International Journal of Theoretical Physics, Vol. 33, No. 1, 1994

Dissonance: A Nervous System Analog to Quantum Incompatibility

Gin McCollum[1]

Received July 22, 1993

Motor control in animals, including development of motor control, has an important discrete aspect, even though the mechanics of body movement are well described by continuous mathematics. Physiologically, movement is controlled in large part as transitions between and efforts to remain within discrete spatial regions, such as chair seats and doorways. Based on observations in human development and rehabilitation, this study continues efforts to unify discrete with continuous aspects of motor control. The continuous aspects arise mostly from mechanics; the discrete, from physiology.

1. Quantum Mechanics and This Model of Motor Control Have in Common: Continuous and Discrete Aspects, and Separation of Variables (As in Noncommutativity)

To simplify motor control, the nervous system separates variables into "rules of thumb" or simple implementation strategies governing different parameters, even though the combination of implementation strategies may be physically incomplete or redundant. In contrast, physical models must not achieve simplicity at the expense of incompleteness or redundancy. However, in quantum mechanics, a physical measurement separates one variable (e.g., position or momentum) from all others. Without such separation, there could not be quantum incompatibility.

Foulis and Randall (1985) have studied the structure of manuals of measurements. An organism may have an analogous manual of implementation strategies. Rather than commutativity, the important relations may be expressed by a set of rules of combination, generating sets of implementation strategies that combine to allow motor acts.

[1]R. S. Dow Neurological Sciences Institute, Good Samaritan Hospital and Medical Center, Portland, Oregon 97209.

0020-7748/94/0100-0041$07.00/0

A combination of implementation strategies that gives an appropriate motor act in healthy organisms may give a faulty or dissonant motor act in unhealthy organisms such as human patients and in other circumstances the combination was not designed for. In those cases, the implementation strategies can be thought of as dissonant with each other.

2. d-Spaces Combine a Continuous Space with an Ordered Structure Determined by Physiologically Important Subsets

This section defines a set of discrete regions of body position space crossed with physical space and relations between them. Then an analog to physical movements is defined. Mathematics relating the discrete regions which are of interest to and available to patients could yield more general explanations of the rehabilitation processes, and perhaps eventually lead to suggestions for therapy. However, many factors must be brought together, including range of joint motion, pain, muscle strength, how muscles are activated in combination, sensory loss, and use of senses, besides body mechanics. Body mechanics, including relationships between force, torque, linear and angular momentum, etc., is Newtonian mechanics applied to the body. However, that is not a good place to start in relating the many factors together, because force and torque are produced by muscles and muscle combinations, gravitational force transfer depends on body position, and mechanics is standardly expressed in equations describing continuous mathematics. Muscle combinations are naturally discrete, because muscles are anatomically distinct from each other, but muscle use and its result depend on body position and movement. After considering many options, it seems that simple position in space may be the best place to start. A discrete structure can be built based on the linear space descriptions of physical space and joint angle space.

Definitions. A *d-space* is a set $\{D_i\}$ of discrete regions of a body position space B crossed with physical space P, with two relations on $\{D_i\}$. (In most figures, the cross-product is not depicted in the usual way, because of the number of parameters.) One relation is a partial ordering: a restriction of inclusion in $B \times P$ to the regions in $\{D_i\}$. The partial ordering is reflexive, antisymmetric, and transitive. The other relation is a *contiguity relation* on $\{D_i\}$, which holds only between elements that are incomparable according to the partial ordering. The contiguity relation agrees with contiguity in the body position space, and is reflexive, symmetric, and not transitive.

A *coincidence* C_i is a totally ordered subset of $\{D_i\}$ that includes the null set.

Consider two coincidences, C_1 and C_2. They have some regions in common, at least the null set. Let the regions not in common be $\{E_i\} \subset C_1$ and $\{F_i\} \subset C_2$. Then C_1 is *contiguous* to C_2 if every F_i contains an F_k that is contiguous to an E_j, and every E_i contains an E_k that is contiguous to an F_j. A *coincidence sequence* is an ordered set of pairwise contiguous coincidences.

