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THE ECOLOGICAL APPROACH TO PERCEIVING–ACTING: A PICTORIAL ESSAY

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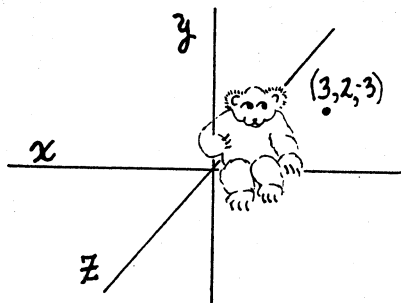*State University of New York at Binghamton, USA*

1. Introduction

Fig. 1.1. In conventional discussions of space perception, 'space' is a mathematical concept. Theory and experiments focus on how an observer perceives points, distances between points and motions of points localized by triplets of values in a Cartesian coordinate system. The mathematical conception of space is traditional and, perhaps, convenient but it has little bearing on what animals (including humans) need to perceive in order to get around successfully in their cluttered environments.

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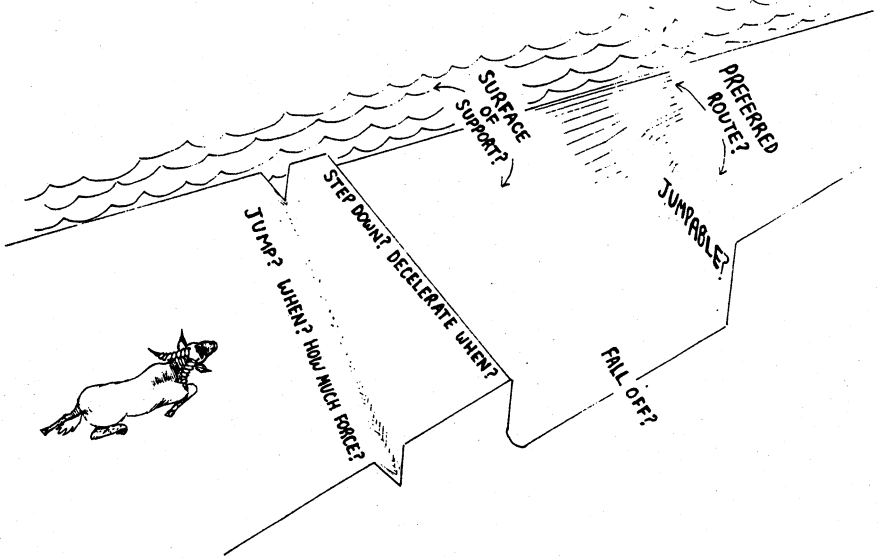
Fig. 1.2. Terrestrial animals encounter prosaic 'problems' in the everyday course of locomoting. As Gibson (1979) put it: 'What animals perceive are the substances, places, objects, and events of the environment instead of objects in space. What animals discriminate are the meaningful properties of substances, surfaces, etc., instead of the primary and secondary qualities of physical objects. What they move around in is the medium instead of space. What they see is the layout, the dihedrals and curves that surfaces make to one another, instead of depth in space.'

We wish to discuss perceiving–acting in the context of the ecological reappraisal of the so-called problem of space perception. This perspective asserts that answers to the questions encountered by the gazelle of fig. 1.2 must be lawfully grounded. To anticipate, the ecological approach to perceiving–acting is interpreted in some quarters as an enterprise that asks: what are the laws, scalars, symmetry operations, adiabatic invariants, etc., at the ecological scale that make perceiving–acting (its evolution, its everyday realization) possible? What are the deep constraints; that is, what states do perceiving–acting systems relax onto or regulate around in the absence of imposed boundary conditions? Physically speaking, perceiving–acting is a circularly causal process involving: (a) forces giving rise to flows/forms/times, and (b) flows/forms/times constraining or giving rise to forces. Orthodox physics embraces a but not b. The physical challenge posed

by the ecological approach is to identify the physical principles by which flows, etc., give rise to proportionate forces. Whereas ordinarily, neural processes are viewed as 'efficient causes' – they are said to *produce* percepts and actions – the emphasis on laws, etc., (and certain philosophical considerations) biases the ecological approach to a different metaphor: neural processes are one of the 'supportive bases' of perceiving–acting. Nestings of lawfully related properties are what matter. Consequently, in perceiving–acting the nervous system 'functions vicariously' (Gibson 1966).

In the following discussion of this approach, both the text and the figures are necessary for a full appreciation of the arguments to be developed.

2. Force-to-flow / form / time laws

Animals, their tissues and their organs, are in accord with the laws of mechanics (particle and statistical) and thermodynamics (equilibrium and nonequilibrium). As a class, these laws can be thought of as statements of forces producing flows or forms or times. There are kinetic properties (which always include the dimension of mass) giving rise to kinematic properties (built only from the dimensions of length and time) or geometric properties (built solely from the dimension of length) or temporal properties (built solely from the dimension of time).
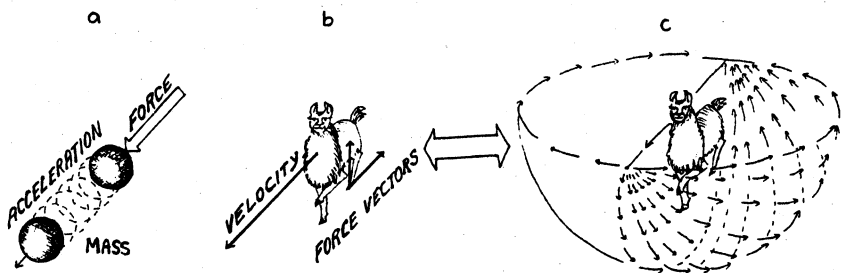

