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FEEDFORWARD, FEEDBACK AND UCM IN MOTOR CONTROL IN HUMANS

Wacław Petryński
Katowice School of Economics, Katowice, POLAND
Email: waclaw.petrynski@interia.pl / **10.02.2010 / 20.02.2010**

Abstract

From among possible movements control methods most efficient is no doubt the feedforward mode. Unfortunately, it may be adopted only in predictable environment, i.e. where the probability of achieving a desirable result by applying a given pattern of action is acceptably high. So, this control mode cannot be adopted in not predictable environment, which forces to current regulation according to instantaneous changes in environment, when the changes cannot be fully anticipated with acceptable probability. In such situation application of feedback mode, slower and involving higher information processing load is necessary. Pure feedforward and feedback modes are in fact some extreme theoretical models of movements' control, but neither of them can be applied in reality in its "pure" form. In practice some combination of both these modes has to be employed, and its theoretical description is addressed as uncontrolled manifold (UCM). However, this notion is not homogenous and unambiguous. The presented paper is devoted to its more detailed description in the light of Bernstein's theory.

Keywords: motor control, feedforward, feedback, uncontrolled manifold, Bernstein's theory.

Introduction

The problem of motor control modes in humans (and animals, too) is one of the crucial issues in motor science. The attempts to describe the whole process mathematically did not give by now satisfactory results. In this respect very promising way seems to be systemic approach. One of first scientists who developed systemic description of motor control in humans was Russian neurophysiologist N.A. Bernstein, founder of what he termed "physiology of activeness" [N.A. Bernstein, 1947; 1991; 1996]. In this theory he harmoniously combined biological, neurological and cybernetic elements. His ideas, along with newer achievements of science, may enable new description of motor control processes in humans.

1. Basic motor control modes

Two basic modes of movements' control are feedforward and feedback (Fig. 1). It has to be noted that in English the word "feedback" has many meanings. In Webster's Dictionary one finds, among others, such definitions of the entry "feedback":

1. *A reaction or response to a particular process or activity: to get feedback from a speech.*
2. *Information derived from such a reaction or response: to use the feedback from an audience survey.*
3. *A self-regulatory biological system, as in the synthesis of some hormones, in which the output or response affects the input, either positively or negatively* [Webster's Dictionary, 1989].

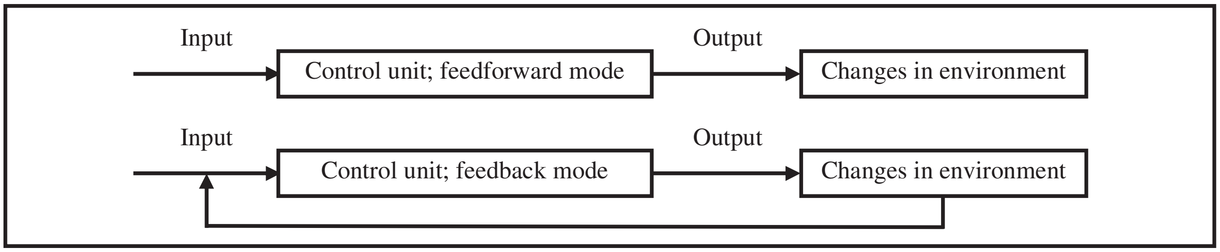


Fig. 1. Feedforward and feedback mode of control.

So, in general the word "feedback" may denote either:

- INFORMATION, received after a given task or part of the task has been already performed, or
- COUPLING of information received after the action with input to information processing system before next action starts.

Across a similar problem one comes with the verb "to control". In English it has, among others, the following meanings:

1. *To exercise restraint or direction over; dominate, regulate, or command.*
2. *To test or verify (a scientific experiment) by a parallel experiment or other standard of comparison* [Webster's Dictionary, 1989].

Looking at Fig. 1 one may learn that basic process in movement management is feedforward process; such a management is described with the word "control". If all goes right, there is no need to apply any other action. However, if something goes wrong, feedforward mode collapses and it becomes necessary to add a feedback loop. Verifying, whether it is necessary or not, is termed in English also "control".

