ACTION AS AN ORGANIZER OF LEARNING AND DEVELOPMENT

The Minnesota Symposia
on Child Psychology

Volume 33

Edited by
John J. Rieser • Jeffrey J. Lockman
Charles A. Nelson

ROUTLEDGE

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IN MEMORIAM

Esther Stillman Thelen
1941–2004

Esther Thelen died on December 29, 2004, at the end of a most courageous year-long battle with cancer, an illness from which she had been in remission for 25 years. She was a renowned scientist, a leader in her profession, and a generous, caring mentor. Beginning with her early meticulous observations of infants' rhythmic movements, she was responsible for a renaissance in the study of motor development. She introduced developmentalists to the utility of dynamical systems principles for understanding the emergent nature of development, especially motor development. (See her chapter in Volume 22 of this series.) Most recently, as exemplified by her chapter in the present volume, she has shown how dynamic field theory can be expanded and applied to understanding more general problems of remembering and learning in development.

Esther's presentations at scientific meetings were always characterized by deeply penetrating arguments delivered with grace and enthusiasm and intellectual rigor. We were pleased and honored when Esther accepted the invitation to participate in the Minnesota Symposium "Action as an Organizer of Learning and Development." We could never have imagined on that occasion that we would be deprived of the joy of many more exhilarating discussions (accompanied by good food and wine) with her over coming years. We are both proud and sad that what is nearly her last major contribution breaking new ground in our understanding of learning and development appears in this volume. Our field has lost a brilliant scholar and we have lost a cherished friend. We are grateful to have known her.

—Anne and Herb Pick
February 2005

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Preface

The Minnesota Symposium is always a time for celebration, but when the Symposium celebrates some of its own, the occasion is extra special. So it is the case with the 33rd Minnesota Symposium on Child Psychology, which took place at the University of Minnesota from October 10 to 12, 2002. The Symposium was held to honor the scientific and mentoring contributions of Anne Danielson Pick and Herbert L. Pick, Jr., two long-time and beloved professors of the Institute of Child Development.

For many students and colleagues, Anne and Herb have helped to define the spirit of the Institute. They arrived at the Institute of Child Development in the 1960s: Herb made a slight detour at the University of Wisconsin after finishing his degree at Cornell; Anne's detour from Cornell was at Macalester College. At Cornell, both had studied with James J. and Eleanor J. Gibson, with Anne concentrating on studies of perceptual learning with Eleanor Gibson and Herb also concentrating on studies of perception with Richard Walk and Robbie MacLeod.

In the Picks' subsequent work, individually and together, they did much to shape the emerging field of perceptual development and establish it as a core area within the field of child psychology. Ever mindful of the Gibsonian perspective, they extended it to address questions and topics that were not immediately associated with the field of perception—at least at that time. Consider, for example, Anne's widely cited research on reading and selective attention or Herb's influential work on cognitive mapping. Both programs of research richly illustrate how the Gibsonian ecological perspective can introduce new theoretical and substantive questions about topics not traditionally considered to be problems of perceptual or perception-action development.

Yet these achievements tell only part of the story. Like their own mentors James and Eleanor Gibson, Anne and Herb have been extraordinary teachers and advisors—not just to current or former Institute students, but to colleagues around the nation and across the globe. Anne's and Herb's wisdom and generosity have made them a treasure to all who have had the good fortune to study or consult with them.

For all these reasons and more, many former students and colleagues felt that the time was appropriate, if not past due, to honor Anne and Herb for their contributions to the field. When we began discussing this possibility, it was immediately obvious that a Minnesota Symposium was the ideal way to do so. In the collective memories of all who have passed through the Institute, Anne and Herb are clearly identified with the Symposium series. For many years, Anne organized and edited the Symposia volumes—from 1971 to 1976. At each Symposium, Herb always seemed to be in the audience asking *the* question of a presenter—even if the presenter's topic was far outside Herb's research area. Those lessons were not lost on the fledgling developmental psychologists in the audience. The never flagging intellectual curiosity, the good questions, the joy that comes from hearing about elegant and sound experimental methods: these are all qualities that Anne and Herb displayed at symposium after symposium and that many of us have tried to emulate in our own academic careers long after we exited those symposia audiences.

As might have been predicted, when we first contacted Anne and Herb about the idea of holding a Minnesota Symposium in recognition of their contributions, they were honored, but embarrassed. In their typical selfless way, they were quick to say that if a Minnesota Symposium were to be held in their honor, they did not want it about them or their past work. Rather they were interested in seeing a forward-looking symposium—one that would help set the agenda for the field in the areas that they have cared so deeply about in their own research.

