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Learning as a feedback-control process

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Abstract *- It is not easy to decide which of many learning theories known from literature describes reality better, since experiments for verification or falsification cannot possibly be repeated under the same initial conditions: Learners change their behavior while learning. Therefore, only statistical evaluations are possible. However, some models derived from learning theories might be re-arranged in a way that engineers would recognize them as models describing feedback control processes. The latter have been intensively researched by engineering scientists. Their analysis of learning models might be complementary to the interpretation of psychologists or pedagogues, thus providing new impetus to the evolution of learning models. This development is accompanied by considerable progress in neuropsychology. Due to advances in neuroimaging, "in-vivo" verification of some aspects of learning models is possible to some degree. Therefore, in a novel model emphasis is shifted from psychological aspects towards aspects of signal processing. It turns out that the feedback loop of learning is an adaptive loop. This means that it changes its properties with time. This adaptation is again done by other feedback-control loops. In summary, necessary steps in the process of learning are identified. The important message is that all these steps need time for performance, and that some steps cannot possibly be done before others have been successfully managed. In the light of this model, parts of Bloom's taxonomy for learning, teaching and assessing in its revised form as given by Anderson et al. are analyzed and adapted. The novel model might be used as a working hypothesis to explain what distinguishes learning by rote from learning to understand and gaining comprehension. For verification, collaboration between engineering and education faculty is necessary.*

Index Terms *- Learning theories, relations between learning theories and curriculum design, taxonomy of learning.*

INTRODUCTION

Many models of human learning are in use in the pedagogical, psychological, and neuropsychological literature. The most important ones have been developed mainly during the last century. Pioneers of learning theories, e.g. Dewey [1], and Lewin [2], have set up models that are still in use. Theories that are more modern have been introduced by Piaget [3], Gagné [4], Bandura [5], and many others.

Following Leonard [6], most of these theories might be categorized under four major learning paradigms. These are behaviorism, cognitivism, constructivism, and humanism.

Behaviorism might roughly be described as a learning theory where a set of stimuli is repeatedly offered to the learner in such a way that he or she adapts to these stimuli by reacting through a defined set of responses. Behaviorism is based on Skinner's research work [7] and that of many others.

Cognitivism claims that human thinking and learning might be explained more or less by signal processing in the human mind. Thereby internal mental states are taken into consideration. Publications by Atkinson and Shiffrin [8], Schneider and Shiffrin [9], Shiffrin and Schneider [10], and Craik and Lockhart [11] are pioneering works of cognitivism.

Constructivism (due to Leonard [6]) is "the belief that learners, having some prior knowledge and experience as a basis from which to test out their hypotheses, built their own set of content to solve a particular set of problems posed by the instructor. Constructivism is a learner-centric educational paradigm, in which content is constructed by the learners … in a … learning environment". Vygotskii [12], Piaget [3], Bruner [13], and many others are seen as protagonists of constructivism.

Humanism (due to Leonard [6]) is "the belief that human thinking and learning … are driven by the growth of the self as a whole, mature, and complete human being, who has a strong character and an ability to make decisions that positively influence others". Among the many great humanist thinkers, Dewey [1] is mentioned because of his particular relation to the following work.

Which of modern, competing models describes reality better is not easy to decide, since it is extremely difficult to verify or to falsify them. The reason for this difficulty is that such experiments cannot possibly be repeated under the same initial conditions: Learners change their behavior while learning. Therefore, only statistical evaluations are possible, and without a change of methods, progress is made only slowly and gradually.

Interestingly, Dewey's, Lewin's, and Gagné's models might be re-arranged in a way that engineers would recognize them as models describing feedback control processes. This is done representatively for Gagné's model in Figure 1.

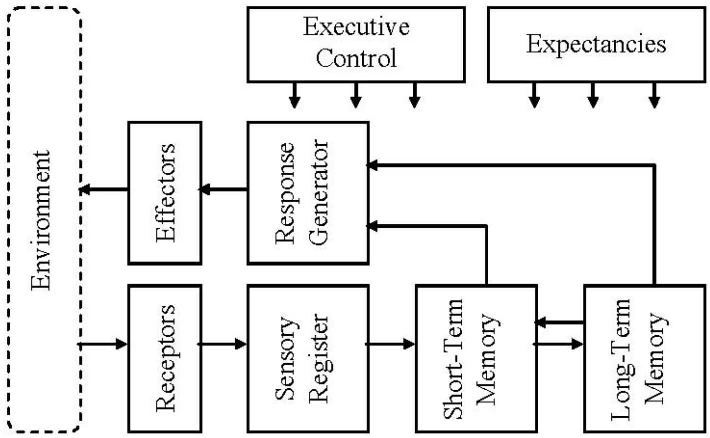

FIGURE 1
GAGNÉ'S AND DRISCOLL'S FEEDBACK LOOP OF LEARNING, ADAPTED FROM [4].