In general the word "control" may denote either:

- STEERING or MANAGING, or
- CHECKING or VERIFYING.

Feedforward and feedback processes are also termed “open-loop control” and “closed-loop control” [R.A. Schmidt, T.D. Lee, 2005; R.A. Schmidt, C.A. Wrisberg, 2008; M.L. Latash, 2008]. I suggest removing these terms from motor control dictionary, because according to Ockham’s razor rule (*entities must not be multiplied beyond necessity*) there is no need to use two different terms for the same phenomena. Moreover, the term “open loop” is internally incoherent, because if something is open, then it is no longer a loop. In fact, the basic control mode is feedforward one. Feedback mode may be described as small feedforward chunks accompanied later by feedback process. The word “chunk” has been used here not accidentally. According to G.A. Miller, human memory may process at once maximum 7±2 chunks of information [G.A. Miller, 1956], so one feedforward chunk may be compared to chunk of information (a solution of a task or partial task, worked out in mind) which initiates some motor action. Feedback process, including identification of changes in environment, brought about by just being ended action (first meaning of English word “feedback”) and adjusting next actions to it (second meaning of “feedback”) is characterized by high flexibility. However, the cost of each sensorimotor activity includes two components: physical (mechanical) effort and information processing load. To make such activity economical, it is necessary to reduce both these components to as low level as possible. The mechanical effort results from environmental conditions and its reduction is hardly possible. On the other hand, the information processing load may be significantly reduced and just here one may look for higher efficiency of sensorimotor activities, e.g. in competitive sport. The efficacious way leading to information processing load reduction makes the “feedforward chunks” bigger and bigger. Just this process makes the basis of gaining skill.

The “feedforward chunks” are theoretically described as “uncontrolled manifolds” (UCM) [J.P. Scholz, G. Schöner, 1999]. This term is highly scientific – the term “manifold” comes from topology – but is not coherent with existing motor control terminology. Moreover, it is quite confusing, because its proper name should read “externally uncontrolled manifold”. Inside the “manifold” – or, more coherent with motor control terminology, inside the “feedforward chunk” – all partial processes are controlled. However, there is no stimulus-response constant mapping inside the feed forward chunk (UCM). The essence of the feed forward chunk may be succinctly illustrated by the minimal intervention principle as stated by E. Todorov and M.I. Jordan (2002):

In a wide range of tasks, variability is not eliminated, but instead is allowed to accumulate in task-irrelevant (redundant) dimensions. Our explanation of this phenomenon follows from an intuitive property of optimal feedback control that we call the “minimal intervention” principle: deviations from the average trajectory are corrected only when they interfere with task performance [E. Todorov, M.I. Jordan, 2002].

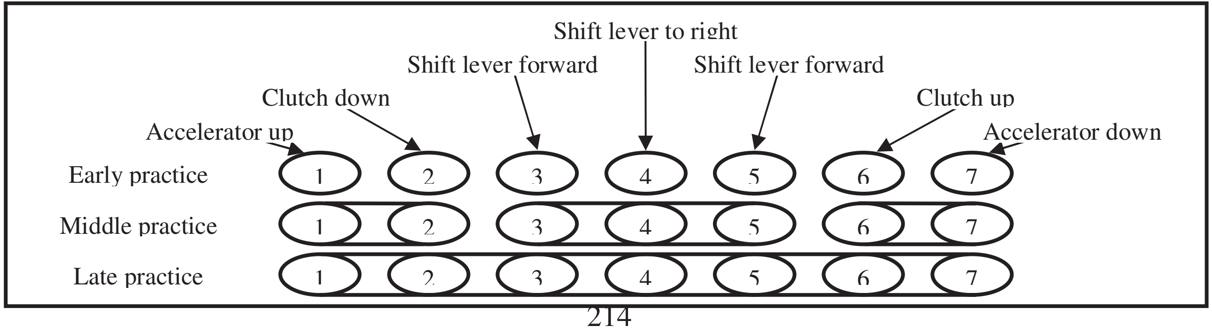
The phenomenon being a manifestation of feedforward chunks action has been described by Bernstein already in twenties of 20th century. He worked then in Work Institute in Moscow and his task was to research the hammer hit made by blacksmith, to teach novices more efficiently. He discovered that hammer’s trajectory is different at each hit performed by novice. However, to his surprise, also in skilled blacksmiths each hit had its own, distinct trajectory. Bernstein termed this phenomenon “repetitions without repetitions” [I.M. Feigenberg, 2004; M.L. Latash, 2008]. The only difference was that the hits performed by skilled blacksmiths always met the desirable point (this phenomenon is now popularly termed “equifinality”) while novices’ hits – did not.