So it is in this spirit that the 33rd Minnesota Symposia on Child Psychology evolved. The topic of the Symposia is "Action as an Organizer of Learning and Development." It is a theme that has been central in the Picks' own research in their more than almost 80 collective years in the field. The goal of this Minnesota Symposium was not to look backward, but to integrate the best and most innovative research on the role of action in perceiving and understanding—in other words, in the research areas that Anne and Herb have helped to define.

Given the honorees, it was an easy task to assemble a stellar group of contributors to this Minnesota Symposium. Perhaps less obvious, but nonetheless equally impressive, Anne and/or Herb have served, at one point or another, as mentors or advisors to most all of the distinguished presenters to the 33rd Minnesota Symposium on Child Psychology. More broadly, the impact that Anne and Herb have had on the field through their mentoring of new generations of developmental scientists has been truly exceptional.

Anne's and Herb's mentoring accomplishments speak both to the past and future, as does the work presented at the 33rd Minnesota Symposium on Child Psychology. The Symposium was organized to consider the general theme of "Action as an Organizer of Learning and Development." Contemporary thinking about the role of action in learning and development is in flux. Recent theoretical advances concerning the relation between the development of perception and action are opening new research questions while posing new conceptual challenges. Theoretical advances associated with the work of the Gibsons and Picks have led developmental scientists to realize that the development of perception and action is inextricably linked: Perception guides action, but new motor skills have important consequences for the way in which the world is perceived. People learn to perceive and perceive in order to learn. Additionally, empirical work over the past decade or so indicates that the role of experience in the emergence of so-called *gross motor skills* has been underestimated. Researchers are increasingly recognizing that the development of locomotor skills involves a complex interplay between maturational and experiential factors.

Against this backdrop, there has also been great controversy about what motor behavior can tell us about conceptual development. In large part, the controversy stems from the interpretation of infant visual habituation and looking time studies. These studies have been hailed by some for uncovering astonishing conceptual capacities in infants, but faulted by others for making rich interpretations of looking time differences in infants. How can it be, go the critics, that infants are credited with abundant physical understanding when toddlers show little evidence of such understanding in their manual actions? Although the present Symposium does not fully resolve this particular question, it does ask researchers to take a step back and ask more basic questions regarding how action may help organize learning and development both in infants and older children.

To address these issues and more, we arranged the presentations and resulting chapters from the 33rd Minnesota Symposium into four sections. The first section is concerned with the general topic of "Using Information to Guide Action." In chapter 1, David N. Lee discusses his foundational research on the informational variable *tau,* which corresponds roughly to time to contact. Dr. Lee's work across a variety of species illustrates how the environment is rich in information to help organisms control action. Based on this work, Dr. Lee argues that there are likely biological universals that organisms may use to act adaptively in their respective environments. In chapter 2, Claes von Hofsten discusses the important problem of prospective control in two basic action systems: looking and reaching. Dr. von Hofsten is at the forefront of efforts to uncover the building blocks of humans' sophisticated perceptuomotor abilities by studying the degree to which infants are able to coordinate perception and action. The problem of prospective control is basic to such coordination. In his chapter, Dr. von Hofsten illustrates how prospective control may be achieved by infants through use of information in the environment, enabling infants to engage in anticipatory looking and, remarkably, catching. Chapter 3 by Karen E. Adolph continues to explore the theme of how infants use information in the environment to control action. Dr. Adolph challenges long-standing maturational views about motor development and highlights the importance of experience and learning to learn. She reports extraordinary data obtained in infants' homes regarding their vast amount of crawling and walking experience—experience that unquestionably helps infants to perfect their new locomotor skills. Finally, in chapter 4, William H. Warren provides a discussion of these chapters. Dr. Warren is a leading expert on the visual control of action and ecological psychology. In his discussion, he places the current chapters in the larger context of past and present research aimed at uncovering regularities in the ways in which organisms and environments physically interact.

Section II represents a reunion of sorts for three Institute alumni. Richard N. Aslin (University of Rochester), Martin S. Banks (University of California, Berkeley), and Emily W. Bushnell (Tufts University) not only overlapped during their years of graduate study at the Institute, but attended at that time the same research group meetings while beginning to make their respective marks on the field of perceptual development. Since that time, each has gone on to make fundamental contributions to the field. Their contributions to the Symposium address the topic of "Computational Complexity and the Integration of Information." In chapter 5, Richard N. Aslin discusses his influential research on statistical learning and the complex problem of object recognition: Organisms may have evolved specialized learning mechanisms to recognize objects based on detecting regularities in informational input. As Dr. Aslin reports, however, statistical learning based on passive perceptual exposure is shown relative to active perceptuomotor responding, which occurs more quickly. This difference, in turn, raises intriguing questions about the nature and extent of object knowledge when perception versus perception and action are involved—an issue that is considered in subsequent chapters as well. In chapter 6, Martin S. Banks describes his recent work on a related problem of object recognition—how individuals combine information about object properties within and across modalities. To address this problem, Dr. Banks proposes that individuals employ a weighting mechanism to solve this fundamental combinatorial problem. In the chapter, Dr. Banks provides support for this proposal through a seamless integration of empirical and modeling studies conducted in his laboratory. As Emily N. Bushnell shows in chapter 7, the processing mechanisms formulated by Aslin and Banks have important implications for understanding the acquisition of a variety of developmental milestones, many of which involve some form of perceptuomotor learning.