Fig. 2.1. (a) The most renowned law of mechanics can be expressed as a ratio of kinetic properties (force/mass) producing a kinematic property (acceleration). (b) An animal generates forces that propel it forward with a certain velocity. This is a familiar instance of a force-to-flow/form/time law at the ecological scale of nature. (c) At the same time as b, the forward driving forces give rise to a particular optical pattern that is revealed at appropriate scales of space and time. This is an unfamiliar instance of a force-to-flow/form/time law.
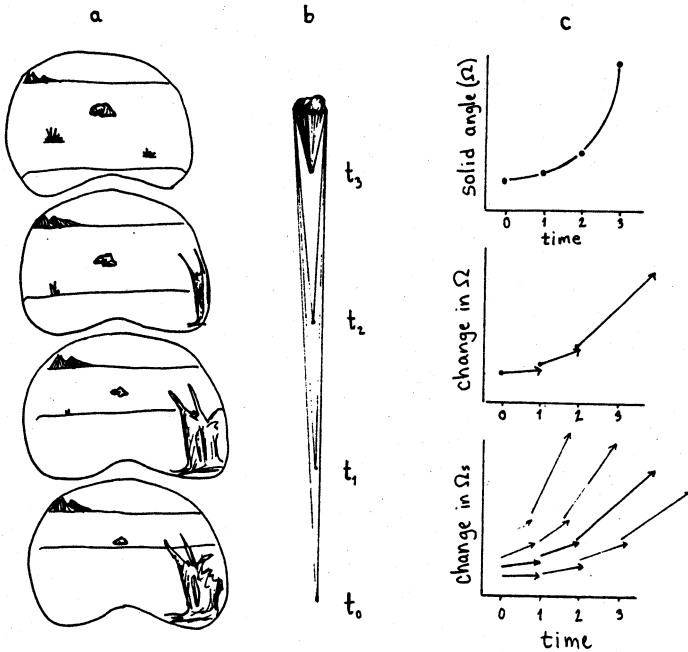
Fig. 2.2. What Gibson termed the optical flow field can be constructed in the following way. As a material point approaches, say, a rock (a), the size of the optical solid angle that has the rock as its base and the point at its apex expands (b). The rate of change of optical solid angles can be seen to generate a vector flow field (c). The particular flow field that is generated depends on the style of change which the material point is undergoing.
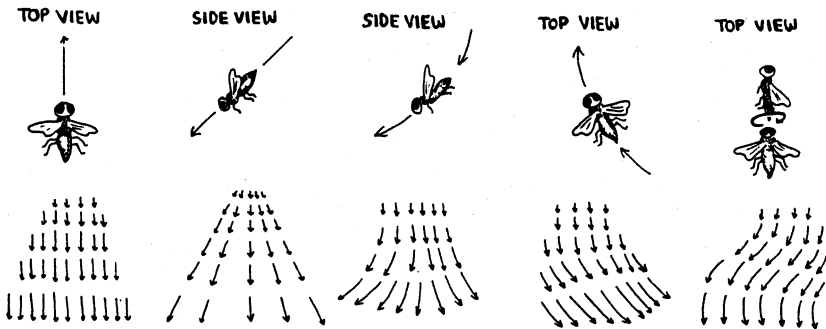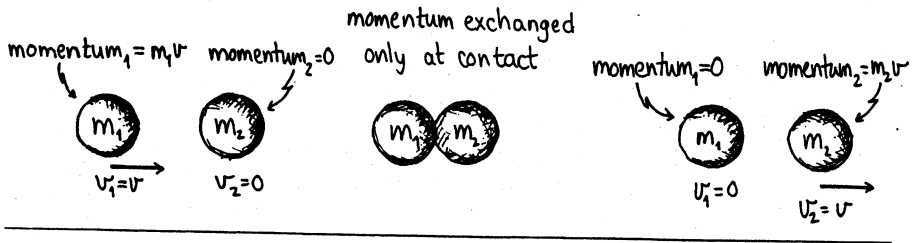

Fig. 2.3. A flying insect generates different patterns of force (by locomoting forward, descending, decelerating, turning, rolling, etc.). Different patterns of optical flow – different velocity vector fields – arise.

Specialized ecological instances of the class of force-to-flow/form/time laws have, to date, received little study and almost no formalization. But the fact that they are unfamiliar to science does not mean, of course, that they are insignificant to the design of animals. These instances, no more nor less than the familiar instances, were present before and during the lengthy process of terrestrial evolution. In this important sense optical flow fields and the traditional retinal image are markedly different conceptions of the optical support for perceiving–acting. Optical flow fields depend neither on the existence of eyes nor on the kinds of eyes that came into existence (through evolution). The optic array and its transformations are just descriptions of the nested structure of reflected light ambient to a point. The optic array and its lawfulness predate ocular systems and visually-guided locomotion and are a likely basis for their current design and successful evolution. The same cannot be said of retinal images.

3. Flow/form/time to force laws

The ecological scale of nature seems to define and richly exploit laws of yet another kind. Animals, of course, are not point masses. They have rich interiors. They carry – on board – supplies of chemical energy that are convertible into mechanical forces. Consequently, they can resist within limits, the biases of the external force fields in which they are immersed. A physically minded student of locomotion's control might ask what is the lawful basis for relating the forces produced to the demands of the environment (refer back to fig. 1.2). If there is such a basis, it is not likely to assume the ordinary structure of natural laws, roughly, forces giving rise to flows/forms/times. To enforce this point let's briefly examine the 'collisions' between an animal and its surroundings.

a. AN EXAMPLE OF A CLASSICAL COLLISION

momentum exchanged
$momentum_1 = m_1 v$ $momentum_2 = 0$ only at contact $momentum_1 = 0$ $momentum_2 = m_2 v$

$v_1 = v$ $v_2 = 0$ $v_1 = 0$ $v_2 = v$

| SOFT | HARD | NONE |
| Momentum dissipated prior to contact | Momentum generated prior to contact | Momentum redirected prior to contact |

b. EXAMPLES OF NONCLASSICAL, CONTROLLED COLLISIONS

Fig. 3.1. In locomoting, an animal and its surroundings exchange momentum. If an animal's momentum were reduced or augmented only at the time of contact with a surface, then locomotion would fall within the purview of the (classical) theory of collisions (a). It is obviously the case, however, that changes in momentum occur prior to surface contact. A locomoting animal can slow down so that its collision with a surface is soft (little momentum exchange), speed up so that the collision is hard (a lot of momentum exchange), or change direction so that no collision (and no momentum exchange) occurs (b).

In short, locomotion does not fit the mold of collision theory. The momentum exchanges are controlled prospectively. To effect prospective control visually, the forces produced must be constrained by the flows and forms and times of the optic array (cf. Kugler et al. 1985). The idea is that there are lawful regularities in which the causal arrow runs from flows/forms/times to forces. Global optical flows and their consequences might be interpreted as notable, if simple, instances of such regularities.
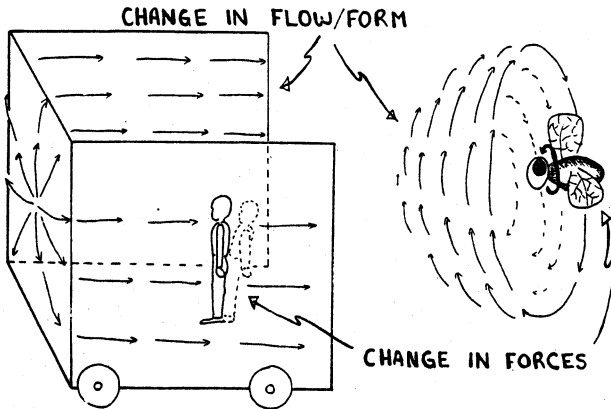
Flow/Form-to-Force "Laws"

Fig. 3.2. (Left) The global outflow artificially created by an arrangement of surfaces enclosing a person, displacing as a unit relative to the person results in posture-preserving muscular forces that are closely proportional to the outflow (in this sense: they are proportional to the degree of departure from upright posture suggested by the flow) (Lishman and Lee 1973). (Right) Similarly, subjecting a flying insect to a large scale rotary optical flow results in muscular forces (wing beats) in proportion to the magnitude of the rotary flow (cf. Gotz 1968).