3. One Physiologically Important Region is the Set of Positions in Which One Can Stand Upright

Force and torque are exerted and transferred between limbs contacting discrete mechanical structures, such as a hand on a wall and a foot on the floor. An important case of transferred force is gravitational force transferred to the support surface in erect stance. Human bone and muscle configurations only allow a person to stand upright within a region about erect stance, the "stability cone."

When patients first try to sit or stand after suffering a stroke or trauma, their functional stability cones may be narrow or off-center (Fig. 1). Their stride may be considerably shorter, to avoiding an unbalanced position right before footfall. There is a similar unbalanced position in flopping into a chair, just before hitting the seat; it may be better for a

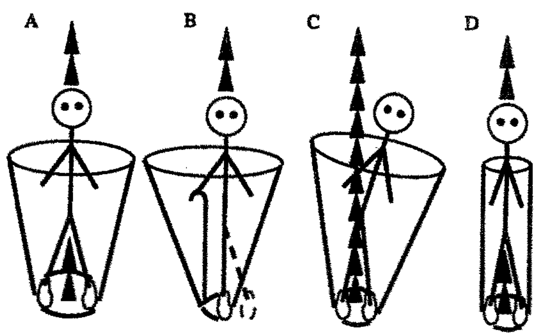

Fig. 1. Varying functional stability cones: regions in which subjects are comfortable standing. The cones are only schematic, not accurate, and are drawn wide for clarity in the differences between them. A. Healthy person with upright cone. B. Person with mechanical impairment of one leg, so that the cone is not centered with respect to the legs. There is no impairment of balance perception, so the cone is upright with respect to gravity. C. Person with impairment of balance perception, either sensory or in the central nervous system, resulting in a tilted cone. Such a person is unwilling to lean to the right, but tends to fall to the left by leaning too far. D. Person with an unusually narrow cone. This might be a child who has just achieved independent stance or a patient with a mechanical or perceptual impairment.

patient to learn to hold on, avoiding unbalanced positions. Relationships between joint mobility, muscle strength, perception of balance, and other factors often explain movement patterns in patients during rehabilitation.

The figures concentrate on d-spaces used to model walking. Steps move from stability cone to stability cone through atoms that may or may not be balanced. The atoms can be suppressed in describing particular walks. In developmental and rehabilitation research, it is of practical benefit to relate people's stability cones to the sets of steps they take. The relationship can be used to find the constraints that relate sets of steps to stability cones or other physiologically important spatial regions.

4. Biological Tasks Are often So Complex That an Animal Chooses to Implement a Solution Using Strategies That Are Sufficient but Not Necessary

The task of walking, for example, can be accomplished in many ways, given a particular body, planet, and terrain. The set of possible walks determines a set of trajectories in a d-space or a continuum with appropriate joint and physical dimensions (Figs. 2–4). An animal can choose a

