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Phase Transitions in Learning

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Two classic learning situations are critically reviewed and interpreted from a synergetic point of view: (a) human learning of complex skills, and (b) animal discrimination learning. Both show typical characteristics of nonlinear phase transitions: instability, fluctuations, critical slowing down and reorganisation. Plateaus in the acquisition curves of complex skills can be viewed as phases of arrested progress in which a *reorganisation* of simple skills is necessary before their integration into complex units is possible. *Fluctuations* and *critical slowing* down are expressed in instances of "vicarious trial-and-error," which describe the oscillating behavior of rats at a choice point that is shown only just before discrimination learning is completed. It is concluded that education might pay more attention to the role of individual learning rhythms.

The existence of nonlinear phenomena in the behavior of a system is a necessary condition and a strong hint at self-organization processes. All the fascinating examples of self-organization discovered and elaborated in the fields of physics, chemistry, and biology during the last three decades started with irritating and unexpected observations of spontaneous and sudden changes in the behavior of natural systems. In spite of the basic theoretical assumption of continuity in nature (*natura saltum non facit*) the complex dynamic of self-organizing systems is able to jump from one to another stable state of order in self-organizing systems. From a microscopic viewpoint of the nervous processes the systems are unpredictable. In phases of instability they are open to minimal influences causing maximal behavioral effects.

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Early Evidence of Self-Organization

The brain is a system which seems to be able to produce a nearly endless variety of ordered macroscopic (behavioral and phenomenal) states and it is probably the most complex system in nature. There is much neurophysiological evidence that the brain has to be understood as a self-organizing system, and this is an obvious and by no means new idea. Already in 1925 Wolfgang Köhler (1925), the important protagonist of Gestalt theory, wrote: "The somatic processes underlying static unusual fields are stationary equilibrium distributions developed from the inner dynamics of the optical system itself" (p. 512). Though the holistic approach of Gestalt theory was constricted by the concepts of linear thermodynamics of those days, Gestalt theory can be understood as a precursor of the modern theories of self-organizing systems, especially synergetics. In contrast to this early conceptualization of a theory of self-organization in brain, behavior and cognition, nonlinear phenomena are only rarely reported in the psychological literature. What are the possible reasons for the discrepancy between the theoretical evidence of self-organization processes in behavior and cognition and the lack of empirical reports of nonlinear phenomena in psychological research?

One basic reason may be that up to now conceptualizations in psychology have been directed more or less strictly toward homeostatic modeling. This preference reflects the fact that the least questionable goal of a living system is to survive. Life in a biological system is strictly bound to homeostasis. In homeostatic modeling the preservation of a clearly defined stable state is the basic mode of operation of the system. Unpredictable spontaneous changes can only be regarded as a breakdown of normal functioning. Therefore, also in cognitive and behavioral organization, nonlinearities and phase transitions seemed to be marginal phenomena and were not in the focus of interest. Yet, a purposeful reanalysis of already existing empirical results of psychological research might bring to light more nonlinear phenomena than found at first sight.

A second closely related reason can be seen in the narrow band in which phase transitions occur. In the behavioral space of a biological system phase transitions are necessarily limited to well-defined border conditions. Regimes of linear system behavior are the rule and nonlinearities have to be the exception to guarantee a stable basis of living and action. For cognitive functions like perception or thinking, the problem is even further intensified. To guarantee a stable basis of action a phase transition from one state to another, if existent at all, has to be very quick — not much conscious capacity should be wasted on recognizing the process of cognitive order formation. Therefore, by principle, it will not be easy to detect and measure phase transitions in psychological experiments. Psychological measurements are dependent on highly indirect methods.