A hammer’s hit is typical ballistic movement, i.e. there are no possible any corrections, when started. What informational mechanism controls, then, the different hammer trajectories? And, what’s more interesting, what makes them to meet the desirable point? N.A. Bernstein already in 1935 described this phenomenon by means of topological manifold. Moreover, he formulated the following “Law of Equal Easiness”:

In each structural scheme, which may perform many different elementary processes belonging to the same specific manifold, the lines of equal easiness suit these directions inside the manifold, using of which does not change neither structure, nor activity principles of the scheme [N.A. Bernstein, 1975].

The process of building and expanding the feedforward chunks may be illustrated by “gearshift analogy” (Fig. 2) by Richard Schmidt and Timothy Lee [R.A.Schmidt, T.D.Lee, 2005, p. 423].

Fig 2. Gearshift analogy (R.A. Schmidt, T.D. Lee, 2005; by permission of Authors).



The feedforward chunk at middle practice level is greater than those at early practice and smaller than at late practice one. So, in motor learning the process of chunk's size increasing proceeds until optimal size of the chunk is achieved, or such a size which guarantees best combination of swiftness, flexibility, stability, physical effort and information processing load, i.e. optimal efficiency. It has to be noted that each chunk has its own internal structure, which gives some flexibility to it. So, a skilled driver can drive different cars (with manual gearbox), even if he has to drive a specific model for the first time in his life.

The feedforward chunk dimension has still another consequence. Taking into account that – according to Miller – a human may process simultaneously at most 7±2 chunks of information, a novice has to engage all his information processing capabilities in gear shifting (7 chunks), while experienced driver engages only one chunk and has at least six other ones "free". It is to be noted that such "chunk growing" runs at the same information processing level, or "rung" of "Bernstein's ladder".

2. Motor control system in humans: the Bernstein's ladder

While building a systemic model of human motor control mechanisms, N.A. Bernstein analysed the development (which not always was a progress) of living creatures' nervous system along with their motor capabilities in the course of whole evolution [N.A. Bernstein, 1947; 1991]. He especially focused his attention on vertebrates. Basing on his analyses, and previous ideas by John Hughling Jackson [N.A. Bernstein, 2003], Bernstein had built a five-level model of human movements' management. It is founded on three primary, clearly recognizable principles (though Bernstein himself never listed them as below).

1. Each motor performance has its main control level where performer's attention is focused.
2. The lower levels make "background" for the main one and work without engagement of performer's attention; they work automatically.
3. In the course of biological evolution, the emerging of higher level of motor control does not suppress, but increases the capabilities of lower ones.

In humans Bernstein ascribed particular levels of motor control (cybernetics) to the particular elements of the CNS (neurophysiology), and to specific motor capabilities (motor control). Then he assembled them into one coherent system which may be termed "Bernstein's ladder" (Fig. 3) [W. Petryński, J.M. Feigenberg, 2009].