What is entailed by the claim that flows/forms/times at the ecological scale provide a principled basis for constraining forces? One conjecture is that flows/forms/times are a source of spatial and temporal operators that change potential functions (for biological systems, the major potential is the internal concentration of chemical energy) into mechanical force functions (Kugler et al. 1985). If correct, then uncovering such operators and understanding their relation to intentionality (roughly, how they are harnessed by an animal's goals) is central to a principled, law-based account of perceiving–acting (Turvey et al. 1981). Elucidating operators is a long-term enterprise. In the meantime, we can get a glimpse of the strategy by which a law-based account of perceiving–acting might be provided. This will start with a look at the invariances of quadruped locomotion and human rhythmic movements and proceed to an examination of the nature of information.

4. Lawfulness of locomotion

For those terrestrial animals that, like humans, are subject to gravitational and reactive forces when they walk and run, there are three notable design constants: density, elasticity, and tensile strength (Economos 1982). Each constant defines a relationship among variables (for example, density = mass/volume) and together they impose strict restrictions on the relationships among the representative quantities of the basic dimensions of mass, length, and time (for example, ML^{-3} = constant). Through similarity analysis, the constants establish what are termed biological scaling laws. These are time $\propto$ mass$^{1/4}$, time $\propto$ length^1. These can be expressed as a single, fundamental scaling law for biological systems in which $M \propto L^4$; $T \propto$ (mass$^{1/4}$ × length^0), or $T \propto$ (mass^0 × length^1) (cf. Kugler and Turvey, in press). This law is 'adjusted' by the mechanical advantages associated with a given activity. For quadruped locomotion, for example, it becomes $T \propto$ (mass$^{1/8}$ × length^0), or $T \propto$ (mass^0 × length$^{1/2}$).
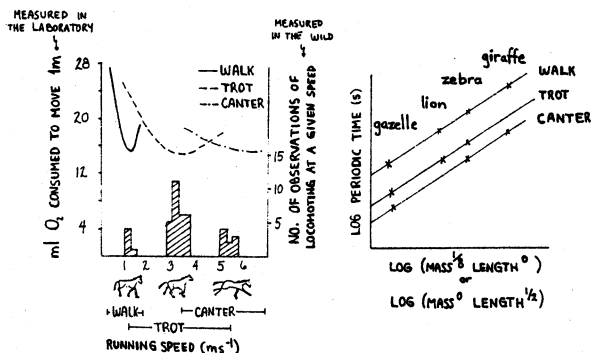

Fig. 4.1. (Left) A variety of animals locomoting freely at the three major gaits – walk, trot, and canter – will locomote primarily in the energetically least costly comfort mode (Hoyt and Taylor 1981). (Right) The gait parameters will be those of an equilibrium state. Observation reveals that the preferred stride frequencies or periodic times of all three gaits are linked, as the similarity analysis suggests, to the product of an animal's mass and the length of its hind limbs expressed as either $M^{1/8}L^0$ or $M^0L^{1/2}$ (Kugler and Turvey, in press).

There is a proportionate decrease in stride period from walk to trot to canter that is the same regardless of the size of the animal (Pennycuick 1975). This remarkable fact suggests a common, limited set of stable states or 'attractors' for quadruped locomotion. In other situa-

tions, admittedly molecular, a spectral series like that of fig. 4.1.b is referred to integer multiples of a universal constant. There are hints that the acceleration due to gravity at the ecological scale may be playing the role of such a constant in the gait series. Analysis has revealed that the periodicities of walking, trotting, and cantering are very close to those of a single, simple-pendulum equivalent of the four limbs oscillating with respect to gravity $x2$, gravity $x7$, and gravity $x10$, respectively (Kugler and Turvey, in press).

Another remarkable fact is that the gaits exhibit an invariable characteristic with respect to the unstable state that marks the transition in free locomotion from the trot to the (fast) canter. At the transition, the ratio of the stride frequency to body mass raised to the 1/8 power is a constant (Heglund et al. 1974). Apparently both stationary and transitory aspects of terrestrial locomotion conform to laws. Humans, of course, produce a variety of rhythmic movements outside of locomotion. The understanding of these movements promises to be just as principled.
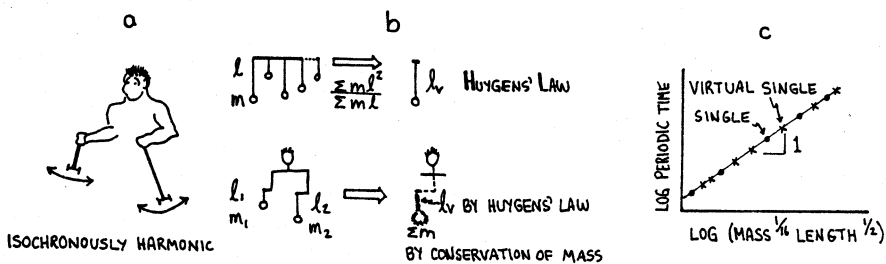

Fig. 4.2. (a) A person swings two hand-held pendulums, 180° out of phase, at a common tempo. For different pendulum parameters (length and mass) and for pendulous motions defined over two wrist–pendulum systems or just one wrist–pendulum, a person will settle on different preferred tempos (comfort modes). The mechanical advantage term associated with a wrist–pendulum yields the following variant of the fundamental scaling law: $T \propto (M^{1/16}L^{1/2})$. That is, preferred tempos are expected to go as the pendulum mass$^{1/16}$ times the pendulum length$^{1/2}$. (b) An interesting feature of a pair of wrist–pendulum systems is that they can be represented as a single wrist–pendulum system. This virtual system has a length given by Huygens' Law for an ensemble of rigidly connected simple pendulums. And it has as its mass the sum of the two individual masses given, of course, by the conservation of mass. Huygens' Law replaces many micro systems by a single equivalent macro system on the grounds of the conservation of energy. (The way in which it was derived is a forerunner of the modern conservational bookkeeping strategy in statistical mechanics.) (c) In short, a virtual single system is assembled according to the conservations. It turns out that single wrist pendulum systems (where a weighted pendulum is swung in just one hand) and virtual single wrist–pendulum systems both obey the scaling law. They sit on the same trajectory in a log periodic time × log($M^{1/16}L^{1/2}$) coordinate space (Kugler and Turvey, in press).