Like the second, a third reason refers to a theoretical and a methodological aspect. In experimental psychology a tendency exists to try to reduce the complexity of behavioral and cognitive phenomena by analyzing elementary processes under very restricted conditions. This is due to the requirements of the experimental methods used on the one hand, and from the assumption that the complexity may be rebuilt by connecting the elementary findings on the other hand. In some cases the research is even limited by the technical equipment available. To observe the full dynamics of a complex living system it is necessary to look for experimental methods which allow a systematic analysis of behavior without reducing and constraining the system too much. Self-organization characteristics will only appear when the system behavior is unconstrained. That is, the system must be able to follow its own inner dynamics more or less freely.

The reevaluation of the significance of nonlinearities in empirical psychology is the starting point and the consequence of a self-organization theory of learning. In the theoretical framework of *synergetics* (Haken, 1977) the first step of analysis is to demonstrate the existence of phase transitions in a complex system. If such phase transitions can be shown, then a number of distinct theoretical expectations have to be satisfied to categorize the phenomenon as a consequence of a self-organization process. For the spontaneous reorganization a certain *control parameter* has to be defined which releases the sudden transition from one to another stable state of order when continuously enhanced (see Figure 1). Approaching the point of change by gradually increasing the control parameter the system behavior should show a tendency to persist in the previous stable state (*hysteresis*). Before the phase transition an autocatalytic destabilization of the system appears. This destabilization is

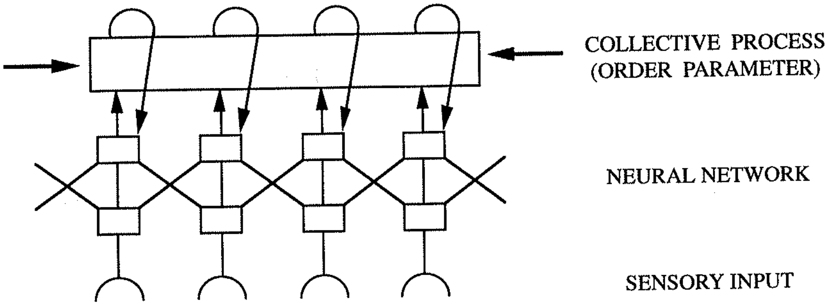

Figure 1: The relation between microscopic and macroscopic processes in the brain.

manifested by so-called *critical fluctuations* and by a *critical slowing down* of the process in order to conserve the existing stable state of order. In synergetics the autonomous reorganizations are explained by the appearance of different modes of behavior competing until one of them predominates the other by slaving the behavior of the elementary components of the system. This predominating mode is called an *order parameter*. The self-organization process is characterized by a certain circular causality between the microscopic and the macroscopic level of system behavior. The macroscopic stable states (that is, the order parameters) organize the microscopic interactions of elementary components of the system from which they have emerged.

Purpose

The foregoing characteristics of phase transitions have been shown to occur in perception (Kruse and Stadler, 1995). In perception the instabilities and the phase transitions are directly represented and can be measured by psychophysical procedures. Unfortunately the phenomenal representation of phase transitions has not been shown in learning processes. Therefore, in this paper we shall try to reanalyze some early experimental results of research on learning from a synergetic perspective.

Theoretically certain types of learning can be understood as processes of self-organized order formation. Continuous learning effort leads to a "heating" of the cognitive system which can be interpreted as the raising of a control parameter. Learning achievement is the result of emerging cognitive structures which can be interpreted as an order parameter. If this learning is a process of self-organization, it has to be expected that the achievement curve of the learner does not linearily increase over time. The learning curves should show phases of linear increase, phases of stagnation, and phases of significant sudden improvement of performance. During the linear increase a cognitive structure is optimized and transferred into performance. Maximum optimization at a given time of the learning process shows up as a stagnation. After some time this stagnation is followed by a destabilization of the existing structures, which is followed by a phase of sudden improvement in performance correlated to the emergence of a higher state of order. Three empirical hypotheses can be derived if such a process takes place:

1. When measured over sufficiently long time, with nearly constant learning effort and linear increase of task difficulty, learning processes will show characteristic nonlinearities in performance (*phase transitions*).
2. The stability of some parameters of the performance will break down at the end of each phase of stagnation (*critical fluctuations*).

