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Mechanisms of knowledge learning and acquisition

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Summary

The mechanism by which knowledge enters into memory has been a source of debate for some time. Theorists have proposed several models that aim at explaining the sequence of events from the perception of a stimulus, to its entrance into long-term storage. Much of this work was prompted by early research into the nuances of classical conditioning where it was first firmly established that organisms are capable of detecting covariations of stimuli within their environment. Subsequent work in the field has shown that these covariations form the basis for the mental representation of our surroundings, as well as the basis of learning. Work within the field of classical conditioning, along with the advance of computer technology and neuroscience has made these architectural models even more complex. Furthermore, experiments designed to support some of these proposed models have revealed that there are several conditions that can either aid or inhibit the transition of information into permanent storage. In this review we explore a number of these models, along with some classic critiques that have been levied against them. We also provide some history into the form of knowledge, termed 'implicit knowledge', as well as some of the proposed mechanisms of implicit knowledge acquisition. We conclude by exploring the newly proposed theoretical framework within which implicit learning theory operates.

key words: **network models • knowledge acquisition • implicit learning • learning mechanisms**

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Background

This review is an attempt to bridge the gap between two diverse areas within the cognitive neurosciences; explicit and implicit knowledge acquisition, and the proposed mechanisms by which each occurs. By reviewing some archival literature on these topics, we hope to clarify the intent of some current research being conducted in the field of learning, while this review is thorough, it is in no way exhaustive.

Early work by cognitive psychologists attempted to categorize human knowledge in terms of classes or groups. In one of these groups we have 'objects.' (dogs and cats) and in the other group we have the relations between those objects, such as above and below [1]. There has recently been a lot of research into how different objects get grouped together in a given category, and how these objects are related to one another hierarchically. For example the notion of 'dog' and 'cat' are subordinates of the more general 'animal' category.

Traditional theories have maintained that we categorize objects by virtue of their similarities with other objects. An animal is a dog if it has fur and barks. Notice that inherent in this assumption we neglect certain other physical characteristics such as the sizes and colors. This occurs presumably because this information has no impact on whether or not an animal is a dog [2]. This theory falls short of the truth though, since we can clearly contrive a case where a particular object has many of the inherent properties of a given object and yet is something entirely different. Furthermore the above explanation does not say anything about the relationship that may exists between the two categories of objects, such as possible similarities between them. This theory is often referred to as the defining-attribute theory, since we are categorizing objects by virtue of their defining attributes.

More refined research makes use of the superordinate-subordinate relationship which we proposed earlier. Suppose we have the specific concept 'sparrow', which we define as a brown, feathered, two-legged creature. We then introduce the notion of the superordinate which will be the 'bird' concept, which we define as feathered, and two legged. This means that a specific concept will have more attributes in common with its immediate superordinate than with its more distant superordinate [2].

The remarkable thing about this model is that it is cognitively efficient. Suppose we know some distinguishing characteristic that the superodinate category has, by virtue of the model we would automatically know that its subordinate would contain many of those properties. For example we know that a sparrow can fly, since its superordinate 'bird' is generally associated with flight. Thus a wealth of information is contained within the model itself.

While the above explanations are valid it is unclear whether or not they actually take part in explaining knowledge acquisition in more natural environments. The work of Collins and Quillian [3] aimed at answering this question. Quillian [4] developed a mathematical model that represented concepts within hierarchical networks (fig. 1). This model was later amended to include the organization of semantic memory. Their theory was essentially a network version of the defining-attribute theory discussed above.

Collins and Quillian [3] used sentence verification tasks to test their theory. Subjects were asked whether the simple sentences that they were presented with were true or false. First they were asked whether a subordinate was a member of a superordinate (e.g. 'Is a canary an animal?' or 'is a canary a fish?'). Then subjects were asked if a specific had a defining attribute (e.g. 'can a canary fly?' or 'does a canary have skin?'). In both of these cases the predictions set forth by Collins and Quillian were confirmed. In the subordinate superordinate condition it was found that the greater the difference between the subordinate to the superordinate nodes, the longer it took to verify the accuracy of the sentence. And in the specific-attribute condition, the location of the attribute determined the verification time. That is, the time required to determine if a canary can fly was shorter than the time required to determine if canaries have skin, this follows the prediction of the model, that the 'flying' notion is more closely related to birds than the notion of them having skin.