Following the explanations of Gagné and Driscoll [4], "the environment stimulates the learner to perceive information through a receptor. From there it is led to a sensory register, where it is transformed into recognizable patterns that enter the short-term memory. These patterns are transformed when entering the short-term memory by selective perception or feature perception. Information to be remembered is again transformed by a process called semantic encoding to a form that enters long-term memory. Information may be retrieved from long-term memory and returned to short-term memory or from one of the memories to a response generator and is transformed into action. The response generator activates effectors, e.g. muscles etc., which in turn influences the learner's environment. Since it might be observed there, it becomes evident that a learning process has taken place."

Indeed this model is obviously describing an information-processing loop. If avoiding frustrations and gaining well-being are target functions to be optimized, the learning loop is actually a feedback-control loop. Engineering scientists have intensively researched such loops. It might thus be sensible to make use of their experiences, and to introduce a novel model, where the process of learning will be interpreted as a feedback control process.

In this model, emphasis is shifted from psychological aspects towards aspects of signal processing. This does not mean that psychological or educational aspects would not be regarded to be significant. Rather, complementary aspects of the process of learning might be found that have not yet been intensively discussed until now.

Fortunately, the creation of such a model is accompanied by another development, and that is considerable progress in neuropsychology due to advances in neuroimaging. Thus, "in-vivo" verification of some aspects of the novel learning model is made possible to some degree.

THE MODEL

The novel model was recently hypothesized in [14]. There it is assumed that learning consists of multiple steps of acquiring different types of knowledge at different levels. This might be demonstrated by the diagram following Figure 2.

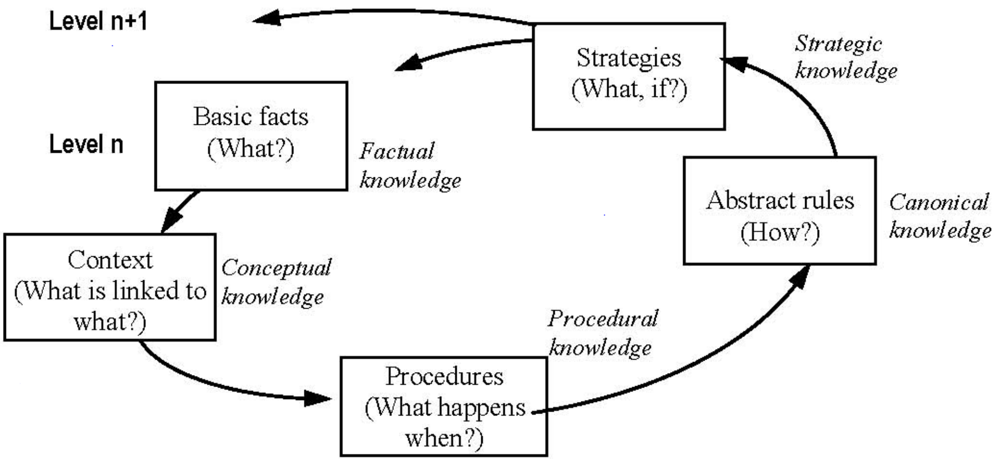

FIGURE 2
A CYCLE OF LEARNING IN THE NOVEL MODEL, ADAPTED FROM [14].

To explain this diagram, an example is taken from speech recognition [15], [16]. Suppose that a learner is going to learn a new language. He or she learns new words, i.e. he or she acquires *factual knowledge*. The learner experiences that these new words are always heard in a certain context, i.e. the learner acquires *conceptual knowledge*. In a next step, the learner drills the automatic usage of these words in certain combinations. That is acquisition of *procedural knowledge*. After a while, the learner recognizes that there are rules behind the usage of words, e.g. how to build the plural form of a word that is known to him or her in its singular form. This is acquisition of *canonical knowledge*. Finally, by thinking of application of rules in different contexts (for example when reading new, unknown words), the learner develops strategies for deliberately acting in new situations, e.g. when listening to a speaker with a richer vocabulary. This is building up *strategic knowledge*.

The process of learning is not yet finished with acquisition of strategic knowledge. Rather new words might be learned, thus initiating a new cycle of learning on the same level as before. Another possibility was to learn about new grammatical constructs, which could only be done successfully when other, more basic factual, conceptual, and procedural knowledge would have been acquired before. This would shift the learning process to a higher level.

The new model establishes relations between human information processing and Bloom's revised taxonomy of learning [17], though the term "procedural knowledge" is used in the new model in a more restricted form, and though there are no terms in Blooms revised taxonomy that directly correspond to "canonical knowledge" or "strategic knowledge".

On very high levels of learning, acquiring strategic knowledge gains a particular meaning. Then the learner might even think on imaginatively breaking rules, which opens the way to creative thinking. A famous example would be reading of Joyce's Ulysses [18].

Acquisition of all these different types of knowledge include comparison of newly input pieces of information with own, stored patterns, detection of the degree of novelty, decision on whether storage in memory is useful or necessary, and finally storage of the new piece of information as pattern for further usage.