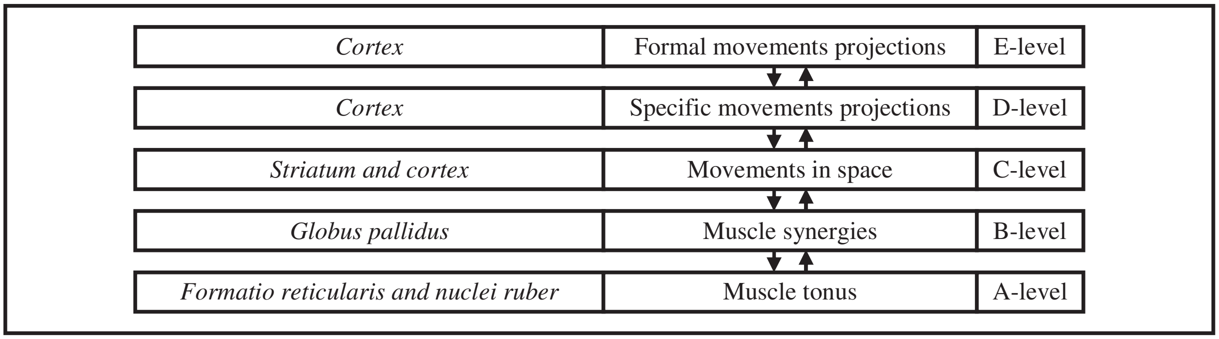


Fig. 3. The five-level Bernstein's ladder – a system of motor control in humans.

Unfortunately, Bernstein himself never made such a diagram; thus, he never termed it "Bernstein's ladder". Nevertheless, though the full presentation of systems theory has been made by Ludwig von Bertalanffy only in 1968 [L. Bertalanfffy, 1968], the model being created by Bernstein already in 1947 is fully consistent with this theory.

According to systems theory, the system is a layered structure of information exchange and processing, built according to following principles:

1. Principle of layers hierarchy: the lower layers (levels) perform the tasks according to orders received from the higher ones.
2. Principle of layers autonomy: each layer performs his particular task without any additional information, i.e. higher levels do not interfere in activities of lower ones,

The listed principles remain in full accordance with two first Bernstein's ones quoted earlier. Moreover, an important consequence of the two principles is the third one, formulated by J.M. Morawski:

3. Principle of scales conformity: each layer uses a definite code of information processing, including temporal relations, "tailored" specifically to its needs [J.M. Morawski 2005].

In short, the scales conformity principle remains in keeping with James Gibson's statement that "perception is specific to information" [M.T. Turvey, 1999]. Nevertheless, Gibson's statement, however accurate it is, unveils only a small peak of the huge iceberg.

Let us consider more closely the latter principle. It means in fact that at given level of a system the three main compounds occur, i.e.:

- The input data – parameters of environment and details of a task,
- The process of information transformations,
- The output data – the response worked out as a result of processing,

They have to be described with the same code, to make possible their common functioning. Moreover, multilevel structure of the whole system of information processing in humans results from rudimental rule of “nature economy”, illustrated e.g. by Sir William Rowan Hamilton with the principle of least action [R.S. Ingarden, A. Jamiołkowski, 1980; F.W. Byron, R.W. Fuller, 1973] or Israel M. Gelfand and M.L. Tsetlin with the principle of minimal interaction [M.L. Latash, 2008]. So, it would not be justified to apply too sophisticated code to simple tasks, because it would be wasteful; probably more effort would be necessary to operate the code itself than to process information. On the other hand, using too primitive code to more complicated ones would be inefficacious.

Usually both contactception and teleception is described with one term exteroception. However, in presented analyses it is necessary to make clear differentiation between contactception and teleception. The former enables receiving the stimuli from the part of space limited by outer surface of a body (skin), while the latter – from the part of space which may be recognized by teleceptors (mainly eyes and ears). Moreover, the quantity and quality of teleceptive data is so great and sophisticated as compared with contactceptive data that already in 1909 Sir Charles Sherrington had stated that in the course of evolution just the teleceptors made the brain [N.A. Bernstein, 1947].

The teleceptors (C-level) caused immense evolutionary leap in information processing, which greatly extended living creatures’ motor capabilities. They enabled identification of three-dimensional space, which in physical reality is inseparably joined with time.