The defining-attribute model set forth by Collins and Quillian has been critiqued in many ways. Their model maintains that any given attribute that defines an object is equally important in determining the category in which the object belongs. Conrad [5] discovered that certain attributes of an object were expressed more by subjects, than other attributes. For example he found that subjects responded faster to the sentence 'a salmon is pink' than they responded to the sentence 'a salmon has scales'. This effect is presumably because we speak more of pink salmon than we do of them having scales. This gives rise to the typicality effect, whereby a subject's response to a given sentence may be faster simply

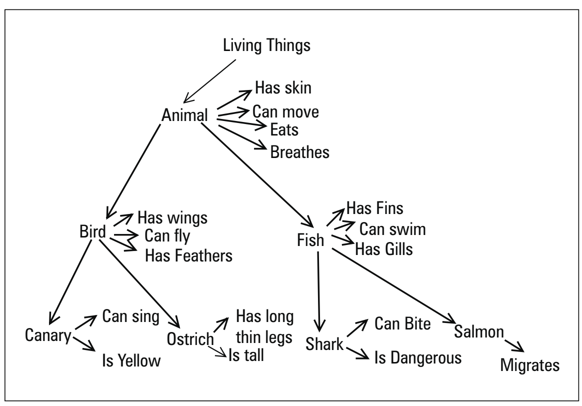

Figure 1. A possible semantic network developed by Collins & Quillian. Note its efficiency in storing information, the lower levels (subordinates) inherit properties of higher levels (superordinates).

because they are exposed to that idea more often, and not necessarily because it is located close in our semantic network.

Some Criticism

Although at first glance it may appear as though the Collins and Quillian model is efficient, further review reveals that this may not be so [6]. Often the more we learn about a given item the more subordinates we tend to develop for that category, this is referred to as the degree of fan. The higher the degree of fan for a particular category the slower the reaction time on sentence verification task. This is do in part to the mental 'searching' which one must do to sift through all the subordinate nodes which protrude from that category, a task which presumably takes time. This means that there is a possible cost to knowing too much, an idea which seems counter intuitive.

Finally, there is valid reason to be critical of the assumed neatness of the model. It seems to classify items very neatly into their respective categories. However often certain things fall under more than one category. That is, a computer may be more than just an electronic device, but will also fall under the office equipment category. This will of course complicate the neatness of the model, which maintains a strict hierarchical relationship between nodes.

It is for the above reasons that psychologists have moved away from the Collins and Quillian model. However it is important that we recognize the contributions that this model made to the field. It is clear that the mind does work in some sort of connectionist fashion. It is also clear that in some cases the speed of recall can be affected by the semantic difference between nodes.

The Next Wave

More recent models take the Collins and Quillian model and modify it, revealing just how powerful this network model can be. This new wave of network models are referred to formally as connectionist models. The most notable of which are the parallel distributing models [7]. In the classic network model each object or idea has a local representation or node, from which spans all information relating to that object or idea. In the parallel models, there are no central nodes, but rather information is contained within the number of activations which occur. This means that if two nodes are activated, the combination of the two give rise to some third idea or attribute.

Variations of this model get much more complex, in that not only can a third idea or attribute be activated, but in can also inhibit a fourth idea (which may inhibit a fifth and so on). Thus giving rise to an increasingly complex and robust model [1].

There is much support to these parallel models in terms of biological sense. The model tends to be similar to the way in which neurons either excite or inhibit each other. Some maintain, however this similarity may just be coincidence [8]. Further critiques maintain that these models are only found in laboratory settings where the experiments tend to draw out results which correspond to the model, there is little information on whether the model holds true in real world settings [9]. By far the most compelling criticism is that human beings are capable of carrying out an extraordinary amount of mental tasks, most of which can not be explained within the connectionist paradigm (for examples, see [10]).

Memory Store Models

Several memory theorists [11] attempted to describe the architecture of our memories in terms of memory 'stores'. As information passes through each of these stores it gets further solidified. In their original model, information entered into the system by way of sensation (audition, touch etc), and was held there until proper attention was given to the event, whereupon it entered a short-term memory store, and only by rehearsal could this information enter our long-term memory store (fig 2).

