönelik alternatif bir yaklaşımdır. Bağlantıcılığın uygulandığı alanlar arasında insanoğlunun gerçekleştiği en önemli eylemlerden biri olan okumanın temelinde yatan bilişsel süreçleri anlama ve modelleme de bulunmaktadır. Bağlantıcılık, 1960 ve 1970'lerde yaygın bir şekilde kullanılan ve insanın bilişsel işleme süreçlerini ve okuma becerisini açıklamaya çalışan yukarıdan-aşağıya (top-down) ve etkileşimli (interactive) yaklaşımların temel varsayımlarını sorgulamıştır. Bağlantıcılık yaklaşımı, okuma süreçlerinin nasıl gerçekleştiğini açıklarken aşağıdan-yukarıya (bottom-up) bir yaklaşımı benimsemiş, kurallar ve semboller yerine parametreler, ağırlıklar, bağlantılar ve kısıtlamalar tarafından yönetilen bir örüntü tanıma yöntemini benimsemiştir (artificial neural networks). Dilbilim, psikoloji, felsefe ve yapay zeka literatüründe bağlantıcılık yaklaşımını temel alarak insanın okuma süreçlerini irdelemeyi hedefleyen önemli sayıda akademik çalışma bulunmasına ve bu yaklaşımın okuma becerisini anlamaya yönelik büyük bir katkı potansiyeli olmasına rağmen, bağlantıcılık yaklaşımının tanınırlığı henüz düşük düzeydedir. Bu makalede, okuma becerisinin

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altında yatan bilişsel süreçleri anlamaya ve açıklamaya çalışan bağlantıcılık yaklaşımları ve yapay sinir ağ modellemesi hakkında temel bilgiler sunulmuştur. Buna ek olarak, bağlantıcılık yaklaşımı, özellikle okuma alanyazında yaygın bir biçimde kullanılan geleneksel yapıdaki aşağıdan yukarıya, yukarıdan aşağıya ve etkileşimli yaklaşımlar gibi diğer yaklaşımlarla karşılaştırılmıştır. Son olarak, ilgili alanyazında oldukça etkili olduğu kanıtlanmış bağlantıcılık modellerine de yer verilmiş ve bu yaklaşımın okuma becerisini anlama ve modellemeye ilişkin potansiyeline ve kısıtlılıklarına değinilmiştir.

Anahtar kelimeler: Bağlantıcılık, yapay sinir ağları, dilbilim, bilişsel psikoloji, okuma.

Connectionism is an approach to cognitive science that aims to explain and account for cognitive abilities and processes such as reading. Since its inception in the late 20th century, connectionism has attracted the considerable attention of researchers, for it yields a novel framework to study and gain more profound insights into the mind and its links to the brain (Plaut, 2005). Such an approach is novel in that it challenges the widely acknowledged analogy that the mind works similar to a digital computer while processing symbolic language. Connectionism tries to account for cognitive abilities by utilizing artificial neural networks which are simplified models of the brain consisting a large number of units that are analogs of the neurons in the brain, and the connections between these units. By using these artificial neural networks, it is possible to model processes such as face recognition and reading.

Connectionist models have lent themselves as more sophisticated and powerful alternatives to bottom-up, top-down and interactive approaches to reading that have extensively been used in reading research. These three approaches and their representative models have served as useful frameworks to understand human reading in the first and second languages, define the nature of reading, and provide individuals with pedagogical implications about reading. When compared to these approaches, on top of these functions, connectionist models have the potential to come up with comprehensive and universal cognitive structures that explain human reading and validate their findings and implications through empirical evidence. Although the use of connectionist models has mainly been limited to word recognition and syntactic parsing, it should be noted that future research on the application of connectionist models on reading is likely to produce fruitful and promising results.

This paper aims to provide fundamental information about connectionist or neural network modeling which has great potential for uncovering or explaining the processes that underlie human reading. The paper is structured as follows; initially brief information is provided about traditional approaches to reading. Then, information about the nature and properties of the connectionist models is presented in greater detail. And then, special attention is paid to several connectionist models that have been extensively used in the reading literature. Finally, implications of the connectionist models for reading are discussed.

Bottom-up Approaches to Reading

Views about the nature of reading have constantly changed over the last three decades, in line with the paradigm shift observed in the field of psychology (McNeil, 2012). The shift from a more behavioral focused paradigm to a more cognitively oriented one in psychology has exerted a drastic impact on reading research as well (Gao, 2006). Until the late 1970s, reading was regarded as a language-based, bottom-up process, in which readers were assumed to construct meaning in a set of sequential phases.

