Memory, Probabilistic Prognosis, and Presetting for Action

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Abstract. Organism's reactions to changes in the environment require mobilizing numerous physiological systems, and therefore a certain time period. The more difficult the reaction, the more time its realization requires; however, too slow reactions may become meaningless. In the course of evolution, a mechanism has elaborated to ameliorate this situation. Information on the probabilistic structure of previous individual experience is stored in memory. On the basis of this information, a probabilistic prognosis is constructed about the most likely future events. If in earlier experience, a certain individual event A has followed an event B with high probability, then in response to the actual occurrence of A the organism is able to execute a presetting – it is able to activate the structures necessary for reacting to the yet not present, but highly probably prognosed event B. The higher developed the organism is, the better its capacity for probabilistic prognosis, and the more accurate, quick, and economic its reactions to changes in the surrounding environment.

Keywords: Physiology of Activity, Nikolai Bernstein, Probabilistic Prognosis, Conditioned Reflex, Memory, Pre-Signal Anticipatory Preparation for Action

1 Introduction

The classical works of N.A. Bernstein (1896 - 1966) laid the beginnings of the paradigm of activity, which was to replace the earlier paradigm of reflexes developed in physiology successfully from Descartes (1596 - 1650) to Pavlov (1849 - 1936). The scientific significance of Bernstein's research and the novelty of his methods were recognized already in 1933 by the academician A.A. Ukhtomsky, who compared them to the contribution that the method of microscopy, developed by Leeuwenhoek and Malpighi, had given to the natural sciences [1].

An animal is not a reactive entity, who's behavior would simply consist of responses to already present stimuli. It is instead an active being, who's behavior is directed to the achievement of certain results. An image of these results is encoded in the nervous system – in the "model of the intended future" according to Bernstein. All action is preceded by the generation of a model about the expected outcomes of action.

The ideas of the physiology of activeness were not easily recognized. The 1950-s – some of the worst years of Stalinist terror (and even the years subsequent to Stalin's death) – were most difficult also for Bernstein. His laboratories were closed down, and his articles were not accepted for publication. He sat in his room of a communal apartment and worked on creating of the physiology of activeness, while earning his living by referencing and reviewing foreign physiological literature. Only in 1961 was it possible for him to publish a large (60 pp.) article "Current problems in the theoretical physiology of activity" (written by Bernstein already in 1958). The article was published in "Problems of Cybernetics", edited by the mathematician A.A. Lyapunov [2]. The idea of the necessity of anticipating the future in the realization of movements was already sketched in this article. Bernstein writes: "The conclusion is inevitable that, when speaking about the program of a motor act as a whole, we do not find for it a defining factor other than the anticipatory image of its result. The subject aims towards it by his conception of a certain movement task" [2, pp. 138].

In 1962, Bernstein writes in the article "New Lines of Development in Contemporary Physiology": "The most peculiar and characteristic circumstance that physiology runs up against when it turns to the problem of activeness is the following. The next action task formulated by the individual "from within," taking into account, but not mechanically conditioned by, the current situation, is of necessity constructed as a kind of extrapolation of the future. It is possible to program an action in conformity with a goal only on the basis of a definite image or model of the result to which this action must lead and for the sake of which it is undertaken. But because forthcoming events can be evaluated or foreseen only "by way of probabilistic forecasting" (the apt term of J.M. Feigenberg), it is clear that our approach to the analysis of all the physiological processes concealed here must also be based on probability theory and its latest offshoots" [3].[1]

[1] The translation refers to the English version: Bernstein, N.A.: New Lines of Development in Contemporary Physiology. Journal of Russian and East European Psychology 44(2), 60-67 (2006)

Probabilistic prognosis became the object of detailed investigations by the author of the current paper [4]. This line of research has become an integral part of the physiology of activeness. Bernstein specifically indicates the place of probabilistic prognosis in the physiology of activeness: "... here we face two interconnected processes. On of them is the probabilistic prognosis based on the current perceived situation... Alongside with this probabilistic extrapolation of the course of surrounding events (presuming no "interference" in their course), also the action necessary for realizing the intended future is programmed" [5, pp. 438].