This theory was later modified by Baddeley and Hitch [12], who proposed a theoretical framework that allows for the above mechanism. They introduced the notion of the central executive, which they defined as the attention-focusing device of consciousness. This executive controls several slave systems, which perform individual tasks on the incoming information. One of these subordinate systems is the working memory store. In the Atkinson and Schiffrin model [11] it was assumed that passage of knowledge from short term to long term is a linear process by which information necessarily enters long-term storage. The notion of working memory allows for a more dynamic process where knowledge can enter into long-term storage only by way of elaborative rehearsal [12].

The proposed method by which this rehearsal occurs is accounted for by one of the central executives other slave systems, the articulatory rehearsal loop. This allows perceived information to enter into long-term storage after they are sufficiently rehearsed or elaborated upon. This means that the more we think about something the stronger its representation will be in memory [13].

This finding is further supported by the results of several letter span tests, where memory is tested by the use of free recall tests. Subjects are typically able to execute this task reasonably well until about eight strings long, where upon errors persist. Interestingly enough, though these errors are often systematic, in that subjects

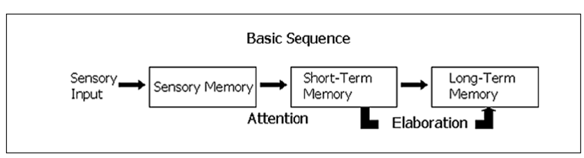

Figure 2. Diagrammatic representation of the classic Atkinson & Shiffrin model.

report back letters with phonological similarities to those of the correct letter. Presumably this is because they have not done the proper rehearsal on the given information and make errors consistent with this lower level of encoding [14]. This finding is quite important in that it shows that memory depends on the rate of rehearsal and form of encoding.

Craik and Lockhart [15] elaborated on the findings of Baddely and developed the levels-of-processing theory. They argued that there are a number of different levels of processing, ranging from the physical analysis of words (e.g. capital letters) to deep semantic analysis. Their model makes two fundamental predictions. The first is that the more elaborate the rehearsal the greater the memorability of the word. The second is that the more elaborate the rehearsal the stronger the memory trace of that given word in memory.

Craik and Tulving [16] obtained further support of the levels-of-processing-theory from several experiments. In one of them subjects were presented with a word and a sentence that contained a blank, and were asked whether the word would fit appropriately into the blank. Elaboration was manipulated by varying the complexity of the sentence, from the simple, 'she cooked the____' to the much more complex, 'The great bird swooped down and carried off the struggling____'. Cued recall of the words was greater for the words that were placed in the more complex sentences than those placed in the more simple sentences, showing that the more elaborate the rehearsal the better the recall.

One of the fundamental problems with research in the area of elaboration effects on memory, is being able to define what sort of elaboration is actually going on at the time of learning. For example Hyde and Jenkins [17] have long argued that the task of deciding which part of speech a given word falls into, is a shallow processing task, but other researchers have claimed that it is a deep and elaborative task. The problem arises from a lack of clear definition as to what exactly deep processing refers to; this ambiguity plagues most of our discussion.

The levels-of-processing theory first set forth by Craik and Tulving [16] has been critiqued in several ways. Research has indicated that memory depends on the kind of elaborations as well as the amount of elaboration. Bransford et. al [18] presented subjects with sentences that contained similes (e.g. 'a mosquito is like a doctor because they both draw blood') or multiple similes (e.g. 'a mosquito is like a raccoon because they both have heads, legs, and jaws'). The recall was much greater for the minimally elaborated similes then the multiple ones. This indicates that the nature and degree of the elaboration are relevant when predicting retention.

Others have maintained that while elaboration may aid in retention, it is not the entire process. Eysenck [19] argued that long-term retention is affected by distinctiveness of processing, as well as well as elaboration of processing. This means that memories that are unique or distinct in a given fashion are more likely to be retained. Eysenck and Eysenck [20] tested this theory. They presented subjects with nouns having irregular pronunciations, given their spelling (i.e. the word comb, with its silent 'b'), subjects read these words as they would have normally, however it was believed that the memory traces for these word should be more distinct. Other nouns were presented with normal phonemic pronunciations as well as words that were processed in terms of their semantic meaning.

On a subsequent, and unexpected recognition test, the nouns which contained the distinct, silent letter where much better remembered than those of the other two conditions. This finding demonstrates the importance of distinctiveness on retention.