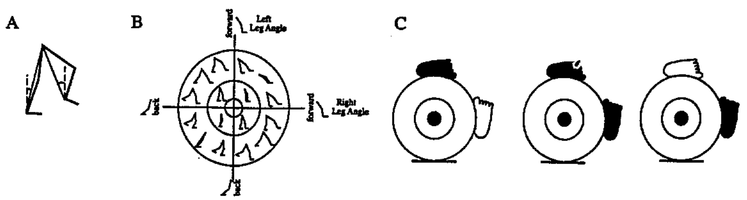

Fig. 2. Diagrams to be used in illustrating d-spaces. A. Definition of leg angles to vertical in the sagittal plane. Heavy lines are stick figure human legs. Dashed lines show the direction of gravitational vertical. Light lines join the hip to the ankles; the leg angles are the angles between these light lines and the vertical, as indicated by arcs. B. Two-dimensional leg angle space, with one axis for each leg. The axes are used to develop a schematic diagram to approximately display relations between regions of body position space. In the case of particular patients, more accuracy would be used where it is needed. The center circle includes erect stance at the origin and small variations around erect stance. The second circle contains small deviations from the vertical, still within the mechanical stability cone, plus foot separations involving small leg angle displacements. Between the second and outer circles, deviation from the vertical with the feet together is mechanically unbalanced, but some other positions are balanced, depending on the supporting foot or feet. C. Narrow region around erect stance. Which foot or feet are supporting the body are indicated in each diagram by filling in the foot. This is a notational short cut, abbreviating the distance to the floor as contact or no contact. Even though it is possible to have a foot in contact with the floor and not available to bear weight (for example, because of pain or for mechanical reasons), for the purposes of this paper it will be assumed that a filled in foot is in contact with the floor and available to bear weight. The position of erect stance is balanced for each support configuration, so each diagram is underlined, indicating a balanced position.

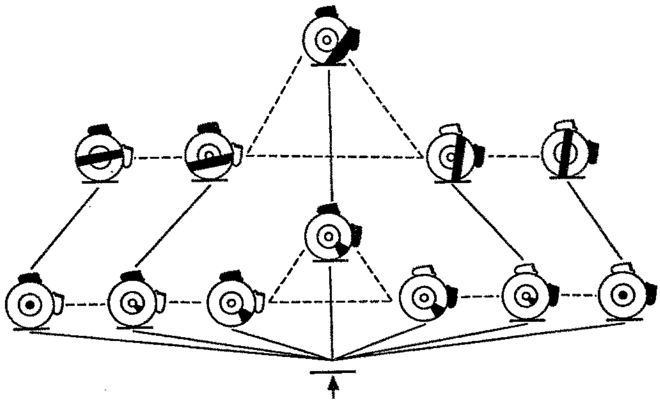

Fig. 3. A simple d-space, partially modeling walking. Diagrams as in Fig. 2 are used to indicate leg angles, support configuration, and balance. The null set is denoted by a line with an arrow under it, to indicate the acceleration of the floor upward relative to the body, a way to represent gravity. Solid lines indicate ordering, with the included element lower on the page. Dashed lines indicate contiguity. Note that contiguity does not separate the d-space into layers; if it did, the definition of coincidence contiguity would be too restrictive.

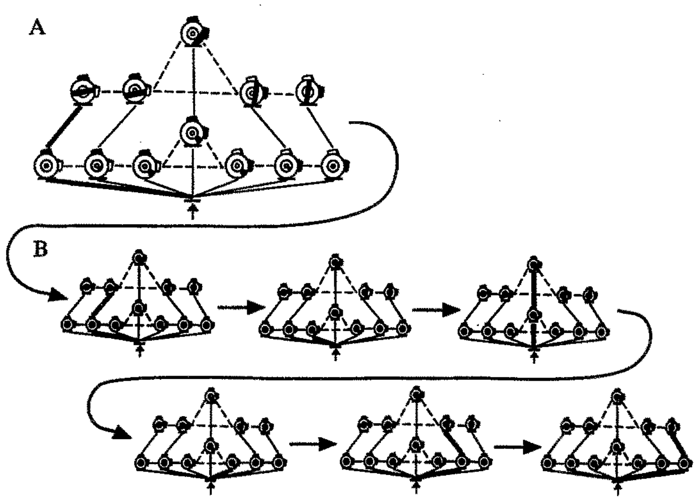

Fig. 4. Simple step consisting of a coincidence sequence in the d-space of Fig. 3. A. The d-space of Fig. 3 with the starting coincidence indicated by a heavy line: erect stance on the left foot. B. The rest of the step. For clarity, the poset is redrawn to display each succeeding coincidence. In each coincidence, the deviations of the two leg angles from vertical are equal but of opposite sign.

simple set of implementation strategies that can produce a satisfactory set of trajectories: a subset of the set of all possible trajectories. That is, the implementation strategies are sufficient to allow the animal to walk, but not necessary because there are other viable walks not generated by the implementation strategies.