Readers were viewed as passive organisms whose major responsibility was to extract meaning through identifying and processing letters, words, and sentences.

Approaches that embraced these assumptions about reading are historically called bottom-up approaches. Gough (1972), Carver (1977) and LaBerge and Samuels (1974) can be considered as the representatives of reading models that are bottom-up. For instance, LaBerge and Samuels (1974) proposed that reading is comprised of two aspects that are decoding and comprehension. During the early phases of reading, decoding heavily relies on the attention mechanisms. Gradually, as the decoding process becomes more automated, it becomes possible to allow greater attention and resources to comprehension. LaBerge and Samuels further (1974) claimed that three separate stages, which are the visual memory, phonological memory, and the response system are crucial to reading, and these stages are assumed to function linearly.

Top-down Approaches to Reading

In the early 70s, top-down approaches to reading started challenging the tenets of bottom-up approaches, which regard reading as a language-based, linear decoding process. These top-down approaches assumed that background knowledge that readers possess influences reading process to a great extent and consequently, the reading process is adjusted by readers' contributions. Goodman (1967) and Smith (1971) are the two well-known representatives of these top-down reading models. Particularly, Goodman's "psycholinguistic guessing game" has shaped the landscape of second language reading research to a great extent. Both Smith (1971) and Goodman (1967) claimed that reading is more than merely decoding letters and is based on confirming and refuting the predictions that readers make when they read. In other words, they regarded reading as a hypothesis-driven process that is largely shaped by readers' background knowledge.

Interactive Approaches to Reading

The one-way explanation of reading which assumed that reading occurs either in a bottom-up or top-down fashion became a matter of debate in the 1980s and 1990s. Reading literature came to emphasize the simultaneous interaction between the bottom-up and top-down processes entailed in reading (Rumelhart, 1977; Stanovich, 1980). Reading models which highlighted the interactive nature of reading are historically called interactive models, and they posit that readers do not typically use either top down or bottom up processes, on the contrary, utilize both lower and higher level reading processes simultaneously. These models also attach great importance to background knowledge. To illustrate, one of the proponents of the interactive approach, Rumelhart (1977), proposed that the schemata impact reading process considerably and the processes involved in reading follow an interactive fashion rather than a linear one.

Based on this approach, one could argue that a reader may start reading by decoding words and instantly making interpretations depending on this incomplete decoding, or s/he may first create one or several hypotheses related to the text, then decode the words to check the accuracy of these hypotheses. Of interest, Stanovich's interactive-compensatory model (1980) posits that if one reading process is weak, other reading processes that are stronger would try to make up for the deficiency or inefficiency of the weak one. To illustrate, if a reader is weak at recognizing words, he may rely more on the contextual clues to compensate for this weakness. On the contrary, if s/he is skilled at recognizing words, he may not need to rely on the context that much.

Connectionist Approaches to Reading

The inception of the connectionist models or parallel distributed processing models (PDPs), marked by the development of Seidenberg and McClelland's (1989) models, sparked great excitement and enthusiasm in the field of cognitive science in the early 1990s. Connectionist models were regarded as the most sophisticated and powerful approaches to be used to examine human cognitive processes (Hulme, Snowling, & Quinlan, 1991). These models were inspired by the ideas of Hebb (1949), who proposed that it is possible to model complex behaviors that involve some sort of associative learning by aggregating simple neural processing units.

The idea seems conceivable since connectionist models are typically trained thousands of times on a large corpus that contains hundreds or thousands of words. Training is given so that connectionist models could deduce the links between orthography and phonology of words by applying various learning algorithms (Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004). In the context of connectionism, cognitive processes are depicted through a set of interactions among a large number of neuron-like units and these interactions can be both cooperative and competitive (Plaut, 2005). While each unit possesses an activity level, the interactions between these units are guided by connections that have different weights. These connections also include the knowledge of the system that is accumulated through learning and experience, a knowledge base which increases gradually. Units can be organized and grouped under different banners, each group assuming different roles such as enciphering the orthography (letters and how they are sequenced in words), phonology (patterns of sounds in words), or semantics (meanings of words) of a written word. The remaining or hidden, units include learned representations and knowledge that act as a bridge between inputs and outputs. Figure 1 illustrates a neural network modeling that includes orthographic, phonological, and semantic information in word reading based on frameworks proposed by Seidenberg and McClelland (1989) and Plaut (2005).