For an action to be quick and accurate, the organism prepares for it before it becomes necessary to carry it out – it performs a presetting, a preparation for action in systems that will have to realize the movement. Thus, a sportsman waiting for the signal before the start of a run assumes the respective pose, and prepares the respective muscle groups for activity that will have to execute the run after the upcoming signal. The action is carried out much faster, more economically and accurately in response to the signal in case its occurrence has been prognosed with high probability, and a presetting has taken place to mobilize namely those particular organs (e.g., muscles) that will have to implement the activity – and only those muscles (whence the economy of the act). If the signal to act appears unexpectedly, leaving no time for preliminary presetting (anticipation of the triggering signal), this will lead to non-dexterous, insufficiently fast and accurate execution of the performance.

The prognosis of the future is based on memory – remembering how and with what probability a situation, similar to the one which the organism is now facing, changed in the past. How is the memory of past events organized to ensure the probabilistic prognosis of the future? What is the nature of the presetting that supports in advance the fast, economical, and accurate reaction that is adequate to the prognosis of the forthcoming situation? How does the reaction itself (for example, its speed) depend on the accuracy of the probabilistic prognosis? The following sections are devoted to these questions.

It's been argued that action is preceded by the formation of a model about its necessary results, and by a prognosis of the situation (signal), which requires the goal-directed activity to begin. However, where could the prognosis for an upcoming, not yet existing future event come from? It is formed as a result of available information on the present situation, and on the basis of remembering what situations and with what probability followed similar situations in the past. Thus, actions are realized according to the model: "seeing – foreseeing – acting": seeing the given situation, foreseeing what situations and with what probabilities can follow it, presetting for the most probable actions in the upcoming (prognosed) situation, and carrying them out.

2 From Reflex to Probabilistic Prognosis

The classical reflex consists of an organism's behavioral response to an already occurred stimulus. The action (A) of the organism is adequate to the nature of the stimulus (S). This can be schematically depicted as follows:

S – A (S) (for example: prick – withdrawal of the paw; food – salivation).

The Pavlovian conditioned reflex has an essentially different structure. After repeated occurrence of a situation where S1 is necessarily followed by S2, and an adequate reaction (A) to this stimulus A (S2) is required, the organism starts to respond after stimulus S1 with a reaction (behavior) that is adequate to stimulus S2, and this in advance of the occurrence of stimulus S2. Let's depict this schematically as follows:

S1 – A (S2) – S2

In the Pavlovian school, during conditioned reflex elaboration the conditional stimulus (S1) is necessarily followed by an unconditional stimulus (S2), which leads to the reaction registered by the experimenter. The stimulus (S1) initially doesn't evoke this reaction. Unlike in the classical reflex, the nature of the reaction in the conditioned reflex does not correspond to the stimulus (S1) preceding the reaction, but to the stimulus that is yet not present, but prognosed to occur in the future with high probability. The reaction corresponding to the stimulus (S2) therefore anticipates the occurrence of this stimulus (or situation):

S1 – A2 – S2

On the basis of past experience, the organism foresees, prognoses the occurrence of the situation S2 and, without waiting for it to occur, reacts adequately towards it (anticipating the moment when the situation is supposed to occur). In the Pavlovian school, the unconditional stimulus necessarily follows the conditional one. Sound-proof buildings, the so-called "towers of silence" were even built for carrying out experiments without any interference from unforeseen stimuli. In these conditions, prognosis of the appearance of unconditional stimuli after conditional ones becomes absolute. They can be prognosed with a probability equal to 1.

S1 – Prognosis of S2 – A2 (*Prognosis – "precognition" in Greek*)

As opposed to Pavlov's research, we decided to experimentally verify what kind of activities a person would undertake in conditions of probabilistic (uncertain) appearance of stimuli, when they follow each other in random sequences with certain probabilistic properties. After all, this is how events take place in real life. We'll briefly report here the results of a series of experiments among several ones we've conducted.

In the first experiment [6], one of two light signals appeared in random order before the subject. Let's designate these signals with letters A and B. In response to both of them, the subject had to quickly press one of two buttons – depending on which signal (A or B) appeared. Reaction time was registered (in milliseconds).

The temporal order of signals was random, but the probability of signal A was twice as high as that of signal B. In these conditions, the average response time to signal A turned out to be about two times less than the reaction time to signal B. Perhaps this was due to signal A having been more frequent than signal B? (This view was held by some physiologists and psychologists). To control that, we conducted a series of analogous experiments, with the difference that the same group of 6 consecutive signals was repeated: AAABABAAABABAAABABAAABAB….