In contradiction to naive expectation one hypothesis should be that at the end of the highly optimized performance the rate of errors increases.

3. Again in contradiction to naive expectation the learner will also show a significant increase in sensitivity to disturbances at the end of this phase of optimized performance (*critical slowing down*).

Phase Transition in the Learning Curve

Sometimes in learning of complex tasks like piano-playing, reading or even typewriting, people report of stages in which no advance is made despite their high effort. This is often said to be followed by sudden improvement in which a new level of control is reached. In learning curves these periods of arrested progress are indicated by *plateaus*.

The phenomenon was first studied a hundred years ago by Bryan and Harter (1897), whose subjects had to learn to send as well as to receive telegraphic language (Morse code). The achievement over a long period showed a normal learning curve in sending — but in receiving a significant plateau was found (see Figure 2). In a following experiment Bryan and Harter (1899) varied their stimulus material for receiving systematically in its degree of semantic information: (a) they sent series of letters that formed words and sentences, (b) series of letters that formed words but no sentences

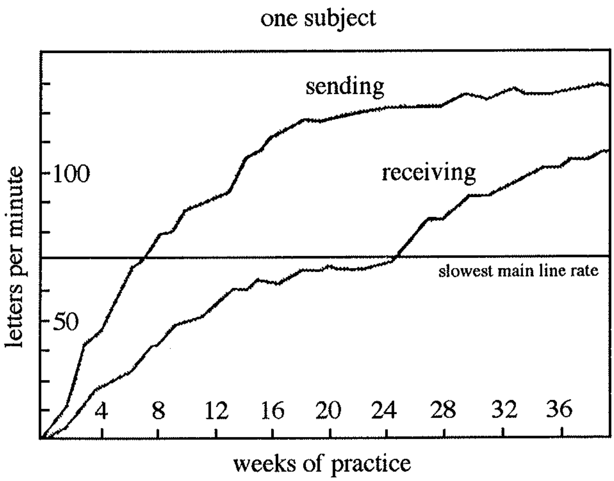

Figure 2: A plateau in the learning curve of receiving telegraphic language.

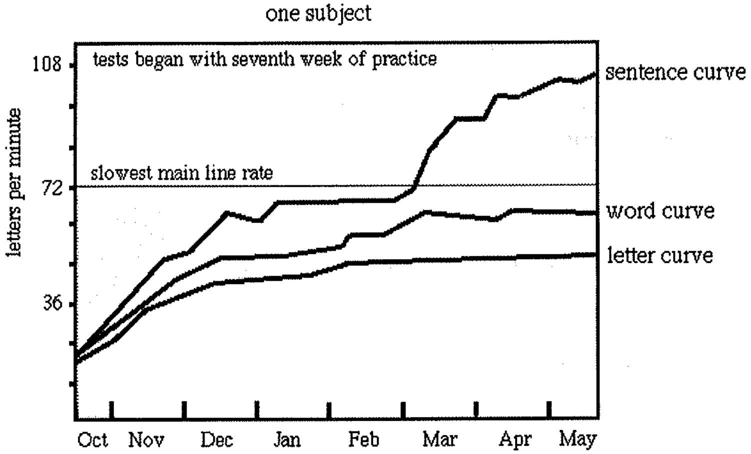

Figure 3: Learning to receive telegraphic language: letters that form no words (lower curve); letters that form words, but no sentences (middle curve) and letters that form words and sentences (upper curve).

and (c) series of letters that didn't form words (Figure 3). In single-letter-reception no plateaus occurred. Single words produced slight plateaus and whole sentences produced distinct plateaus. This was interpreted as an asynchronous improvement of different hierarchical habits. Freezing of attention to lower order habits (recognition of letters) until they had become automatic impeded the improvement of higher order habits (recognition of words and sentences). Bryan and Harter's results are controversial. Several attempts to replicate them failed (Cook, 1957; Taylor, 1943) which led Keller (1958) to the conclusion that the plateau is no more than a "phantom." Pfisterer's (1988) recent studies in Morse code do reveal plateaus, but they are interpreted by him as a natural consequence of the testing procedure because arrested progress is observed at levels where subsections are completed.