Is the amplitude of limb movements similarly principled? Investigations with people swinging hand-held pendulums have pointed to a constant relation between the mechanical energy of an individual wrist–pendulum system and frequency (Kugler and Turvey, in press). Since amplitude is bound up in the energy quantity, then the constant, called action, provides a frequency-to-amplitude link. Technically speaking, the constant is an instance of an adiabatic invariant: it is a quantity that is unaffected by the changes in a mechanical/thermodynamical system when (and only when) those changes: (1) are slow relative to the time course of underlying processes, thereby displacing the system only slightly from equilibrium, if at all; (2) do not incur momentary stoppages of the system's motion; and (3) are not linked to the phase of the system.
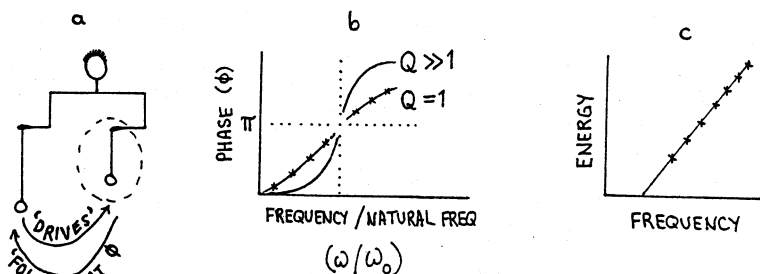

Fig. 4.3. (a) The frequency of a wrist–pendulum system of fixed dimension can be raised and lowered through its coupling to variable wrist–pendulum systems. If both are to swing at a common tempo then, because of the principles noted above, the tempo for any given pairing will be the preferred tempo (defined by the scaling law) of the virtual single system to which the pair of systems give rise. It is useful to image the situation as one in which the fixed wrist–pendulum system is being 'driven' by the variable system. Then, the degree to which the fixed system leads or lags can be measured. This measurement is of the phase angle or difference ϕ between the systems. (b) Plotting ϕ against the ratio of the fixed system's frequency (due to the coupling) to its preferred frequency (the one that it exhibits in the uncoupled state) is very informative about the state of the fixed system. It tells us about the balance between the inertial forces that propel and the viscous forces that retard a wrist–pendulum during a cycle. This is the so-called Quality or Q-factor of a rhythmic system. The higher the Q-factor the less is the energy used up (dissipated) per cycle. For a rhythmic movement, most internal and viscous forces originate from the same source, namely, muscle tissue and its attendant chemical processes. When the Q-factor of a rhythmic movement is unity or less, this means that the energy appearing (and disappearing) in the cyclic movement does not exceed that supplied (and withdrawn) muscularly. More to the point, it means that the system is thermodynamically equilibrated over the range of frequency (ω) variation. (c) When a wrist–pendulum system's trajectory in the ϕ-by-ω/ω_0 space is that of $Q \leq 1$, then the mechanical energy of a rhythmic movement and its frequency seem to change proportionately. That is, amplitude seems to be consistently tailored (increased, decreased) to the periodic timing of the movement according to a constancy of action (Kugler and Turvey, in press; Rosenblum and Turvey 1984).

Action (which is a constant for the boundary conditions determined by the loading on the body's tissues) is an adiabatic invariant onto which rhythmic biological systems will relax when freely permitted to do so. It hints at the natural basis providing fundamental linkages among the observables for biological systems.

This point is important. Ignorance of the lawful basis relating observables leads to special neural and/or computational mechanisms to effect the linkage. This strategy is tantamount to offering engineering accounts for the behavior of a class of objects whose physics is unknown. The result is likely to be arbitrary and fictitious mechanisms. In order to avoid such caprice, the ecological approach seeks to ground perceiving–acting in the sort of physical principles that we have identified. Though unfamiliar and relatively novel, law forms at the ecological scale must be brought into focus. Their pertinence is with respect to the notion of information, to which we now turn.

5. Information

In the ecological view, information is given a strict definition. Let's preface the definition by noting that there are reasons for distinguishing two senses of information, viz., biological systems are characterized by two (complementary) modes of functioning (Pattee 1977) – the discrete (symbolic) and the continuous (dynamical) – and, perforce, two senses of information – the indicational/injunctional (rule-like) and the specificational (based in law) (Reed 1981; Turvey and Kugler 1984). Meeting the challenges presented in fig. 1.2 requires information in the specificational sense. In the case of vision, this means optical structure at a point of observation *lawfully* generated by surface layout and by displacements of the point of observation (irrespective of the ocular system that may occupy it):

PROPERTIES OF LAYOUT — lawfully generate → PROPERTIES OF THE
AND MOVEMENTS   ← specify —   OPTIC ARRAY

These lawfully generated properties of the optic array are: (1) macroscopic and qualitative. They are large-scale properties of the photon light field; (2) kinematic (L, T) or geometric (L) or temporal (T). They are not kinetic (M, L, T) as are the properties of the photic

field; or, synonymously, (3) large-scale, alternative descriptions of a low energy (kinetic) field in which the mass (M) dimension is suppressed (Kugler and Turvey, in press).

It should be apparent that the unfamiliar force-to-flow/form/time laws and the relatively novel flow/form/time-to-force laws illuminated above are illustrations of information in the specificational sense. They illustrate global (all vectors change concurrently) optical morphologies (forms of flow) that specify one fact and one fact only, viz., the displacement of the point of observation relative to the surroundings (for example, that the llama in fig. 2.1.c is walking forward).
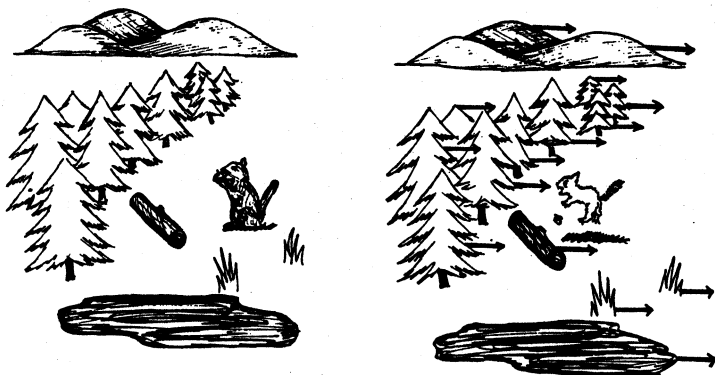

Fig. 5.1. It is important to underscore the nonarbitrariness (that is, lawfulness) of these morphologies and thus their unequivocality (that is, their power to specify). A given morphology, such as the parabolic flow field depicted in fig. 2.1.c, could only arise under the kinetic conditions in which forces operating locally move a material point (of observation) relative to the fixed terrestrial frame of reference (the ground cluttered with attached and unattached objects). The reverse situation, in which there is a unitary displacement of the terrestrial frame or reference relative to a stationary point of observation is kinetically infeasible. It could never have occurred in the ordinary course of evolution. (That it can nowadays be simulated in the laboratory and in the cinema cannot undercut the argument.)

