Commentary on **Anatol G. Feldman and Mindy F. Levin (1995). The origin and use of positional frames of reference in motor control. BBS 18:723–806.**

Abstract of the original article: A hypothesis about sensorimotor integration (the λ model) is described and applied to movement control and kinesthesia. The central idea is that the nervous system organizes positional frames of reference for the sensorimotor apparatus and produces active movements by shifting the frames in terms of spatial coordinates. Kinematic and electromyographic patterns are not programmed, but emerge from the dynamic interaction among the system's components, including external forces within the designated frame of reference. Motoneuronal threshold properties and proprioceptive inputs to motoneurons may be cardinal components of the physiological mechanism that produces positional frames of reference. The hypothesis that intentional movements are produced by shifting the frame of reference is extended to multi-muscle and multi-degrees-of-freedom systems with a solution of the redundancy problem that allows the control of a joint alone or in combination with other joints to produce any desired limb configuration and movement trajectory. The model also implies that for each motor behavior, the nervous system uses a strategy that minimizes the number of changeable control variables and keeps the parameters of these changes invariant. Examples are provided of simulated kinematic and electromyographic signals from single- and multi-joint arm movements produced by suggested patterns of control variables. Empirical support is provided and additional tests of the model are suggested. The model is contrasted with others based on the ideas of programming of motoneuronal activity, muscle forces, stiffness, or movement kinematics.

In search of control variables: A systems approach

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Abstract: Motor processes cannot be modeled by a single (unified) model. Instead, a number of models at different levels of description are needed. The concepts of control and control variable only make sense at the functional level. A clear distinction must be made between external models and internal models. General Systems Theory provides the framework for a proper treatment of these issues.

In the target article by Feldman & Levin (F&L) (1995) a number of issues are discussed that provide a good opportunity to describe the role that General Systems Theory (GST) can play (see Dalenoort 1990). Given the limitations of our cognitions, we cannot in general hope to find for any system a single "correct model." According to GST, the best one can do is to construct a set of models, each of which captures a certain aspect of the system being described. (GST must be distinguished from dynamical systems theory. The latter concerns physical models; control cannot be part of a physical model; [see also Dalenoort 1984].)

Bernstein (in the 1930s, see, e.g., Bizzi et al. 1992) made clear that at least three levels of description are involved in motor control, with a corresponding variety of models:

(1) the system as a whole, that is, the subject, his desires and aims;

(2) the level of subsystems or modules, for example, the arm, muscles, and the central nervous system; and

(3) the physiological level, neurons, membranes, muscle spindles. A further increase in number of models is due to the variety of choices of system boundaries, for example, car and driver as two interacting systems, or car and driver as a single system.

The problems with the attempt to reconcile the models, and to find a single model, come out clearly in F&L's target article, and in the commentaries. In my opinion, most of the controversies evaporate if each model is considered within its own context, and the models are interrelated appropriately (Dalenoort 1990).

A clear distinction must be made between the "internal model a system uses," and the models we make as investigators. If it is not possible to indicate how and where the variables are represented in the system, it is no use to assume the system uses a "model," or that any of the variables can serve as a "control variable." It is probably the architecture of our artificial systems that makes us think that the concept of control is valid at all levels of description. As a consequence, I propose a third condition, above the two proposed by F&L, to decide whether a variable can serve as a control variable: within a given model, the values of a control variable must be represented, and this representation should have a direct action on the process.

F&L used a good example to demonstrate the role of control variables, which is the positions of the handles of a motor car. For a car plus driver the velocity and the direction in which the car is moving (as a function of the position of the steering wheel) are essential control variables. The first variable is explicitly represented on the speedometer, but the figure is not used by the car itself. We, as observers, can make statements about what happens in the engine, gearbox, and differential, and express our account in terms of the speed.

In section 3, F&L assume that the difference between the actual muscle length and the threshold is independent of the length itself, and can therefore serve as a control variable. A change in length of a muscle originates in physiological processes, like contraction of muscle spindles. Because there is a maximum length of a muscle, the physiological changes must be different for different lengths of a muscle; the system must be nonlinear. As a result, the same change has very different consequences if the muscle is near its maximum length compared to the length at rest. Also, fatigue plays a role in the effect of a change. Another argument is that the length of a muscle, changes in length, or its equilibrium length, cannot be directly represented in the CNS; no yardstick is available.