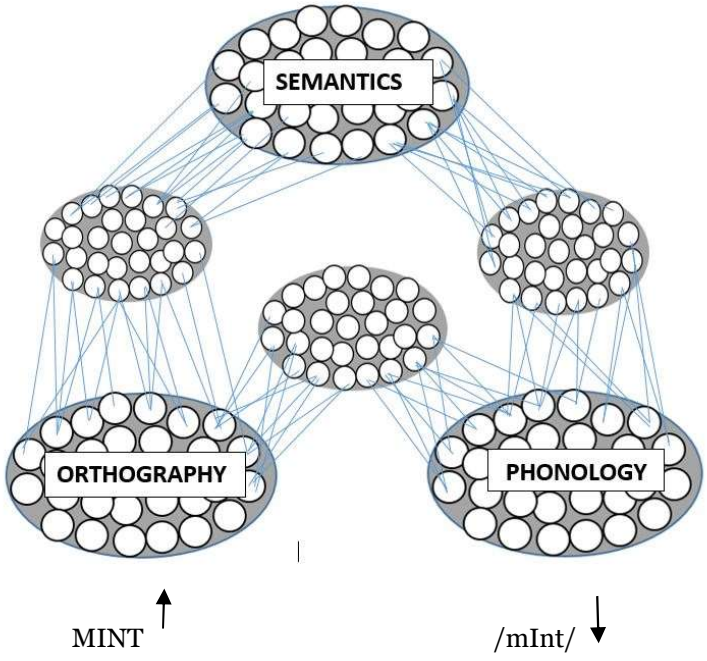

Figure 1. An artificial neural network modeling orthography, phonology, and semantics of words.

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Apart from simulating and modeling human cognitive processes, connectionist models may bear several similarities to human learning in some ways (Plaut, 2005). To illustrate, these models view learning as a gradual process in which knowledge expands through experience and by forming strong links between units. Moreover, they assume that this knowledge is transferrable; meaning once the learning occurs, it becomes possible to generalize what is learned to other situations and contexts. Finally, connectionist models assume that if some damage occurs within a system, this does not necessarily mean that all knowledge will be lost, rather performance could be affected negatively in such an event. Parallelisms can be drawn between these three assumptions, and human reading behavior in that (i) children learn to read and expand their vocabulary knowledge gradually, (ii) children can generalize the knowledge they have to novel situations, and (iii) when a damage occurs in the brain, their reading performance may deteriorate or become inconsistent. Since connectionist models bear such similarities to human reading, they were welcomed with considerable excitement and expectation.

Properties of the Connectionist Models

Connectionist models usually utilize units and codes that are linked together and include several elements such as inputs, intermediate (hidden) and output (Eysenck & Keane, 2010). These neuron-like units impact each other by exciting or inhibiting. The unit functions by taking the weighted sum of all the input links, and yielding an output to another unit when this weighted sum exceeds the threshold value (Plaut, 2005). Networks may vary regarding their structure and generally include a layer or group of input links, a layer of intermediate units and a layer of output units. Networks also encode patterns of activation that associate specific inputs with specific outputs to model human cognitive behaviors. Thus, when networks are trained, they can learn the associations between inputs and outputs by tuning the weights on the links between inputs and outputs. These weights can be adjusted systematically until the network yields the desirable outcome based on the given input (Eysenck & Keane, 2010).

In the context of connectionist models, learning can be shaped and managed in line with three general classes (Plaut, 2005). The first type of learning occurs as a result of unsupervised procedures that do not utilize the performance feedback but modify connection weights to determine the statistical structure of the patterns (Hebb, 1949). The second type of learning is called supervised procedures, such as back-propagation, which is a mechanism that enables a network to learn how to associate an input pattern with an output pattern by comparing the given responses to the correct ones (Eysenck & Keane, 2010). The third type of learning entails reinforcement, which postulates that feedback needs to communicate the level to which outcomes were good or bad.

Modeling Human Reading within Connectionist Approach: Notable Attempts

When applied to reading, most of the connectionist models to date have dealt with word recognition and pronunciation. Although focusing mainly on word recognition may seem limited in scope and depth, these models have produced relatively promising and beneficial results that may help understand and model human reading. One of the most influential and earliest connectionist models is the Interactive Activation Model of McClelland and Rumelhart (1981) which focuses on word recognition by employing a three-layered structure that are letter feature, letter, and word units. The activation of each unit demonstrate the confidence of the network in the assumption that the entity for which the unit stands (e.g., an M in the first position, or the word "MAKE") is included in the correct interpretation. Units have connections between them and these connections also carry weights which display the extent to which a hypothesis is consistent or inconsistent with another one. If units stand for inconsistent

hypothesis, such as a B versus a C in the first letter position, there will be negative connections between the units. On the other hand, units standing for consistent hypothesis (an M in the first position and the work MAKE) will have positive connections between them. Although the Interactive Activation Model of McClelland and Rumelhart (1981) did not employ any learning, it was able to recognize words consisting of four letters.