The other, not less significant revolution was the formation of abstract language (D-level). At first glance the situation was clear: the informational carrying capacity of images is apparently much greater than that of sounds. Important is, however, not only how much information a given carrier contains, but also what is the quality and density of the information. The language is made of words, and sounds are only the physical carriers of words. Andrzej Wierzbicki wrote: *... the invention of a speech was extraordinary shortcut, which changed the character of evolution. It turned out that we may process the signals from environment 10^4 more simple than before. This enabled intergenerational transfer of information and tradition, thus the development of cultural and intellectual legacy of mankind – termed by Karl Popper “the 3rd world” – had been initiated. The biological evolution of a human slowed down (some biologists argue that it stopped at all), but the cultural, intellectual and civilization evolution speeded up* [A.P. Wierzbicki, 2008].

Thus, the visual stimuli may carry much more “rough information”, but in words – the natural carriers of which are sounds – the information is much more condensed.

It seems that in the course of evolution the development of sensory organs went ahead of information processing until C-level had been created. Then the information processing capabilities “overtook” the development of sensory organs. For example, until now human has no specific sensory organs for receiving words. Apparently the development of sensory organs stopped at C-level. An individual may receive only sounds (C-level), and the process of words recognition, i.e. ascribing some meaning to the sets of sounds, comes only in attention at D-level.

It has to be noted that though in Bernstein’s theory particular levels of motor control are quite clearly discernible, they are not separate entities, co-operating with each other as if they were independent mechanisms. On the contrary, they altogether make a coherent, inseparable system. Here illustrative are words by Michael T. Turvey:

> *Reflexes, for example, were not elements of coordinated actions for Bernstein but, rather, elementary coordinated actions and, therefore, part of the problem of coordination rather than contributors to its solution* [M.T. Turvey, 2002].

Such a view gives some homogeny to all motor actions and eliminates possible division into reflexes and other sensorimotor actions.

3. Feedforward chunks and Bernstein’s ladder

Let us take into consideration two conclusions resulting from Bernstein’s and systems theory:

1. Each motor control level has its own code of information processing and storing,
2. According to general nature economy rule, in a skilled person a given task (or partial task) is solved at the lowest possible motor control level.

So, each control level has to create its own feedforward chunks, described with its own, specific code. At A-level such a code is built of intrinsic stimulation; at B-level – of contact stimulation; at C-level – of images (generalized); at D-level – of words; at E-level – of symbols. Thus, at A-level the internal pattern of such feedforward chunk is reflex arch; at B-level – routine; at C-level – schema (as by Schmidt); at D-level – specific motor programme; and at E-level – generalized motor programme [W. Petryński, 2008]. Summing up, one may state that in humans the A-level is “feeling-in-hand” level; B-level is “movement’s harmony” level; C-level – “measure-by-eye” level; D-level – “motor common reason” level: and E-level – “motor fantasy” level (Tab. 1).

Table 1. Selected functions of particular levels of motor control.

Bernstein’s level	Information processing code	Feedforward chunk	Field of action
A	Intrinsic stimulation	Reflex arch	“Feeling-in-hand”

B	Contact stimulation	Movements routine	“Movements harmony”
C	Images	Motor schema	“Measure-by-eye”
D	Words	Specific motor programme	“Motor common reason”
E	Symbols	Generalized motor programme	“Motor fantasy”

Each of the codes enables intelligent, intuitive and instinctive processing of information. Thus, in Bernstein’s theory it is not justified the division into “consciousness” (verbal information processing code) and “sub-consciousness” (non-verbal information processing code). John Eccles and Karl Popper described how a dog is able to BUILD A THEORY CONCERNING FUTURE [I.M. Feigenberg, L.P. Latash, 1996]. Because it cannot use the verbal code, thus other codes are efficacious and efficient enough to enable information processing reaching into future, i.e. building the genuine theory. A human uses higher levels – D or even E one – to do it, but a dog has nothing like this to its disposal and has to use the C-level code. As seen from this example, the image code is efficacious enough to enable such construction, though, of course, not as advanced as built of words or symbols. As seen from Bernstein’s ladder, in motor control the feedforward chunk (UCM) is a “slave unit”, i.e. it works at given level of motor control system “on request” of some higher level. For example, looking at Fig. 2 one may conclude that some cue from D-level (tachometer reading) or C-level (engine sound, driving force) induces a driver to shift the gear, then the feedforward chunk(s), as presented in Fig. 2, is started and the sensorimotor action is being performed (B-level).