We saw above how there is a sameness to the spatio–temporal properties of locomotory limb movements regardless of gait and species. That sameness is because the design of all animals is in accord with the same set of natural laws. Another commonality is the sensitivity of animals to global optical morphologies as specifications of egomovement. This sameness is also due to a design consonant with law. The laws in this latter case – one might call them information laws – are, as noted above, just less familiar. There is a strong inclination in biology

and psychology to treat perceptual phenomena of the kind under discussion as instances of inference-making activity. It is as if the global morphologies could originate from more than one source and, therefore, need to be interpreted. Obviously, this is not the inclination of the ecological approach. To reiterate: rather than figuring out putative brain processes that make the right inferences, the ecological approach promotes the investigation of the form of laws at the ecological scale, the kinds of properties they relate, and the design principles of the biological systems that exploit them.
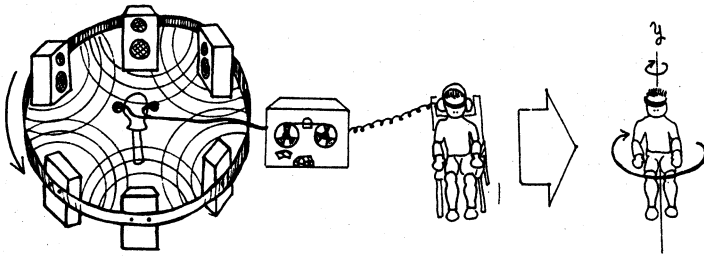
Fig. 5.2. A particular local kinetic pattern (a play of forces) produces a particular global kinematic pattern (a form of flow). The morphology is specific to its cause. Because of the suppression of the mass term in the flow field description, the very same global morphology, specifying the very same fact, can be defined over differently based velocity vectors abstracted from very different low-energy fields. A global morphology defined over compression waves in the air specifies rotation of the body about its vertical axis (Lackner 1977).

𝟄: GRAVITATIONAL FORCE

S: CONTACT FORCE OF SUPPORT

Z: AXIS OF ROTATION
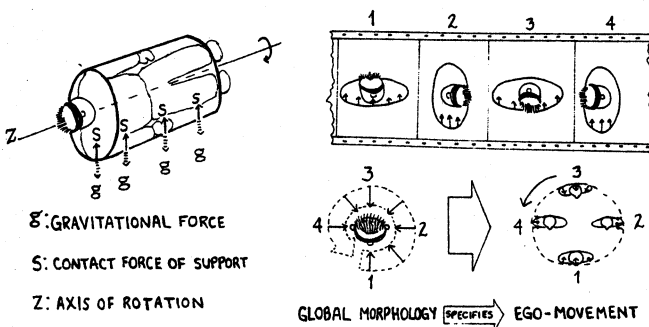
GLOBAL MORPHOLOGY ⟨specifies⟩ EGO-MOVEMENT

Fig. 5.3. For a blindfolded person subjected to 'barbecue spit' rotation, the gradient of the contact force of support countering gravity 'peaks' on the underside (only those vectors are shown). The gradient moves around the body in a direction opposite to that of the rotation. The global morphology thus defined over skin deformations specifies movement of the body on an orbit with the body facing in a constant direction (Lackner 1981).
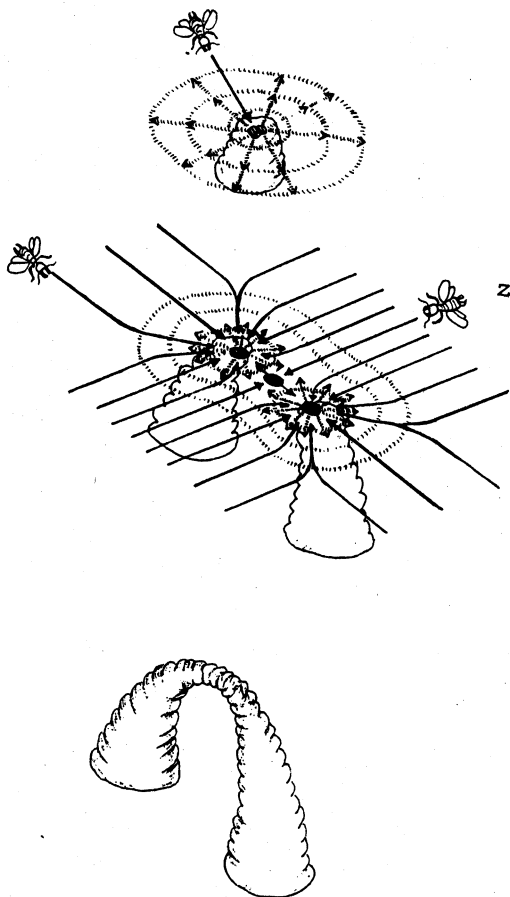
[Text follows on on p. 147.]

Fig. 5.4. Kinematic flow field properties as information for controlling activities may be very general (Kugler and Turvey, in press). In this example, they constrain (guide) the locomotory and building activities of flying termites as they construct their nest. The active pheromones at the top of a pillar currently under construction diffuse into the air. A termite intercepting the flow field moves up the gradient to the active site. The active site functions as a singular point in the field. When two pillars are close by, the diffusive flows from the two sites interact, producing a 'virtual' singularity in between. In three dimensions, the morphology of the resultant field is that of a saddle with the 'virtual' singularity as the saddle point. A termite z moving up the flow gradient on a trajectory to the virtual singularity will find, on reaching the singularity, steeper gradients leading to the active sites. Because of the particular angle of approach, the termite deposits on the side of the pillar that is closest to the neighboring pillar. The eventual outcome is an arch whose peak is in the vicinity of the kinematic flow field's virtual singularity. In this example, the flow field's properties (gradients, singularities) constitute information in the specificational sense. 'Move in the direction of the greatest smell and deposit there' is information in the indicational/injunctional sense: it is the design bias of the termites.

Here again traditional ways of thinking seems to miss the mark as descriptions of figs. 5.2 and 5.3. Light, sound and touch are different energies and are said to be different stimuli. That they could give rise to the same impression is a classical paradox (is one sense the basis for interpreting the neural signals from the others?). Focussing on the lawfully based flow fields removes the paradox. The same information is defined over different 'stimulus energies'. And different perceptual systems can detect that information (that is, be part of the supportive basis for the same lawful relation) (Gibson 1966).
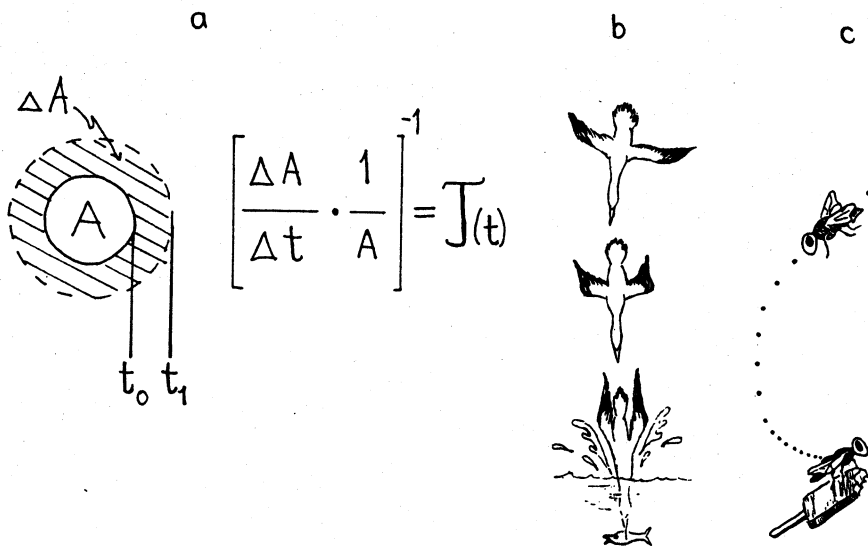
Fig. 5.5. Some properties of flow fields seem especially relevant to the synchronizing of acts to local environmental changes. In pursuing prey, for example, an optical property specifying time to contact a chosen victim would constitute such a property. (a) Simply put, the inverse of the relative rate of dilation of an optical solid angle (of initial area A) is a temporal quantity, $\tau(t)$, that specifies time-to-contact. (b) Obviously, the value of $\tau(t)$ changes as one gains on the thing to be contacted. For a given activity, one of these values may be especially important for controlling activity. A gannet diving for fish will begin to fold its wings at a critical $\tau(t)$ – a value that enables it to snare its prey without fracturing its wings when breaking the water's surface (Lee and Reddish 1981). (c) Flies alighting on a surface do so with a characteristic pattern of deceleration that appears to be initiated at a critical relative rate of dilation, that is, the inverse of $\tau(t)$ (Wagner 1981).
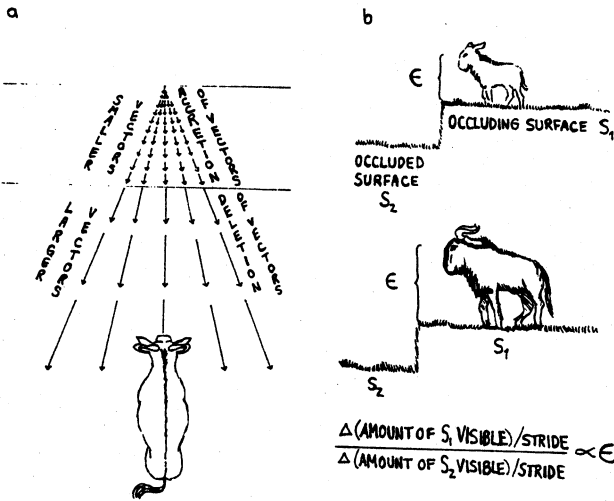
6. Affordances