Reaction time to signals A and B turned out to be identical, and as short as the time of a simple motor reaction to a single signal. However, also in this new sequence the signal A was presented two times more frequently than the signal B. Therefore, it's not a question of the frequency of signals, but of the person being able to correctly prognose the upcoming signal – whether it's A or B. In the previous – random – order, the signal A was prognosed (on the basis of earlier experience) with higher probability than signal B. In the second sequence of signals, both signals are prognosed with absolute certainly – with a probability equal to 1.

Thus, *reaction time speed depends on the probability with which the appearance of a particular signal is prognosed on the basis of earlier experience stored in memory. The higher the probability of the expected signal, the faster the reaction executed in response to it.* This conclusion was confirmed also by other series of experiments we conducted [6].

3 Memory in Probabilistic Prognosis

How could we know something about what has not yet happened, but is expected to happen? The source of such information may be in the memory of the organism about its previous experience. Biological evolution and the life of each individual takes place in a probabilistically organized environment. In such conditions, memory developed as a function useful for the organism. By storing information about what events took place in the past, in which order and with what probability, the organism is able to prognose what is most likely to happen after a certain event. This kind of prognosis can naturally only be probabilistic. It allows the organism to prepare for action in advance of an upcoming situation that has not yet begun. The new situation will not catch the organism unexpectedly by surprise.

What are the necessary features of memory to serve as the basis for probabilistic prognosis? First of all – memory must store not only traces of past events, but also their sequences. Moreover, it has to store information about the probability of each sequence: with what frequency situations B, C, or D occurred, given that they were preceded by situation A.

$$P(B/A), P(C/A), P(D/A)$$

P(B/A): Probability P of situation B, given that A has already occurred (conditional probability).

With this kind of memory, the organism is able to prognose the probability of situations B, C, or D arising given that situation A has already occurred. This kind of memory not only supports the realization of Pavlovian classical conditional reflexes, where the order of stimuli is rigidly determined, but also situations with random probabilistic sequences of events.

However, memory would not support probabilistic prognosis well if it operated upon only recently acquired experience – it would be too credulous, too "light-minded". Its prognosis would depend too much on accidental combinations of recent independent events (this kind of memory is known in pathology). An example of this kind of memory could be an expectation of the following sort: "I must take bus No 5, and No 3 just left. This means the next bus will be the right one – as last time, No 5 came after No 3“.

On the other hand, a memory that doesn't forget and draws equally on the whole past life of the organism would likewise be bad – it would remain too tangential, not sufficiently adaptable to changes in the probabilistic structure of the environment. A person deprived of forgetting has been described in the scientific literature (A.R. Luria's "The Mind of a Mnemonist: A Little Book about a Vast Memory"). The patient described there didn't forget anything, and earned his living by demonstrating his phenomenal memory on stage. However, he suffered from this memory, and said he'd give a lot to get rid of it. The ability to forget is not a deficiency, but an achievement of memory. In a situation where the probabilistic structure of the living environment changes, a memory that doesn't forget would require an enormous amount of new experience to be accumulated – an amount comparable with all preceding life – for changing its probabilistic prognosis.

At the same time, forgetting is not absolute. Memory preserves information also on long-passed events. However, the more distant the event, the less clearly it‘s remembered – its "weighting coefficient" upon recall becomes lower.

This type of memory structure ensures not only sufficient flexibility of remembering and probabilistic prognosis in the face of changing environmental probabilities, but also the reconstruction of apparently "lost" information when the environment returns to its previous probabilistic states. Repeated "re-learning" of something that seems like forgotten requires less time than its initial learning. This finds its clear expression both in animal experiments and in observations of human behavior. We bring only one example.

For an extended period, a dog was fed following an auditory signal. As a result, it began to salivate after the signal and before receiving the food. Thus, information on this specific sequence of events is stored in the dog's memory. After that, however, the situation changed: the auditory signal was paired not with food, but with a painful stimulation of the paw. This caused the dog to withdraw its paw in response to the signal, and salivation ceased to be present. The dog began to behave in a way as if it had forgotten the previous sequence of stimuli and remembered only the new sequence. However, now the experiments were omitted for a period of time – no food was given after the signal, and no stimulation was applied to the paw. In this case, after a while the bell again began to provoke salivation. Thus, the behavior of the dog is such, as if it had "remembered" what was already "forgotten" [6].