4. Motor control and mathematics

The beauty, elegance and “purity” of mathematics make many scientists to overestimate its value. Many of them try to look for solutions of motor control problems in humans just by describing them in categories of numbers and functions. Unfortunately, according to Bernstein’s theory such a scenario seems to be hardly probable (Fig. 3 and Tab. 1).

Mathematical theories use only one code of information processing (numbers, in general), which is not “native” to neither of reality perception levels in humans. Trying to describe human reasoning with, say, Linear Quadratic Regulation or Linear Quadratic Gaussian Estimation [E. Todorov, M.I. Jordan, 2002], it has to be taken into account that the Nature did not equipped humans with Kalman filter [R. Grush, 2004] or estimator of Lyapunov exponent. So, mathematics may be very valuable for checking the correctness of reasoning (in limited area and when mathematical descriptions are constructed properly), but it seems hardly possible that it will create ready solutions. Mathematics may produce an image parallel to reality, but it is not able to replace the reality; it not “sits” inside human minds. In other words, mathematics, however attractive it is, do not release a scientist from thinking, at least in the field of motor control.

In humans situation is especially complicated by the fact that *Homo sapiens* uses at least five different codes, specific to each of the movements’ construction level. On one hand such a structure enables adjusting a proper code to proper task: a human does not need to use fantasy (E-level) to press the clutch pedal in a car (B-level action). On the other hand, a SYSTEMIC construction of information processing in humans makes great challenge to science. The main question is how the inter-level transformation of information happens? Just such transformation makes the dynamics of a system [J.M. Morawski, 2005]. Unfortunately, by now scientists have no idea, how to solve this problem.

There is still another serious difficulty in motor control. Many scientists prefer experimental method of research. Usually, the hypotheses and theories, if not founded on “stiff” experimental data, are at least “suspected”. However, the Bernstein’s theory marks serious limits to experiments. There are only two “input gates” from environment to information processing system in humans, at B- and C-level, and one “output gate” – at A-level (Fig. 4).

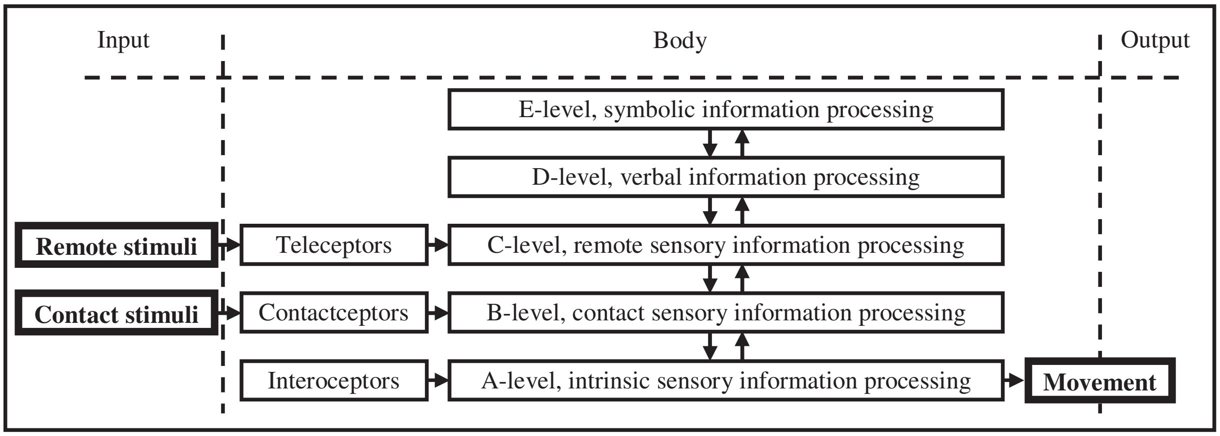


Fig. 4. Input and output „gates” to information processing system in humans.