Fig. 6.1. (a) Certain surface layouts will generate local disturbances within the global morphology. A discontinuous flow field that can be described mathematically as the accretion of generally smaller vectors above a horizontal together with a deletion of generally larger vectors below that horizontal specifies a brink. (b) But the brink's behavioral relevance – its affordance – is not captured until a scaling factor is brought in to distill action categories: a brink may be a falling-off place for an animal of a certain size but a stepping-down place for an animal of a certain larger size. As the ratio of changes (Δ) suggests, approaching a brink yields an optical patterning specific to eye height (ϵ). There may be a very general principle by which optical flow fields are scaled to body dimensions, thereby providing a basis for information about affordances of the kind depicted here.

Fig. 6.1 is a nice illustration of Gibson's (1979) notion of affordance, for these reasons. When a brink is a step-down place (or a jump-down place or a place that cannot be negotiated by these means of locomotion) for a given animal, it is so regardless of the animal's 'state of mind'. It is, therefore, an objective property in the traditional sense. At the same time, to describe a brink as a step-down place is to measure an aspect of the environment (magnitude of drop off) relative to an aspect of the animal (e.g., leg length). There is, therefore, a sense in which a step-down place might be seen as a subjective property. Clearly, the notion of affordance promises a way of construing real properties that does away with the classical dichotomy of objective–subjective.
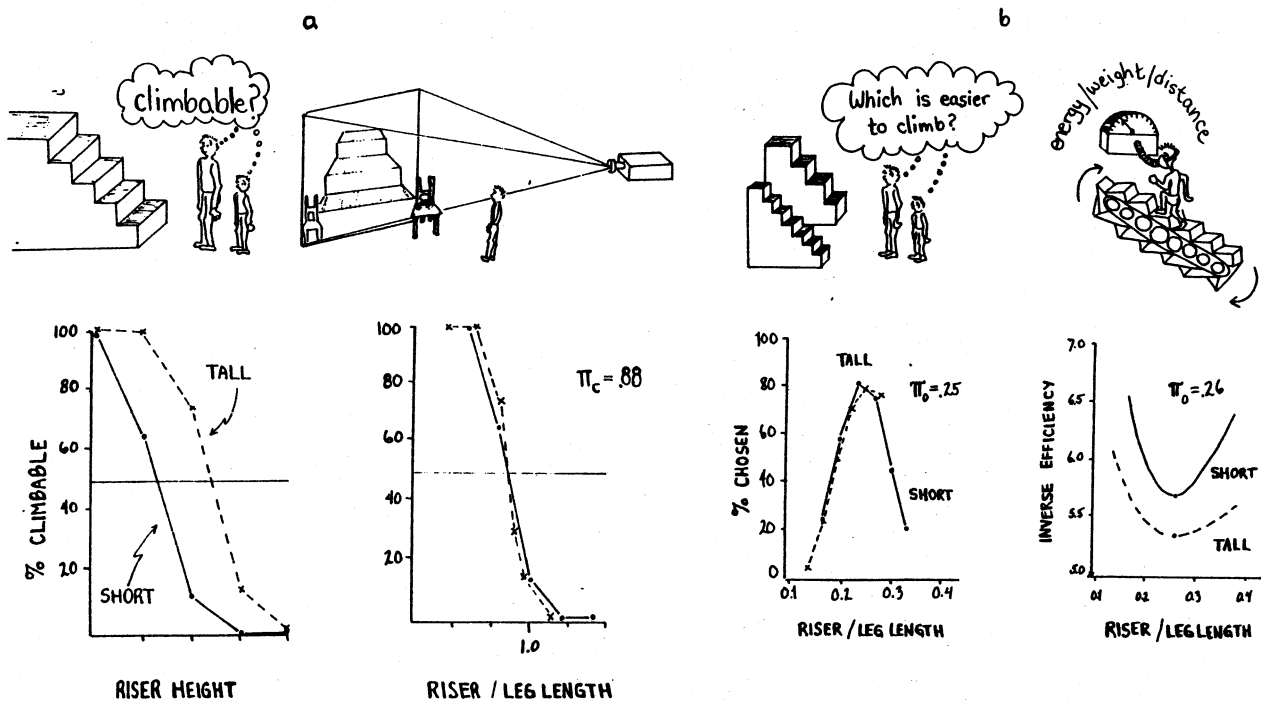
Fig. 6.2. The importance of the notion of body-scaling is, of course, that animals are characterized as perceiving in their own dimensions rather than in units (e.g., inches) extrinsic to the animal–environment system. (a) Actors of different heights were presented with the task of judging whether or not a stairway of a given riser height was climbable. Measured extrinsically, short actors and tall actors gave different perceptual boundaries. When the environment (riser height) was scaled in terms of the person (leg length), however, the boundary between climbable and not climbable was identical. Such intrinsic measures yield dimensionless quantities – so-called pi or π-numbers – that characterize the system's behavior. In this case, $\pi_c = 0.88$ is a critical π-number indexing the category boundary. (b) Perceptual judgements of a preferred stair to climb revealed an optimal π-number, $\pi_0 = 0.26$, that corresponded to the energetically least costly stair to climb as measured metabolically on an adjustable escalator (Warren 1984).
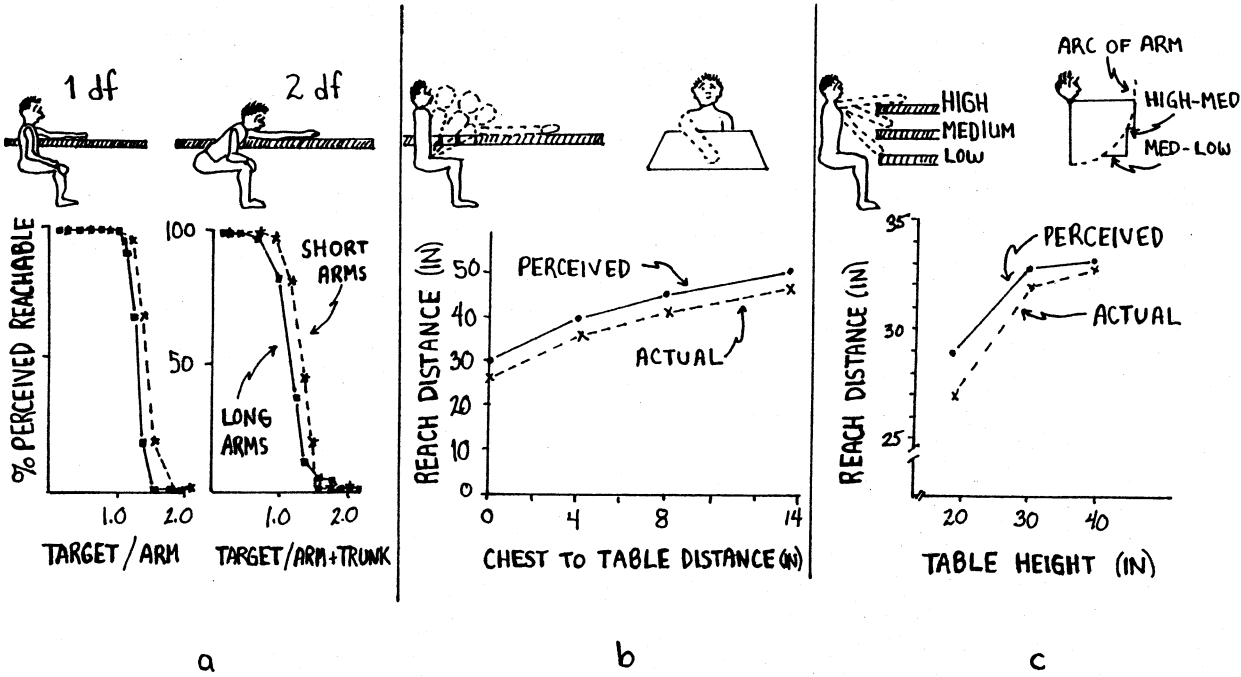