When something that has been assimilated earlier on appears to be forgotten, then its subsequent learning is faster and simpler than the initial one. This means that the earlier information was not entirely wiped out from memory, it was not entirely forgotten.

The realization of probabilistic prognosis is even more effective, since memory stores information not only on the fact that situations A and B have followed each-other with a certain frequency in the past, but it also includes the situations leading up to A: NA, MA, etc. Here, the probability of an event B following an event A depends on what preceded A – whether it was N or M.

$$P(B/NA),\ P(B/MA),\ \ldots \text{ and even } P(B/KNA),\ P(B/RNA),\ P(B/LNA).$$

This property of memory already ensures the ability to plan actions that are more likely to lead to a useful result B. For example, in the case of N's appearance, to achieve situation B respective actions A have to be carried out.

The degree of retention of various events is also not uniform. Unexpected events are better remembered than expected ones. A situation that was prognosed with high probability will be remembered less well than a situation that was unlikely expected to occur. A situation that was expected to occur with absolute certainty can be entirely forgotten. This gives memory its high economy at no costs for probabilistic prognosis. If you're asked after stepping out of a bus whether there was a passenger on board with a blue suit, you're most likely unable to confidently recall whether this was the case. However, if you're asked whether there was a passenger on the bus with an Indian turban, you can say this for sure (both when such a person was on board, and if not). A situation that is unexpected and not prognosed with high certainty is remembered very well. But what is customary and corresponds well to your probabilistic prognosis may not be retained at all by memory. It has also been clearly demonstrated in experiments that the degree of remembering depends on the probabilistic prognosis of the remembered event [6]. It’s a manifestation of the economy of mnemonic functioning: making prognosis is sufficiently good in the given case also without this new information.

For the present purposes, the following features of memory have been found to be essential:

1. Mnemonic storage of information not only on what kind of events have taken place in the past, but also on their temporal order and the frequency (probability) of their possible sequences.

2. The occurrence of forgetting – not in an absolute sense, but to various degrees depending on the temporal distance from remembered events.

3. Better retention of unexpected events. Events prognosed with high probability may be not at all retained in memory.

All these features of memory prove to be highly useful for probabilistic prognosis.

4 Probabilstic Prognosis and Presetting for Action

How does the prognosis of a certain signal (or situation) affect the subsequent reaction – for example, how does it accelerate it? What kind of mechanisms ensure an improved (in particular, faster) reaction to a signal, the appearance of which at a particular moment of time has been prognosed with high probability? To answer these questions, several series of experiments were carried out [6]. These included the bio-electrical measurements of tested subjects on electromyogram (EMG), electroencephalogram (EEG), and galvanic skin reaction (GSR).

In the experimental setting, one of two possible light signals appeared on the panel before the subject. In case the signal had the form of a square, the subject had to press a button with his right hand, and if it was a triangle, he had to do the same with his left hand.

In the first part of the experiment, both triggering (light) signals had a random order with the same probability. 1,5 seconds before the light signal, a sound signal was given that was identical for both light signals. Thus, the sound signal enabled to determine the time of the light signal's appearance, but not what kind of signal it would be – and thus, with which hand to react to it. In response to the sound signal, in these conditions a pronounced increase of electrical activity was observed in the muscles of both hands to the same degree. On the EEG, an activation response was observed in occipital and sensory-motor regions of both brain hemispheres. There was a notable galvanic skin reaction. In the course of signal repetition, the electromyographic reaction gradually shifted towards the moment when the triggering (light) signal appeared, preceding it by a short interval.

Without warning the subject, in the second part of the study the experimenter would begin delivering only one of the light (triggering) stimuli to the participant – the one which required reacting with the left hand. In these conditions, the electrical activity increase of the right hand disappeared from the electromyogram. At the same time, the muscular activity of the left hand became more pronounced than in the first part of the experiment and shifted in time, approaching the moment of delivery of the triggering signal, in response to which the motor reaction occurs. The activation response on the electroencephalogram was preserved only in the right brain hemisphere (related to the left hand) and shifted forward in time, preceding the stimulus by only a short interval.