Craik and Lockhart [15] argued that deep or semantic processing will always lead to better long term recall than will shallow or physical processing. There is much evidence that disconfirms this prediction. Morris [13] argued that stored information is remembered only in extent to the relevance of the memory test. Their subjects answered semantic or rhyme questions about a list of words. Memory was tested by a standard word recognition test in which a mixture of list and non-list words were presented, or they were tested by a rhyming recognition test. In the latter test subjects were told to select the words that rhymed from a given list of words. It was found that subjects who were tested via the rhyming task did not show a significantly greater level of recall.

Morris [13] argued that their findings supported a transfer-appropriate processing theory. According to this theory subjects will acquire different types of knowledge depending on the type of processing that they use to encode this information. Whether or not the subject will perform well on a subsequent recall task is determined by the relevance of the presented information as well as the type of memory test used. For example in there study, storing the information semantically would be irrelevant if the memory test requires that you identify the rhyming of list words.

A final problem with the levels-of-processing theory, is that it maintains that recall is enhanced by the level of elaboration, however it fails to explain exactly why this deep level processing leads to better memory recall than shallow memory processing. Recent literature [21] has maintained the way in which deep processing effects recall is via protein syntheses within the hippocampus region of brain which allows for the growth of dendritic spikes, this presumably establishes more neuronal connections thus increasing recall capacity, however research in this area is still on going.

Implicit Learning

The above theorists have worked in relation to explicit knowledge acquisition. Implicit knowledge has a much more complex and robust mechanism of acquisition, the details of which are only recently being understood.

Implicit learning is the process by which complex knowledge is acquired independent of the subject's awareness of the process and products of acquisition [22]. This is contrasted with explicit learning where the subject is aware of both the type of knowledge being acquired and the products of this acquisition.

Early work into the topic of implicit learning began with George Miller [23]. He used a finite state grammar system which created grammatical strings or symbols. He discovered that it is easier to recall the strings which were presented syntactically correct, than those which were random. Miller explained this finding by arguing that subjects were better able to recall the strings which were presented as grammatical, since they were able to pick up on the sort of grammar that was being used, effectively enhancing recall.

Reber [24] expressed some doubt as to whether or not the subjects can actually pick up on the covert grammar. Furthermore, if subjects really used the system that Miller had proposed, then they should be able to verbalize the type of grammar that they had learned. However in Reber's replication of Millers experiment he found no knowledge of this.

Reber conducted a second study that serves as the template for future studies of implicit learning. In this experiment subjects were asked to memorize strings that were created by a finite state grammar (Fig 3). In a subsequent, unexpected memory test, subjects were informed that the strings were actually formed by a complex rule system. And that their task now is to determine the grammaticality of a number of test strings. The structure of this experiment was ideal in that it allowed for a clear difference between the memorization portion and the testing part. And by using a covert grammar we are relatively certain that no explicit knowledge is being brought into the task. Reber found no evidence on the part of the subject being able to describe the explicit strategies used to recall the strings. Despite this fact though subjects were able to discriminate between grammatical and non-grammatical test strings, at the above chance level. Reber used this as evidence of an implicit learning system, whereby knowledge about the grammaticality of strings is acquired without the subject's knowledge.

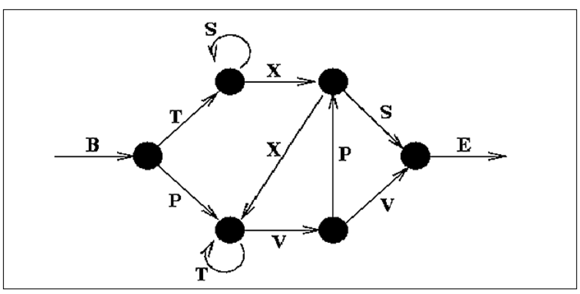

Figure 3. The Artificial Grammar first introduced by Reber. Test strings are created by starting at **B**, and moving from one node to the next, adding letters as you go. When the final **E** is reached the string is completed. If there are two paths we can take (after **T** we can go to either **S** or **X**) we randomly choose one (with equal probability). In this manner we can generate an infinite number of strings.

The above finding revolves around the use of an artificial grammar (AG) as a means of exploring the implicit systems. There are however a number of other paradigms which have been implemented, to explore the notion of implicit learning.