Fig. 6.3. The same story can be told with respect to perceiving the boundary of one's reach, whether that is done with one degree of freedom (just extending the arm) or two degrees of freedom (bringing in the torso and arm): When body-scaled, the boundary (actual and visually adjudged) between reachable and not reachable is the same for long-armed and short-armed actors (a). Action categories are perceived even when barriers are imposed on the extent to which one can use the available degrees of freedom. For example, placing a table at varying distances from a reacher alters the effective torso that can be used to reach, yet perceptual judgements track these changes (b). The boundary of one's reach is also a function of the surface height to which one is reaching. At a shoulder height surface, the reaching boundary is equivalent to the arm length. The geometry of rotating from the shoulder is such that a drop of 10 inches in surface height reduces that maximum reach only a little but a 2nd drop of 10 inches reduces it dramatically. Again, perceptual judgements track these (nonlinear) changes (c) (Solomon et al. 1984b).
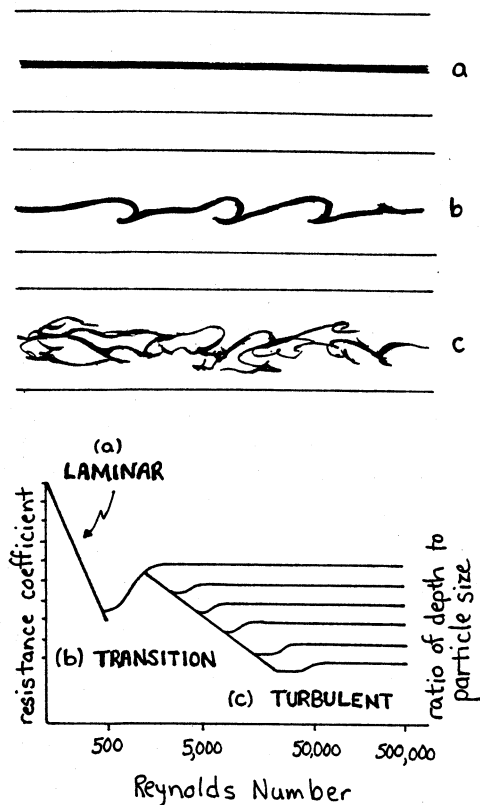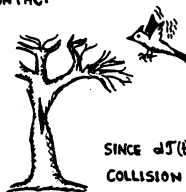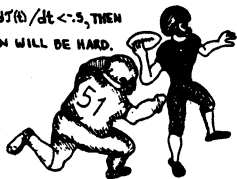
7. Optical π-numbers

Fig. 7.1. The forms of flow of matter in the fluid state (liquid, gas) have been much studied. Do these material flow morphologies have anything to say to optical flow morphologies in which inertial terms are absent? In material flows, critical values have been identified that mark off distinct energetic states. The well-known Reynolds Number is the value of a dimensionless ratio constructed from the variables that enter into the law of inertia and the law of viscous flow. In situations of fluid flows, a critical value of the Reynolds Number divides smooth laminar flow (a) from turbulence (c) – two different ways in which the energy is distributed among the microelements comprising the fluid. With respect to optical flow fields, a critical value of a dimensionless number would parse the field into distinct *specificational* states (Kugler et al. 1985; Solomon et al. 1984a). Optical π-numbers, like a Reynolds Number, create natural categories. In the optical case, the categorical distinctions are of relevance to controlling behavior.
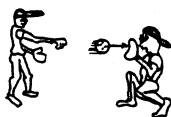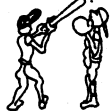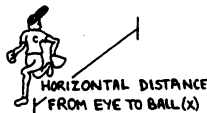
Fig. 7.2. The time-to-contact variable is of particular importance to controlling the behaviors illustrated in figs. 1 and 5. Here, the timing information per se is not as important as what is revealed when $\tau(t)$ is used to construct optical π-numbers – dimensio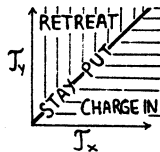nless quantities that specify action categories (Lee 1980). (Top) The derivative of $\tau(t)$ is relevant to the momentum exchanged in a collision (Lee 1980). In order to effect a particular type of contact, an animal must control the optical variable. (Bottom) The trajectory of a projectile can be described in terms of two time-to-contact variables. τ_y specifies when a projectile such as a baseball will intersect a horizontal plane at eye level. τ_x specifies intersection with the plane of the shoulder. Together, τ_y/τ_x specifies what the ball player needs to do in order to intercept the ball (Todd 1981).