Thus, the sound signal for "attention" evoked a marked presetting of those physiological systems – first of all, muscles – which according to the person's prognosis will have to react to the yet non-present triggering signal predicted with high probability by the subject.

This study showed that the probabilistic prognosis of a specific signal (or situation) leads to a prior anticipatory presetting, expressed in the mobilization of those particular muscles which are required for responding to the expected light signal. In conditions of sufficiently uncertain probabilistic prognosis (in the first part of our study), the presetting involves a more widely distributed group of muscles. With increased determinacy of the probabilistic prognosis (in the second part of the study), the presetting becomes more local. The triggering signal doesn't catch the organism unexpectedly by surprise, but with a motor apparatus already prepared by the preset. By the same virtue, the reaction becomes faster, more accurate and economical – it spends less energy. Further series of experiments by us confirmed this conclusion and enabled to specify it to some degree [6].

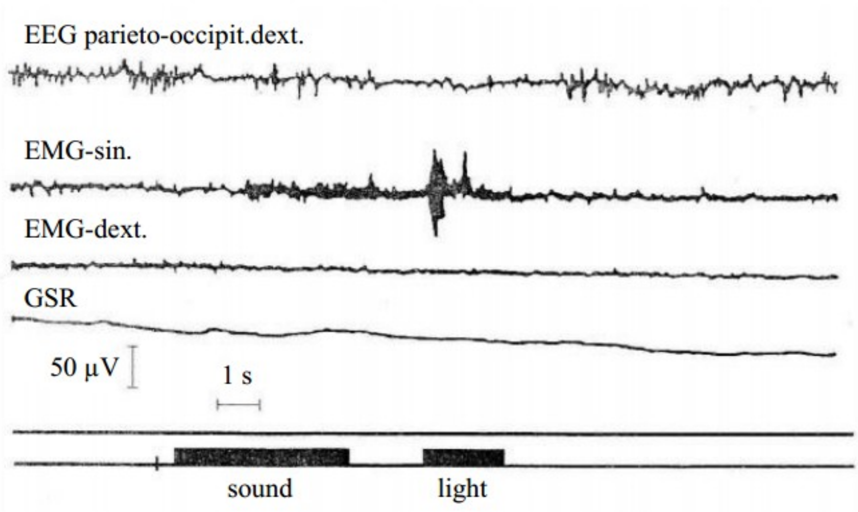

Fig. 1. The acoustic signal "Attention!" warns that the triggering (light) signal will be presented to which the subject will have to respond using the left hand. This causes a local preadjustment of muscles of the left hand.

The figure shows a recording from a section of the study. The presetting is markedly expressed on the electromyogram in the activation of precisely those muscles that will have to react to the signal – a signal that is not yet present, but the appearance of which is prognosed by the person with sufficiently high probability.

Thus, in conditions of highly indeterminate probabilistic prognosis, the presetting following a warning signal was more generalized (less localized in time and space), and the motor reaction by the subject subsequent to the triggering signal was slower. In conditions of more determinate probabilistic prognosis, the presetting was more local, more pronounced, and closer in time to the moment when the signal appears. In the latter case, the person's reaction to the signal was also quicker. As the experiment shows, the presetting is bound to the place and time of the motor reaction according to the person's prognosis.

5 Outlook

The concept of probabilistic prognosis has proven to be fruitful in various areas: in medicine, education, speech analysis and textual perception, and sports. However, how far ahead in time does the probabilistic prognosis have to "glance"? This depends on the nature of the person's activity; and on how variable and mutable the environment is where activity is realized.

The tennis and football player have to prognose the most probable location of the ball within a fraction of a second. The first aid doctor has to prognose the most probable condition of the patient that may develop in the next minutes or hours. A labor organizer at a factory has to "see" the most probable situation that may occur within several days, weeks, or months.

Good educators (including parents of a child) have to prognose the activity of a today's student in a few years and even decades – when the child is no longer a student, but will live and act independently in a world that even the pedagogue can't sufficiently clearly foresee during the studies. However, the highly important questions of education lie already beyond the problems of probabilistic prognosis, and require special treatment [7] (Feigenberg, Lavrik 2011).

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