There are some methodological problems in the measurement of plateaus: they are difficult to trace in experimental settings because of several factors. The definition of what could be titled a "plateau" has not been clarified. Learning curves are influenced by statistical effects such as dispersion. Normally a plateau is defined as a phase in which all results lie below a previously reached level which ignores the fact that a better score could be a mere incident. It is also difficult to predict which kind of tasks will lead to periods of arrested progress. These only seem to occur in complex skills where learning stretches over long periods of time (several months) which makes it complicated to provide constant conditions. The distinction between plateaus due to situational and motivational influences on one side and plateaus due to characteristics of the learning process itself on the other is often impossible. Attempts to solve this problem by taking subjects' introspections after every trial leads to other methodological problems. Motivation and situation should affect the learning process unsystematically leading to clean curves when several scores are superimposed. But a systematic tiring-effect (for example, a gradual loss of concentration) still remains a possible interference. In marathon running for example, a phase of "hitting the wall" is often experienced when physical exhaustion is reached. This period of depression is followed by improved performance and the feeling of a "high." In a study by Summers, Machin, and Sargent (1983) this kind of plateau was reported by 40% of subjects, to most of whom it occurred at a similar distance between 19 and 24 miles.

The last mentioned problem does not apply to the motor tasks reported here, because they do not exceed an average everyday level of physiological strain. Batson (1916) occasionally found long period plateaus in a task of manipulating an apparatus carrying balls that had to be shot into a pocket. Chapman and Hills (1919) found short plateaus in typewriting. Trow and Sears (1927) studied one subject's progress in card dealing where they discovered one plateau which they interpreted as due to conflicting methods of practice, as a period of trial-and-error with selection and rejection of methods.

Smith (1930) investigated several tasks that included motor coordination: ball-throwing, ball-guiding and shorthand. In all of these he occasionally found plateaus which were obviously attributable to factors inherent in the learning process rather than to motivational or situational factors. He explains them as difficulties in the coordination of different components of a task. The way attention was directed either to the parts or to the integrated movement had a crucial effect on improvement. He found that sometimes performance was best when the subjects were not paying conscious attention to the movement at all. Kao (1937) examined two tasks: one that involved the simultaneous control of three variables — timing, angle and force of a pendulum — and one that afforded a certain successive organization of movement for manipulating a ball-throwing device. She investigated how far the prior learning of the individual components influenced the acquisition of the complex task. She believes most of the plateaus can be interpreted as merely statistical irregularities. Yet, there are short but distinct plateaus in the complex pendulum task only for subjects with prior training of the individual components (Figure 4). The periods also show large daily fluctuations. This effect can be clearly attributed to some kind of reorganization of the simple skills. Without that training the subjects produce normal learning curves. That means, if the simple skills have to be integrated on a higher level, a self-organization process must take place that results in a plateau followed

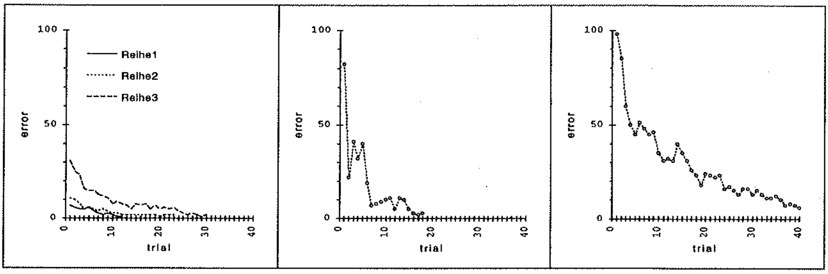

Figure 4: Learning the individual components of a complex task (left diagram); the integration of the individual components exhibits plateaus (middle diagram); learning of the complex task from the beginning shows a normal learning curve (right diagram).