Serial reaction time (SRT) experiments assess subject's abilities to learn a repeating sequence, or a rule generated pattern of light flashes in a spatial array. In this paradigm, subjects typically get faster at responding to the sequences. Implicit learning is demonstrated with dramatic increases in reaction time (RT) after the structured sequence is replaced by a different (often random, or semi random) sequence. The sudden increase in RT after the sequence is changed demonstrates that the faster RT's were produced by the learning of the sequences and not simply by motor learning (getting faster at pressing the keys).

In both the SRT and AG tasks, the knowledge reported by subjects usually cannot account for their success on the task. In fact, many subjects report that they are unaware of having learned anything suggesting that these tasks were learned implicitly.

We should however note that, there are good reasons for suspecting that these two paradigms are different on a number of levels. For example, the AG task is largely perceptual and cognitive in nature whereas the SRT task has a large motoric component [25]. Consequently, comparing across these tasks may prove difficult.

Some Opposition

The notion that knowledge can be acquired implicitly, outside the realm of consciousness has not been accepted without scrutiny. Brody [26], Dulany [27], and Perruchet and Pacteau [28], are often noted as the voices of dissent. Brody's argument is that subjects have a greater cognitive understanding of their own mental states, but may be limited by the open-ended questioning typically used in these experiments. Thus subjects may be acquiring knowledge explicitly, but lack the ability to communicate this knowledge.

The position developed by Dulany [27] and Perruchet and Pacteau [28], is that the exposure to the letter strings during the learning phase of the AG experiment, results in a sort of fragmented explicit grammar that the subject uses. These fragmented grammars are sufficient to explain the obtained results, however they do not necessarily learn the actual implicit rule system, rather they are just forming an explicit representation of the implicit grammar.

Dulany 's [27] conclusion is based on experiments he conducted where he would subsequently ask the subjects which portion of the letter strings presented caused them to perceive it as grammatical. Subjects

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were able to do this, which shows that the grammatical judgments were based on an imperfectly formed explicit version of the implicit rule system.

In resilience to the above critiques, implicit learning as it was described above is a scientifically accepted phenomena and does indeed yield a knowledge base which is formed without conscious awareness. Furthermore implicit learning findings have shown many of the effects often seen in relation to explicit learning such as consolidation effects [29].

The Evolutionary Model

The notion of implicit learning has been explained within the confines of a larger Darwinian framework, which aims at understanding the primacy of the implicit system. In his evolutionary model, Reber [22] postulates that 'consciousness is a late arrival on the evolutionary scene... and sophisticated unconscious perceptual and cognitive functions preceded its emergence by a considerable margin'. It is argued that the implicit takes primacy over the explicit and therefore, implicit systems should be more robust than explicit systems. Darwin has taught us that traits tend to be selected in a forward manner. Traits that are more adaptive to an organism's environment are the ones which are passed genetically to their offspring. This in fact gives their next generation a better chance of survival and a greater chance to reproduce. While the mechanisms of this process are quite complex (i.e, natural selection and random gene mutations). One aspect remains clear, the later the species on the evolutionary scale the more advanced it will tend to be. With this in mind we now have a framework within which to understand the cognitive effect that we call implicit learning. Implicit learning by our definition involves learning without conscious awareness a process which almost certainly arrived on the evolutionary scale many years prior to that of conscious learning. Explicit learning, however tends to be a relative newcomer to the evolutionary timeline, in that it involves cognitive awareness. There is a substantial amount of physiological evidence which lends itself to this theory, most of which revolves around the notion that implicit learning tends to involve areas within the brainstem known to be the evolutionary precursor to the cerebral cortex (which is known to be involved in higher conscious processes, such as explicit learning). There is much supporting evidence from studies involving the mentally ill who lack higher level cerebral processing, but retain lower level brainstem function, and subsequent implicit learning abilities [30], as well as robustness with respect to age [31].

Conclusion

After exploring a number of the different proposed models, we are certain that the methods of knowledge acquisition are indeed complex. While these models are useful in allowing experimenters to determine their limitations they often fall short in explaining knowledge acquisition and learning in real world environments. Furthermore with the advent of implicit learning acting as a monkey wrench into virtually all cognitive models, it is clear that there is a need for a more dynamic and real world paradigm.

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