This process of recognition might be described by the block circuit diagram following Figure 3. A more detailed description is found in [14].

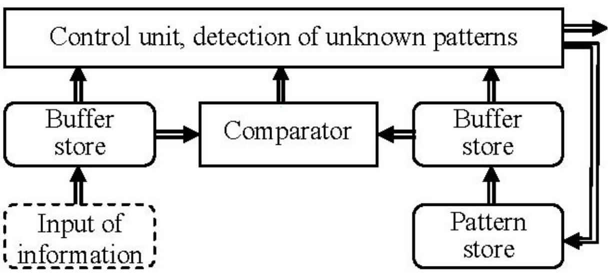

FIGURE 3
THE FEEDBACK LOOP OF DETECTION AND STORAGE OF NEW PATTERNS, ADAPTED FROM [14].

This structure implements an adaptive feedback-control loop: Input information is compared to locally stored information (the patterns). If part of the input information is recognized as known, then the pattern with the best match will be forwarded for further information processing. If however no good match is found, and if attention is directed to the unknown pattern, then the unknown piece of information is automatically or deliberately classified as either to be discarded or being worth storing it. In the latter case, the new piece of information would be stored in the pattern store. (The objective function to be maximized in that control loop would be a feeling of satisfaction).

Using spoken language as an example, it is seen immediately that the process of recognition of spoken sentences is split into several sub-processes that are partly working successively, partly in parallel. In this case, first phonemes of a specific language are recognized. These are the smallest units of speech distinguishing one word element from another [19]. BBC-English, for instance, is based upon 44 different phonemes only [20]. These phonemes are collected to syllables in a next step. In parallel to that, intonation and stress on phonemes (metrical phonology) are registered, then the morphophonological structure ("grouping of the speech stream into words") is found [21]. Further processes of recognition concern syntax and meaning.

From that, it is concluded that every process of more complex recognition is split up into sub-processes of recognition, each being a feedback-control loop. It must even be assumed that the complete process might include higher order feedback connections, as it is demonstrated by the so-called "party effect" where people adapt to recognizing a known speaker in a noisy environment.

CONCLUSIONS

In conclusion, it is stated that acquisition of different types of knowledge needs a plethora of nested, adaptive feedback loops. The latter means that these loops change their properties with time.

On higher levels of learning, learning results even depend on how active the learner is in order to find rules or to develop strategies. Learning success is thus not only depending on offered novel input. It rather depends on the (very complex) internal state of the learner. Learning is thus not seen as a process that could be described by an input-output relation. Behavior of the learner is ***not*** just depending on external stimuli.

Therefore, the process of learning is different for every individual person. It depends on the learner's inner state ***and*** on his or her own activity and capability of recognizing rules and of finding strategies, how fast new patterns are recognized and made accessible for new strategic thoughts.

Every feedback process needs time. Successive feedback-controlled decisions need more time than simple decisions. This means particularly that acquisition of canonical and strategic knowledge needs more time than acquisition of factual, conceptual, and procedural knowledge. Moreover, learning on higher levels makes necessary to learn on lower levels first.

It could be thought of shortening the time for learning by skipping acquisition of canonical or strategic knowledge. Instead, results that normally would be created actively by the learner during the processes of acquiring canonical or strategic knowledge might be summarized by an instructor, and then drilled to obtain an improved procedural knowledge. However, in this case, the learner would not have stored rules for deliberate application in new situations, nor would there be a list of deliberate strategies, which might be applied in new situations. Rather, automatic actions without thinking would be initiated in these situations: The learner would not be capable of comprehending complex relations.

Another conclusion might be drawn from the theory of feedback-control loops. Comparators in the human mind work by using neural networks. These have non-linear properties. There are furthermore connections with integrating behavior. Therefore, the nested system of many feedback-control loops in the learning mind could (theoretically) be described by a higher-order system of non-linear differential equations. It is known from the theory of non-linear feedback-control loops that these systems in principle could show a so-called "chaotic behavior". This means that even very small perturbations of the system or of the input information might result in unforeseen states of the system. These states depend strongly on the internal state of the individual learner. This explains why two different learners and with comparable IQ might achieve significantly different results though they are given the same set of learning instructions by a teacher. Even more, this explains, why individual learners achieve different results on the highest levels of acquiring strategic knowledge. This might explain why creative thinking (developing strategies) is so different in individual learners.

SUMMARY

A new model of learning has been cited. Though this model has not yet been tested by experiments, it is highly plausible, which is demonstrated in [14] in more detail. On the basis of the model's hypotheses, and based on methods found in the theory of non-linear feedback-control loops, some potential explanations of learning-effects could be given that did not have a satisfactory substantiation until now. In particular, it could be explained, why achieving comprehension needs more time than learning by rote.

Verification of the new model is certainly necessary. Since it is assumed that learning is changing a learner's behavior, verification must use statistical methods. Furthermore, since the model uses detailed sub-models of recognition, methods known from cognitive neurosciences should be applied. This makes cooperation between scholars from different areas of expertise necessary.

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