by a destabilization just before the integration. This fits exactly Kao's interpretation: "another group of short periods of little progress with large daily fluctuations is due to difficulty in *changing pattern*. After certain processes had come to be regarded as patterns in themselves, welding them into a single complex pattern proved too difficult at first" (1937, p. 74). Kao's plateaus can be regarded as free of motivational and situational effects. They occur at constant stages in the learning process rather than being unsystematically spread. Physiological exhaustion as a cause is unlikely because the pendulum is controlled by only small movements of the finger.

So we can conclude that phase transitions seem to exist in complex learning tasks at least as long as there is a hierarchy of components to be integrated on higher levels. It is interesting to read the interpretations of the plateaus given by the authors cited: Bryan and Harter (1899) suggested hierarchical acquisition of habits which can be seen as equal to nonlinear emergence of cognitive skill; Trow and Sears (1927) proposed conflicting methods of practice; and Batson (1916), Smith (1930) and Kao (1937) suggested problems with coordination. These can be interpreted as the coexistence of single incompatible motor programs which require reorganization in the form of temporal and spatial coordination in order to be able to emerge into a single complex unit. This proved true most clearly in the experiments of Kao (1937): simple skills that had been learned as units in themselves produced a period of arrested progress when execution was required simultaneously in a complex task. The strong fluctuations in performance during this order formation are typical indicators of a nonlinear phase transition.

The way attention is directed either to the individual parts or to the complex skill strongly influences the process of learning. Both strategies can be effective at different stages. It seems that after sufficient training of the parts some kind of divided attention is necessary to integrate them into a higher level unit. This is when the phase transition occurs. Smith (1930, p. 23) reported that his subjects claimed to have been "in sort of trance," "thinking of other things," or "experiencing a dizzy kind of feeling," and hadn't been paying conscious attention to the movement at all. This reminds one of the "aha" experience in problem solving where solutions often occur to a subject suddenly and passively at a time after intensive effort on a problem was suspended.

Behavioral Fluctuations in the Learning Process

Abrupt discontinuities in the learning curve really were not that unusual for learning psychologists in former times. As early as 1932 Tolman noted: "The fact of sudden drops in the learning curve is of course familiar . . ." (see Tolman 1967, p. 216), referring especially to Thorndike (1911), Yerkes (1916) and Koffka (1928). As already described, this nonlinear behavioral covariation of the learning process can be interpreted as a phase transition from one ordered state to another ordered state.

Fluctuations are, as we have seen, a necessary prerequisite of synergetic phase transitions. In the instable phase (that is, the learning phase) the system exhibits fluctuating behavior, which increases up to critical fluctuations, and thereafter to a new stable state. Are there any behavioral correlates of such fluctuations in learning situations? Numerous experimenters indeed have reported a more or less typical and frequent pattern of behavior which occurs at the point of choice in the discrimination box, in a maze or during the choice process in visual discrimination studies employing jumping stands. This pattern has been variously described as "looking to the right or left before choice," "running back and forth," "head movements" and so forth. To this general pattern of behavior Münzinger and Fletcher (1936) have given the name "*vicarious trial-and-error*" (VTE). Although first used to label choice point behavior of rats prior to spatial or nonspatial discriminative responses, VTE has subsequently been extended to vacillatory behavior in other learning situations and today refers to oscillating behavior of various types of subjects at points of choice in a wide range of learning situations.