By the way: according to Antonio R. Damasio there are five specific "input gates" to brain: vision, hearing, touch, taste and smell [A.R. Damasio, 2002]. This is fully coherent with classification based on Bernstein's theory, because vision, hearing and smell may be categorized as "remote stimuli gate" (C-level), while touch (in general) and taste – as "contact stimuli gate" (B-level).

At B-level a human may receive tactile stimuli. They are poorly differentiated, so the variety of information which may be ascribed to them is also poor. Moreover, the part of space, from which stimuli may be received, is limited by outer skin surface. At C-level a human may receive remote stimuli. Their great variety enables ascribing rich and differentiated information to them and to observe a space much more extensive than one's own body dimensions. Moreover, teleceptors enable discovering (though in limited range) one more very important element of reality: the time. And this is all. *Homo sapiens* has no specific sensory organs to receive stimuli at verbal D-level or symbolic E-level. Thus, we can observe experimentally the interaction stimulus-response only at B- and C-level (assuming that information is not processed at higher levels). As far as D- and E- level is concerned, we have to build hypotheses not founded "stiffly" on hard and unambiguous experimental basis. In other words, in this region of motor control the "centre of gravity" of scientific work has to be shifted from observations and measurements to thinking and hypotheses construction. This was illustratively expressed by Mark Latash, who stated that "motor control is the physics of unobservable objects" [M.L. Latash, 2008].

Conclusion

In the paper two main information processing methods in humans, feedforward and feedback, have been presented as extreme modes of motor control. In practice, some combination of them is usually adopted. It may be termed "feedforward chunk" and its theoretical projection may be identified with uncontrolled manifold (UCM). Feedforward chunk may control a task or sub-task independently, without any external supervision. Such a supervision becomes necessary only when action parameters go beyond acceptable limits; then the feedback mode has to be adopted, which makes the action more flexible, but also much slower. Moreover, it engages a lot of attention, which otherwise could be directed towards other tasks.

The most important component of each control mode is anticipation. The more predictable environment, the more control load may be shifted towards feedforward mode.

In humans information processing is, however, quite complicated and may be depicted with 5-level theoretical model, the Bernstein's ladder. At each of "rungs" of the ladder a specific code of information processing and storing is applied. Thus, in humans there are at least five kinds of feedforward chunks: reflex arch (A-level), routine (B-level), schema (C-level), specific motor programme (D-level) and generalized motor programme (E-level according to Bernstein's theory).

The applicability of experimental method and mathematics in researching the human motor behaviour is also limited. In human the spheres of emotions, intellect and movements are intertwined with each other and make one inseparable system. Great part of this is by now not liable to experimental learning ("motor control is the physics of unobservable objects", as stated by Latash). Moreover, most elegant and efficient language of science, the mathematics, seems to be not fully suitable to describe information processing in humans or other living beings.

Important are also terminological issues. It has been suggested to remove from scientific dictionary the terms "closed loop" and "open loop", because the latter seems to be illogical. Moreover, the main task of science is bringing order into already possessed and newly gained knowledge, so adopting different terms to the same notion violates the "Ockham's razor" rule. Instead of "open loop control" and "closed loop control" it is suggested to use "feedforward" and "feedback" mode, respectively. Moreover, it has to be stressed that in English term "feedback" has two meanings – information and coupling – and that the difference between them is significant. Another terminological problem relates to the verb "to control" which means either steering some process, or checking its correctness. The last remark concerns the term "uncontrolled manifold". It is highly scientific, indeed, but not easily understandable to motor control specialists. Thus, it was suggested to use the term "feedforward chunk" which properly expresses the very meaning of this notion and is congruent with already existing motor control terminology.

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