With regard to these examples, it should be noted that, as with laminar/turbulent flow, the morphologies are distinct. The numbers, whether optical π or Reynolds, are not computed by the system in order to parse its behavior. They are indices for the scientist to describe the parsing.

8. Linking optical (flow field) properties to action (force field) properties
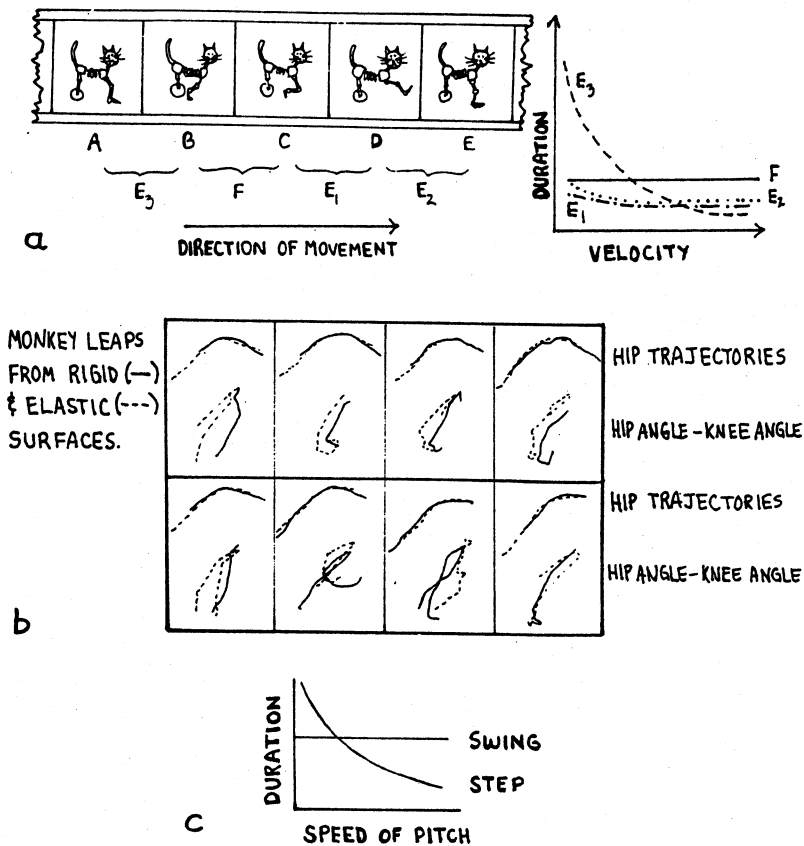

Fig. 8.1. Instances of flow/form/time-to-force laws that characterize the coordination of animal and environment at the ecological scale were described in fig. 3.2. The tight coupling of optical (flow field) properties to action (force field) properties is economical. As Bernstein (1967) noted: in coordinated activity, as many biokinematic variables as possible are kept independent of external conditions. (a) In locomotion, increased velocity is attained by shortening the duration from landing-to-the-next-flexion $[E_3]$ and leaving flexion $[F]$, flexion-to-extension $[E_1]$ and extension-to-landing $[E_2]$ unchanged (Shik and Orlovskii 1965). (b) When monkeys leap from varied surfaces of support to a target shelf, hindlimb joint trajectories remain invariant (only hip trajectories are shown here) even though this is not demanded by the mechanics of the task. The leaps are tuned to the elasticity of the surface by variations in the relationship between the hip angle and knee angle (Johnston 1981). (c) Baseball batters are confronted with pitches whose speed variation is large. Adjustments to this variation are not manifest in the swing, whose duration is constant, but in the speed of opening of the step. Since the start of the swing is linked to (the close of) the step, the swing begins at a constant value of time-to-contact with the ball (Hubbard and Seng 1954). The point of these examples is that only one macroscopic movement parameter – e.g., impulse – appears to change. The argument that follows is that only one macroscopic optical property – $\tau(t)$ – seems relevant to these adjustments.
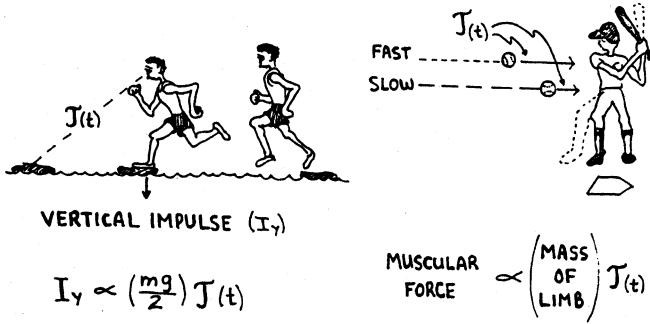
FAST ----------
SLOW ------------

$\mathcal{T}(t)$

VERTICAL IMPULSE (I_y)

$$I_y \propto \left(\frac{mg}{2}\right) \mathcal{T}(t)$$

$$\text{MUSCULAR FORCE} \propto \begin{pmatrix} \text{MASS} \\ \text{OF} \\ \text{LIMB} \end{pmatrix} \mathcal{T}(t)$$

Fig. 8.2. Now we can see how $\tau(t)$ is involved in the particulars of control, viz., the value at time t of an action variable $A(t)$ (e.g., torque at a given joint) is geared to and thus a function of $\tau(t - \Delta t)$, the latest available value of τ. That is, $A(t) = f[\tau(t - \Delta t)]$ where t is a visuomotor delay constant. (Left) In running over irregular terrain, $\tau(t)$ can scale the vertical impulse (I_y) necessary to reach the next safe footfall but only when it is available in the preceding flight phase or E_2 of the current support phase (Warren et al. 1984). The step cycle and its kinetic parameters are assembled afresh every time. (Right) Baseball batters modulate the force of the step – and, thereby, its speed of opening – as a function of $\tau(t)$ of the pitched ball. This has the effect of tuning the swing to the pitch because the swing and step are coordinated in a special way (see fig. 8.1.c).

9. Postscript

At the core of the ecological approach to perceiving–acting is the assertion that perceiving is direct (Gibson 1979; Turvey et al. 1981). Practitioners of the approach, it should be noted, are not in the business of proving direct perception. They are concerned, more particularly, with working out, in a *thoroughgoing* manner, its consequences. Inquiry is constrained by the question of what must be true at nature's ecological scale for perception to be direct (cf. Turvey and Carello 1981). As the philosopher Givner has remarked (personal communication), the fundamental appeal of the theory that perception is direct is that, unlike conventional theory, it generates no epistemological paradoxes. At bottom, that would seem to be the ultimate criterion for a theory of the perceiving that allows animals to control their actions reliably and accurately with respect to their surroundings.

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