And what about critical fluctuations? If the nonlinear drops in the learning curve are due to a phase transition, then shortly before and during such a drop VTE behavior should be expected to increase to a maximum (and then fall again or even disappear). Again it was Tolman (1926) who observed the relationship and emphasized its importance for learning theory: "I have seen at certain stages in their learning very patent instances of such hesitation at the point between two alleys. The rat stops and wiggles its nose from side to side and then finally chooses" (p. 367). Tolman (1967) later suggested that there might be a very specific relation between such choosing behavior and learning: "The fact of sudden drops in the learning curve is of course familiar . . . but what we are seeking, now, is not this mere fact of sudden drops but rather a correlation between the appearance of such drops and the appearance of just preceding 'running back and forth'" (p. 216).

In another paper, Tolman (1938), suggested that these new types of activity be called *catalyzing behavior*, regretting that "the rat psychologists have to date rather pigheadedly . . . ignored such catalyzing behavior" (p. 27). The term "catalyzing" is so near to the concept of critical fluctuations that one might speculate that, had this theory been developed some fifty years earlier Tolman would have adopted a synergetic interpretation. At any rate, he expressed his belief, "that in the future technological advances in recording will bring to the fore many other instances of such catalyzing behavior for study" (p. 27). And it was still another great psychologist, who almost foresaw the theoretical importance of this kind of behavior. Describing the VTEing of dancing mice at the choice point of his discrimination experiments, Yerkes commented as early as 1907 that "could we but discover what the psychical states and the physiological conditions of the animals were during this period of choosing, comparative psychology and physiology would advance by a bound" (pp. 130–131).

In the following years there indeed was some research on VTE behavior and learning, and we shall remind the reader of the data, which are in accordance with the hypothesis derived from self-organization theory formulated above. Münzinger (1938) scored VTEs in relation to mastery of a habit. Adopting two consecutive series of ten errorless trials as a criterion of learning he got the following results. Conceding that any criterion of learning is an arbitrary measure, he notes that nevertheless there seems to be a specific psychological event, which corresponds to the chosen criterion: "The frequencies of VTE in the two series immediately preceding the criterion and during the two series of the criterion are higher than those further removed. The conclusion suggests itself that the frequency of VTE attains its peak during the phase of learning in which the mastery of the habit is established" (pp. 78–79). Theoretically important is a further observation of Münzinger. At the beginning of his research on VTE and learning he assumed that the main function of VTE behavior was to enable the animal to compare the cues to be discriminated, and that without discriminable cues present in the choice alleys there would be only sporadic occurrence of VTE. He tested this idea by training rats to respond to diffuse stimuli in a tone experiment. The source of the sound was suspended one meter above the point of choice, and the animals learned to turn into one alley, when the tone was sounded, and into the other alley, when it was silent. The result was that all animals exhibited VTE and "what was still more surprising, there was the same relationship between frequency of VTE and learning efficiency as in the case of a visual discrimination" (p. 82). Obviously, Münzinger notes, VTEing has another function than the mere comparison of cues in the different alleys. However, "the effect [of it] is likewise a facilitation of learning" (p. 82). This observation seems to strengthen the assumption that VTE in fact is a behavioral correlate of critical system fluctuations shortly before reaching a new stable state.

Further evidence for this kind of relationship is exhibited in learning curves with an elevated discrimination setup obtained by Honzik and presented by Tolman (1938). The animals had to discriminate between a black and a white face each on a door. There was a partition projecting out between the doors. The rats were required to jump a gap just in front of a door. If chosen incorrectly, these animals had to jump back again to the starting platform and then make a second jump to the correct door. The results of the error curves and the VTE-curves are depicted in Figure 5. Each point represents an average of ten trials. Clearly, VTE behavior is at its maximum immediately preceding errorlessness and declines shortly thereafter.