F&L mention an interchange of cause and effect as a possible consequence of a rearrangement of variables. An interchange of cause and effect is never possible. One can only change the representation from a goal-directed one into a causal one, or the reverse. A fundamental problem is to make clear the correspondence between both types of representations (see Dalenoort 1990).

In section 3 it is argued that the movement of a body can be produced by shifting the frame of reference. Usually such shifting is only a Galilean transformation in the observer's model, and it cannot have the consequence that the individual experiences movement. This can only be the case if the frame of reference is represented in the CNS of the subject. One of the big problems of the research on natural neural networks is to discover how all kinds of variables are represented, as has become very clear in the research on artificial neural networks.

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Authors' Response

Control variables in movement production: An experimentally derived concept

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Abstract: The basic concepts of motor control formulated in our target article were derived from specific experiments, a fact which is disregarded in Dalenoort's comments. A purely academic approach to motor control may not result in a clearer understanding of control concepts.

Dalenoort suggests that general systems theory (GST) provides the framework for a proper treatment of motor control issues. This suggestion would be more convincing if Dalenoort gave some constructive examples illustrating the advantages of such a treatment. Instead, he insists that "GST must be distinguished from dynamical systems theory" since the latter, according to Dalenoort, "concerns physical models," that is, models without control. We do not share the opinion that dynamical systems theory is not concerned with control issues. One of the basic ideas of our target article (Feldman & Levin 1995) is that variables characterizing the motor output (including electromyographic signals, muscle force, length, velocity, system's actual or equilibrium position and trajectory, as well as the movement direction) are not programmable but emerge from the *dynamic* interaction between control levels, other components of the system, and the environment. Thus, dynamical systems theory is a natural framework for the description of the system's behavior.

Dalenoort also insists that one should construct a set of models that capture the properties of motor subsystems and forget about constructing a unified model of motor behavior based on the integration of the properties of various subsystems. Note that the purpose of our target article was to formulate some experimentally derived concepts, for example, control variables (CVs), which may be a prerequisite for the understanding of motor behavior at any level of description, from a single motorneuron to the motor system as a whole. Only then can we be in the position to create a unified model of motor control integrating all the basic properties of neuromuscular and sensory subsystems.

A major point of Dalenoort's concerns our definition of CVs. Our definition consists of two points. (1) CVs may be specified by the nervous system *independently* of current external conditions and the variables characterizing the motor output. In other words, the nervous system has the option (which is realized in some behaviors) of specifying a constant value or a particular timing of a CV and of maintaining it regardless of the movement and of changes in external conditions and/or afferent feedback; (2) CVs may influence the motor output.

Dalenoort's suggestion that we assume that "the difference between the actual muscle length and the threshold is . . . a control variable" is incorrect because it is inconsistent with point (1) of the definition that CVs should be independent of variables characterizing motor output (in this case, actual muscle length). Dalenoort goes on to suggest that our definition should be complemented by the statement that "the values of a CV must be represented in the system, and this representation should have a direct action on the process." This suggestion is difficult to discuss because of the lack of a clear definition of the term "representation" in Dalenoort's comments. At the same time, point (1) of our definition concerning the possibility of independent modification of CVs actually implies that the nervous system does, in some way, represent CVs. For example, Weeks et al. (1995) analyzed the rapid adaptation of arm movement to unexpected changes in external load conditions. It was demonstrated that, in sequential trials, the system reproduced the CV specified after correction in the previous trial. These results imply that after each trial a representation of the set of CVs was retained in short-term memory and then reproduced in the subsequent trial. This strategy resulted in the predictable positional errors described in the study. Thus, Dalenoort's requirement that CVs be represented in the system and that they influence motor outcome are satisfied. An extension of our current definition to include an explicit statement about the representation of CVs would be redundant.

Dalenoort also comments on the target article's main idea that active movements are produced by shifting the frame of reference. Trying to criticize this point, he indicates that usually "such shifting is only a Galilean transformation in the observer's model" without influencing movement. A similar statement can indeed be found in our target article (sect. 3). What escaped Dalenoort's attention is that we also illustrate the notion that, because of the specific form of integration of sensory and control signals at any level of the motor system, the generation of neuronal activity and muscle forces is frame-dependent, that is, it depends on the position of the origin of the frame of reference. As a consequence, shifting the origin inevitably influences the neuronal activity and movement performance. According to Dalenoort, this requires a representation of the frame of reference in the CNS of the subject. He may possibly be right but his proposal would be clearer if he defined the term "representation."

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