The example in this section will add more aspects to the model of walking, just enough to contrast a healthy walk to a particular walk observed during recovery from stroke. In a satisfactory walk, a person does not fall; the person is assumed to be moving forward, so not falling is presented as the major criterion for a satisfactory walk (Fig. 5). Within the set of all nonfalling walks are those in which one foot does not catch on the other. A subset of walks with no foot-catching maintain the requirement that each foot stay to its own side. Each foot can be kept to its own side by a set of specific implementation strategies, easily implemented physiologically.

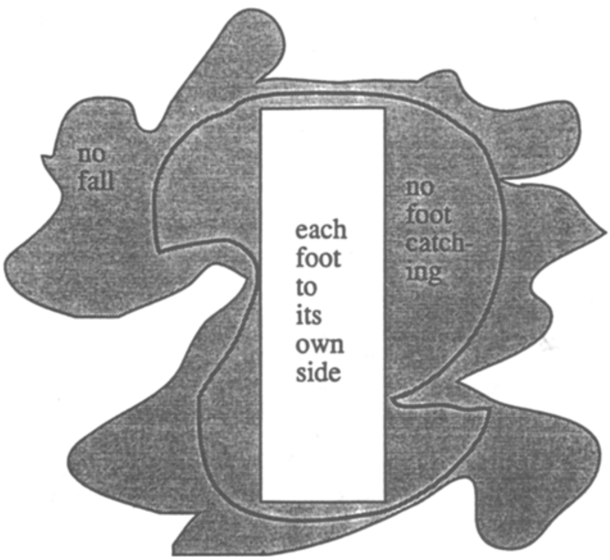

Fig. 5. Venn diagram of the hierarchy of implementation strategies. The walking model presented here is based on the assumption that the complex requirements of biological tasks are satisfied by finding a set of implementation strategies that are sufficient but not necessary. The largest set in the figure are walks with no falls. It is difficult to specify that full set as motor control imperatives. Within that set is one with no foot-catching, also a complex physical situation to describe, involving positions and velocities of various body segments, friction of clothes and shoes, etc. Within that set is a simple one to describe, in which each foot is kept well to its own side. The implementation strategies detailed in Fig. 7 maintain this last, simplest requirement.

Each specific implementation strategy in this model is an approach to a goal; each goal is a d-space region. There are three types of goals:

Goal 1. Forward position at footfall of the swing foot with respect to the stance foot (Fig. 6A).

Goal 2. Lateral position at footfall of the swing foot with respect to the projection of the hip position on the support surface (Fig. 6B).

Goal 3. Lateral position of the projection of the hip on the support surface with respect to the stance foot, both as the hip passes over the foot in the forward direction and at footfall (Fig. 6C).

The d-space representation of walking displays the combinations of goals 2 and 3 that are sufficient to keep each foot on its own side of the other foot. In a healthy walk, each footfall position is included in the set of positions with each foot on its own side of the other foot (Figs. 7 and 8). Keeping each foot on its own side is a simple rule that is sufficient but not necessary for avoiding foot-catching. Using this simple rule for avoiding foot-catching also allows separation of lateral balance as a module that can be added to forward–backward (saggital) balance to get