In still another setting (maze learning), Peterson (1917) observed that "just before entrance [into the blind alley] is eliminated completely, there frequently occurs a peculiar and rapid vibration of the rat's head between the directions of the true part and that of the tempting blind alley" (p. 52). Similarly, for animals learning a horizontal versus vertical bar discrimination

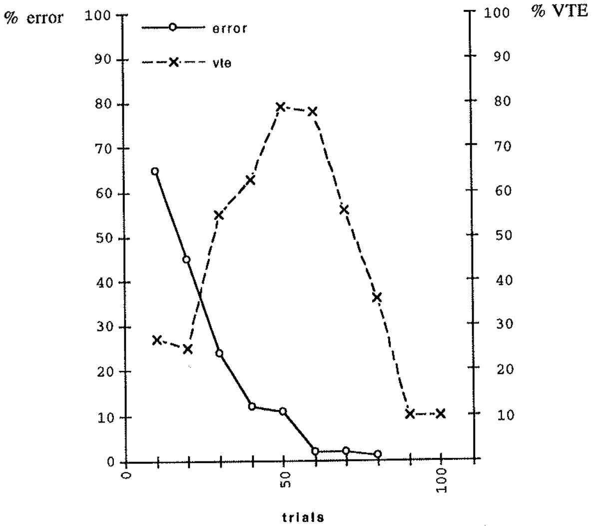

Figure 5: The relation of VTE behavior and learning success.

in a modified Grice-apparatus, Lane (1952) reported the appearance of "much VTE-behavior from the 5th day of training on until just before the animal learned the discrimination" (p. 48).

Very interestingly, there seems to be a difference between easy and difficult discriminations. Thus it has been observed that the described relationship (that is, maximum VTE just before mastery, then a drop) holds for easy, not however for difficult discriminations. When more difficult discriminations are required, VTE frequency tends to remain at a certain level for at least a while even after reaching the criterion (Goss and Wischner, 1956). As already mentioned, any learning criterion is an arbitrary measure. From the point of view of synergetics one would argue that the learning criterion is reached when the appropriate order state, the new stability, is *fully established*, that is, when no more behavioral fluctuations are being exhibited.

We can switch our hypothesis the other way round and predict in what phase of the learning process VTE behavior (that is, fluctuations) should not be expected. In discrimination and other choice situations animals occasionally start the learning trials with what is called position preferences. In a white/black discrimination for instance, when the stimuli are randomly presented either on the right or on the left side during learning, these animals start with a habit, namely always responding to one specific side. If it is true that VTE indicates system fluctuations in the destabilized transition phase, then one should expect absence of VTE in clearly stable phases, like those position preference habits. One would describe this situation as a phase transition from one ordered state to another, that is, VTE should be absent at the beginning of learning. Actually this is the case. Goss and Wischner (1956) summarized Klüver's (1933) observations that monkeys had shown no VTE behavior in weight discrimination training when responding in terms of a right position preference. And inspection of curves presented by Tolman (1939) indicates that in the early stages of discrimination learning, if position habits were operating, there was very little VTEing. As the animals began to respond with fewer than chance errors, VTE frequency increased. So, it may be summarized, VTE behavior of animals occurs in the destabilized phase transitions of the learning process and not in the stable states, as would be expected by the synergetic phase transition theory.

Critical Slowing Down

We come to the third hypothesis concerning characteristics of synergetic phase transitions in learning: if self-organization theory holds for the reported learning situations, then one might expect to observe still another phenomenon. The theory assumes, that the time needed for a system being in an instable phase to find a new stable state increases the closer the point of sudden transition is approached. Consequently, if VTE is a behavioral correlate of system fluctuations, one would expect a positive correlation of VTE and response latencies. Indeed, Crannell (1942) reported an increase in VTEing and *hesitation time* as rats approached criterion in multiple-path mazes. And this is not a unique result. In their review on VTE, Goss and Wischner (1956) pointed out that a number of investigators found (Jackson, 1943; McCord, 1939; Tolman, 1939) that VTE frequency and hesitation time were positively correlated in discrimination, trial and error, and delayed response situations. Unfortunately there are no studies measuring the fluctuations and the critical slowing down of animals in learning processes independently. So, in most cases the slowing down of the learning process just before the phase transition might be a simple consequence of the increase of VTE behavior which takes additional time for the animals to exhibit.