Another classic study was conducted by Sejnowski and Rosenberg (1987), in which the researchers trained a connectionist network system named NETtalk on a set of 1000 words. This set of 1000 words was given to NETtalk in 50.000 trials, and in the end, NETtalk was able to attain 95% success in processing these words on which it was trained by learning and applying the rules of English pronunciation. However, when the processing performance of NETtalk system was evaluated concerning all the words pronounced accurately, it was concluded that NETtalk performed poorly compared to skilled readers. Plaut (2005) argued that this situation may have to do with the sequential processing employed by NETtalk. Plaut (2005) maintained that while NETtalk relied on sequential processing even on the shortest word it encountered, skilled readers employ parallel processing on much of the input they encounter and continue processing by redirecting fixation. This outcome suggests that while unskilled reading involves sequential processing, skilled reading involves parallel processing, and reading progresses over time.

Apart from these, one of the most well-known connectionist models is the one generated by Seidenberg and McClelland (1989). This model can be regarded as the prototype of connectionist models in that it rejects symbolic (i.e., lexicon) level representations and exhibits different features than the parallel activation models of Perfetti (1991). Seidenberg and McClelland's (1989) model, which elaborates on how individuals recognize and pronounce printed words, includes three levels of word recognition that are phonology, orthography, and meaning. More specifically, the model includes orthographic units that help code the letters, phonological units that help code the phonological information and hidden meaning units binding these two sets of units together. However, syntactic features related to comprehension are not included in the model since the model centers around pronunciation and word recognition. In their model, Seidenberg and McClelland (1989) represented letters and phonemes in a local context, in other words, the context of surrounding letters was presented to ensure and facilitate word recognition. This process can be regarded to be similar to a child's word recognition process, in which the context of surrounding letters may function as a clue and help the child to recognize words (Hulme et al., 1991). In addition to these aspects, mapping the orthography and semantics of words has also received scholarly attention. For instance, Hinton and Shallice (1991) employed the method of back-propagation to train a network to map orthography and semantics of 40 words from five semantic categories. The researchers wanted to find out possible consequences of damage to the system, and when they deliberately damaged the network by removing several units, they demonstrated that the output caused by the input fell into a neighbor basin, producing an error response.

Finally, another notable connectionist model is that of Plaut, McClelland, Seidenberg, and Patterson (1996), which is an update of Seidenberg and McClelland's model (1989). The reading model in Plaut et al. (1996) was trained by using 2998 words while each word and its pronunciation were provided to the model on 300 instances. Plaut et al. (1996) demonstrated that the limitations of the earlier models, specifically Seidenberg and McClelland's model (1989), did not have anything to do with the abilities of the networks but the poor construction and utilization of the representations. They concluded that if the contribution that each phoneme makes to their surrounding is extremely sensitive, it may not be possible to detect the resemblances between the written and spoken forms of a word. This led the

researchers to hypothesize that when more properly structured representations are utilized, the chances that a network can learn to pronounce words as competent readers may increase.

Conclusions

Connectionist models can learn to read when they are exposed to printed words and their corresponding pronunciations. Although many attempts have produced relatively satisfactory results regarding modeling human reading, the amount of effort put to train a model is tremendous. On the other hand, when we think about human reading, a child does not need to see a word and hear its correct pronunciation hundreds and thousands of times. Hence, it would be safe to posit that children's learning to read outperforms connectionist models' learning to read behavior. Although it could be claimed that children do not learn a great number of words and their pronunciation at one time, and their reading develops gradually, on certain occasions, connectionist models of reading tend to perform poorly even if the number of words is relatively limited. Thus, a key question would be related to the adequacy of connectionist models in accounting for the complexity of human reading behavior.

Despite limitations, findings from the relevant literature suggest that connectionist models seem to hold promise for accounting for human reading, at least at lower level reading processes such as word recognition, syntactic parsing and reading aloud. Connectionist models may aid in understanding how humans move from one stage to another; from logographic stage to alphabetic stage, and finally to orthographic stage (Foorman, 1994). Moreover, connectionist models may cast light on how reading is acquired, what kinds of patterns reading impairments exhibit after brain damages and possible ways to remedy deficits that are developmental or acquired in nature (Plaut, 1996).

Yet, more research efforts are needed to gain a deeper understanding of human reading and modeling higher level reading processes such as literal understanding and inferencing. Moreover, since most connectionist models fall short in coming up with new predictions, lack creativity and de-emphasize the motivational and emotional factors in learning, future research on connectionist models may deal with finding solutions to these issues (Eysenck & Keane, 2010).

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