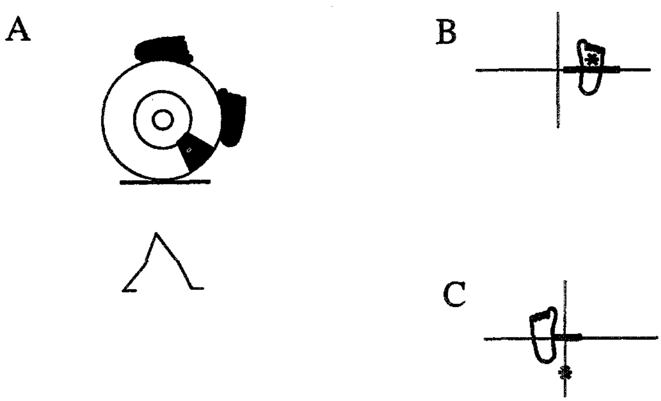

Fig. 6. Diagrams of individual implementation strategy goals. A. Goal 1: forward position at footfall of the swing foot with respect to the stance foot. Underneath the diagram is a stick figure showing leg position. B. Goal 2: lateral position at the footfall of the swing foot with respect to the hip. The thin horizontal line is the axis indicating lateral position; its origin is at the position of the projection of the hip onto the support surface (thin vertical line). The thick horizontal bar is the goal region on the horizontal axis; the region is one-dimensional in this case. The footprint, right in this case, indicates that it is the foot that is moving into alignment rather than the hip, and that the region is fixed with respect to the hip. C. Goal 3: lateral position of the hip with respect to the foot. The diagram is constructed of the same elements as in B. The asterisk is on the hip position line, indicating that it is the hip that is moving into alignment rather than the foot, and that the region is fixed with respect to the foot.

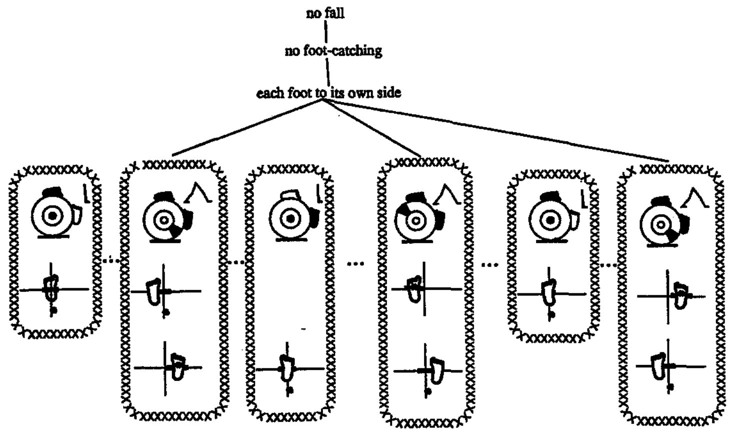

Fig. 7. Selected elements of a d-space showing a normal control model for walking, with atoms between stability cones omitted. At the very top is the set of all walks with no falls. Included in that set is the set of walks with no foot-catching. As a way of avoiding foot-catching, one may restrict oneself to the included set of walks in which each foot stays to its own side of the other foot. In each of these sets, the assumption is made that the body is moving forward, which is made explicit in the round foot position diagrams, like the one in Fig. 6A. Beside each foot position diagram is a stick figure showing leg position. Diagrams indicating forward foot position, lateral foot position, and lateral hip position are shown over six stages of the step cycle: vertical during left leg stance, right footfall, vertical during right leg stance, left footfall, vertical during left leg stance, and right footfall. Simultaneous goals are shown enclosed in lines of x's. Formally, the spaces so enclosed are crossed together (Fig. 8); the physiological operation is more complicated. Ellipses between goals indicate that a sequence of contiguous d-space regions has been omitted.

upright stance or can be added to alternating forward foot motion to get locomotion.

5. A Set of Implementation Strategies, Even for One Particular Task, Need Not Be Complete or Consistent

The nervous system stores assumptions of implementation strategies (carried out at one level, say cerebellum, spinal cord, cerebral cortex, basal ganglia, red nucleus, superior colliculus) in conditions not under that level's control, for example, the amplitude and direction of gravity, the length and weight of a leg, the pendulum period of the leg, the verticality and hardness of walls, the properties of tactile, auditory, inner ear (vestibular) receptors, ...

This is where the walking model becomes like quantum mechanics: from the point of view of classical mechanics, the space is broken up. It is not well modeled.