Conclusion: Consequences of Nonlinear Phase Transitions for Education

If, as has been made probable by the data presented, some forms of learning are processes of self-organization rather than self-gratification, conclusions can be drawn that may stimulate further research. The first conclusion is that the dominance of conditioning and compulsory education by means of reward and punishment be reduced and more attention paid to individual differences. *Let them learn to find their own self-organized rhythm.* Systematic observations of babies' habits have shown that they find their rhythm without being driven by their parents. Such observations were made long ago, before chaos and synergetic theory became adopted by psychologists. Families were asked to feed their babies at any time they cried for food, and *never* when their mothers thought they should be hungry. Such a diagram of the feeding times of a baby between the 5th and the 11th week of life is depicted in Figure 6 (drawn after Metzger, 1975). Figure 6 shows that the feeding times following only the needs of the baby seem to have a chaotic distribution over the daily hours in the first weeks. Beginning from about the 8th week of life the feeding times organize regularly and seem to have found their stable distribution after the 10th week when a daily order of five meals is found. T. Elbert (personal communication) from the University of Münster found a very similar development of the sleeping times of babies, which at first followed a chaotic attractor and then showed a self-organized phase transition to a periodic attractor. So it looks as if the cyclic needs in human development find their self-organized order in a fashion that their rhythm is synchronized and adapted to the circadian rhythm.

The second conclusion concerning children's education might be: *let them make mistakes*, don't punish them for errors. As has been seen in this paper, an increased number of mistakes appear in the instable phase of fluctuations

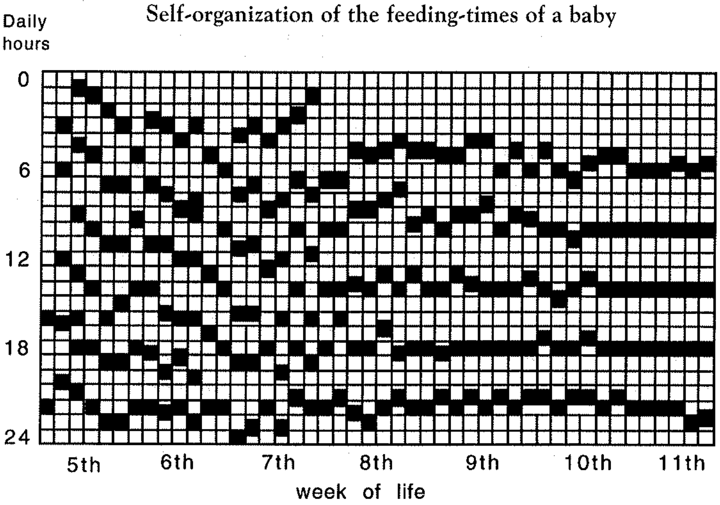

Figure 6: Record of the feeding times of a baby between the 5th and the 11th week of life.

just before a learning process becomes stabilized at a higher order state. Thus mistakes might be a necessary feature of the accomplishment of the learning process. As an example one may take children learning to read in the first two classes at school. In such a learning process they follow certain plateaus very similar to those found by Bryan and Harter (1897, 1899). First children learn to combine letters to words and then, when they recognize the word at a glance, they learn to combine words to sentences. Reading by words means for the children not to combine the single letters but instead to organize them in terms of meaning. In the transition between the two strategies mistakes may occur. A child may for instance read "tone" instead of "tune," being mistaken in one letter only but changing the meaning of the word entirely. Such mistakes may occur more frequently just before the plateau of letter reading is left, and the child has passed on through a period of fluctuations to the higher level of word reading. Empirical research on the Gestalt organization of human errors has shown that typical mistakes occur when behavior is suddenly governed by higher ordered states (Wehner and Stadler, 1994). The view on learning as a self-organizing process not only explains the peculiarities of behavior in the estabilized phase transition but also underlines the creative power of these behavioral "pathologies."

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