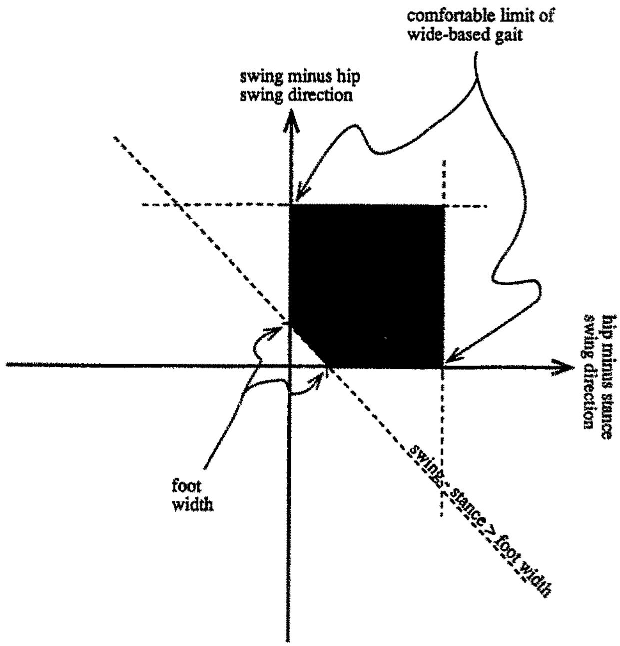

Fig. 8. Region given by the cross-product of lateral position goals, 2 and 3, at footfall. "Swing" is the lateral position of the foot that is swinging; "stance" is the lateral position of the weight-bearing foot; "hip" is the lateral position of the projection of the hip onto the support surface. The regions shown in Fig. 7 are more restrictive; this diagram shows some outer limits, within which steps normally fall. In constructing this cross-product, the assumption has been made that "hip" is obtained throughout using the same projection onto the support surface.

6. An Adult Patient May Use the Same Set of Implementation Strategies as before a Stroke or Trauma, Even Though the Assumptions of the Implementation Strategies No Longer Hold

In the example considered here, the patient was tripping because she caught her left toe on her right heel as she swung her left foot past her right in walking. The patient may have had a d-space like Fig. 7 as an internal model; however, in approaching goal 2, she used a diagonal rather than a perpendicular projection to judge the position of the foot with respect to the hip. In the previous step, the right (swing) foot was placed to the left of the left (stance) foot, so that when the left foot was moved it caught on the right and caused the patient to trip and fall (Figs. 9 and 10). The misperception of the vertical may have been caused by peripheral sensory or by central nervous system disorders. Her stroke had paralyzed her left

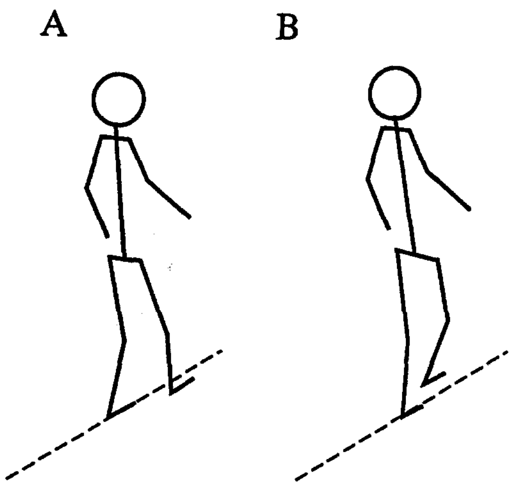

Fig. 9. Physical results of diagonal rather than perpendicular projection in goal 2. Steps of the right foot forward are shown from the back of the person and a little to the right. The path lines beneath the stick figures are to aid in seeing the directions intended. A. Healthy person. The right foot, as it is put forward, is also positioned a little to the right of the hip. B. Patient. The right foot, as it is put forward, is aligned where the patient judges it to be a little to the right of the body. However, the illustrated physical result is that the right foot is directly beneath the body or slightly to the left.

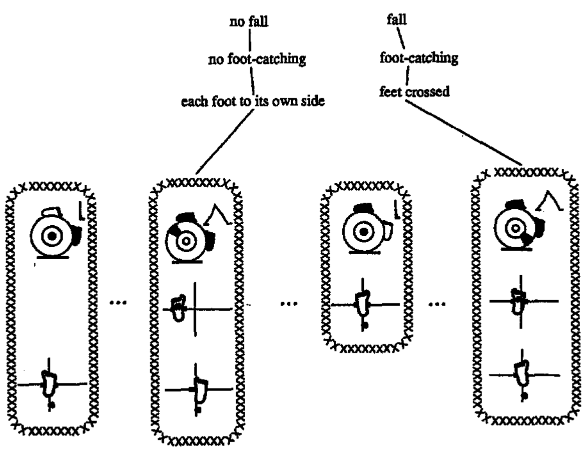

Fig. 10. d-Space showing the patient's physical walk exiting the set of positions with each foot to its own side. Diagram elements as in Fig. 6. The first three positions, vertical during the right leg stance, left footfall, and vertical during left leg stance, are like those of the healthy model shown in Fig. 7. At right footfall, the feet become crossed. The left foot is now headed for catching on the right heel. Because the body is moving forward, the left foot catching means that the body is headed for a fall.

leg, so that in early standing attempts the right foot had had to be directly under the body. As strength returned in the left leg, the two legs did not symmetrize, but the left often paralleled the right, so that the whole body leaned to the right. Such lateral deviations are common in stroke and trauma patients (Fig. 1).

Achieving each implementation strategy goal does not ensure that the requirement of keeping each foot on its own side will be met, because each implementation strategy goal uses the hip as a reference, not the other foot. In the healthy case, the requirement is met because a tacit assumption, correct perception of the vertical, is met; in the patient's case, it is not. The disadvantage of using a set of implementation strategies with essential tacit assumptions is that they may not give the desired result, and the causes for the failure will be obscure to the person using them. The advantage is that they make life simple enough to live.

7. Future Work Will Explore the Structure of Sets of Implementation Strategies

As various projects explore different movements and aspects of movements, the ideas of d-spaces and collection of implementation strategies will develop. Some mechanical and physiological extensions will be studied. Each region with foot contact, or more generally, body contact with an external support, is a sensory opportunity and an opportunity to exert or transfer force and torque. Mechanically, movements are caused by force and torque; the mechanics of movements should eventually be interrelated with the movements in this discrete formalism. However, a physiologically more interesting extension of the present work would be to include the muscle synergies that are effective in causing movement within and between regions.

A manual of implementation strategies should emerge. Some will be used in combination to produce motor acts, appropriate or dissonant. Rather than commutativity, combinability may be the more salient relation. Rules of combination have already been used in studying sensory receptive fields, the range of sensory input to which a particular neuron is sensitive (McCollum, 1992). The parallel study of receptive fields and implementation strategies is being pursued in order to make a bridge between the behavioral and neural levels.

At some point, the process of matching to physical outcome will be studied. There are at least two behavioral methods: (1) exploring the combinations among a set of implementation strategies, perhaps completing the set of combinations; and (2) finding a combination of implementation strategies that give the desired results. Both of these should be observed in development and learning. Beyond finding an appropriate combination, one can keep improving a combination of implementation strategies to improve the motor result.

ACKNOWLEDGMENTS

I am indebted to Anne Shumway-Cook for access to patients for observation and especially for collaborating in developing the physiological ideas leading to this formal summary. I appreciate Jan Holly's specific comments on the manuscript.

REFERENCES

Foulis, D. J., and Randall, C. H. (1985). Dirac revisited, in *Symposium on the Foundations of Modern Physics*, P. Lahti and P. Mittelstaedt, eds., World Scientific, Singapore, pp. 97–112.

McCollum, G. (1992). Rules of combination that generate climbing fiber tactile receptive fields, *Neuroscience*, **50**, 707–725.