The chapters in Section III are devoted to the topic of "Active Learning During Early Development." In chapter 8, Nora S. Newcombe leads off the section with a chapter that considers the roles of language and action in coding spatial location while moving in space. She focuses on recent claims that young children rely on geometric rather than local landmark information to encode an object's location. Her systematic studies illustrate that children's use of such geometric information to code location is not absolute. Rather she favors a cue validity approach based on the values of different types of spatial reference system information given the demands of particular spatial tasks. Note that in a formal sense, the solution via sampling different types of spatial cues advocated by Newcombe shares much in common with the weighting mechanisms advocated by Aslin, Banks, and Bushnell in their chapters on object recognition. Chapter 9 by Esther Thelen and Virgil Whitmyer offers a far-reaching theoretical and empirical synthesis of research on action, perception, and cognition. In their chapter, Drs. Thelen and Whitmyer draw from research on object permanence, visual habituation, and early physical knowledge to present a unified account of how object knowledge is rooted in action. They present a new theoretical approach based on dynamic field theory to integrate these often separate research areas. In so doing, they also account for previously ignored findings and offer new, testable, and exciting predictions. More broadly and like Banks, Drs. Thelen and Whitmyer demonstrate the potential value of combining behavioral and modeling approaches to study the processes that govern learning and development. In chapter 10, Bennett I. Bertenthal discusses the Newcombe and Thelen and Whitmyer chapters in relation to the more general question of what it means to have knowledge of an object. For this purpose, he integrates research from psychology and the neurosciences and argues how the current chapters support the idea that knowledge about what an object is and how to act on an object may be dissociable. As Dr. Bertenthal suggests, understanding how these two basic sources of knowledge become progressively coordinated during development needs to become an explicit goal of future research.

Section IV is organized around the topic of "Using Representations to Guide Action." Throughout the Symposium, a key issue that emerged concerned the different ways in which researchers invoke the notion of representation in their research. The chapters in the present section deal with the particular issue of how children use representations to guide and control action. In chapter 11, Rachel Keen focuses on young children's physical knowledge or lack thereof when attempting to find hidden objects. These difficulties are especially surprising in light of prior research indicating that infants possess sophisticated knowledge about the continuity and solidity of objects—knowledge that should enable preschool children to solve the problems used by Keen. Dr. Keen presents a clever and programmatic series of studies designed to investigate the source of children's difficulties. These studies do much more, however. They go beyond this particular search task and address deep-seated issues about the nature of object knowledge. Dr. Keen's chapter thus raises important questions about how dissociations across different dependent measures of object knowledge—looking versus manual action—should be interpreted, a theme echoed by other contributors to this Symposium volume. In chapter 12, Lynn S. Liben focuses on a different problem of representational use: how children employ external representations to guide action. Dr. Liben reviews her path-breaking research on children's use of maps and other types of place representations. In this connection, she addresses the complementary issues of how human action affects and is affected by external representations of place—issues informed by a consideration of both Gibsonian and Piagetian theoretical traditions. As Dr. Liben notes, conclusions from her studies have important implications for how children should be taught about maps and other graphic representations in school settings. In chapter 13, Janellen Huttenlocher offers not only a commentary on the preceding two chapters, but a cogent distillation of how the term *representation* has been used and perhaps misused in work in developmental psychology over recent years. Dr. Huttenlocher has conducted pioneering research about imagery, spatial representations, and concepts. Her discussion here provides new insights about the relation between motor development and conceptual development, and, more generally, thought and action.

As a reader, you are in for a treat. The chapters that follow certainly capture the intellectual excitement that characterized the 33rd Minnesota Symposium on Child Psychology. If you read between the lines, you may also get a sense of the tributes to Anne and Herb that accompanied each presentation in addition to those from other friends, colleagues, and former students who attended the Symposium. One tribute needs to be highlighted, however. Eleanor J. Gibson, in failing health and shortly before she died a few months after the Symposium, recorded a very special video tribute to her two former students, Anne and Herb. After that surprise tribute was shown at the end of the Symposium, there were no dry eyes in the house, especially the ones of those two former students.

A collective undertaking like the Symposium depends on the contributions of many individuals. Without the help of the staff, graduate students, and faculty of the Institute of Child Development, this Symposium would not have been possible. We are especially grateful to Signe Bobbitt, Claudia Johnston, and Kay O'Geay of the Institute of Child Development for all their efforts connected with making the Symposium seem, well, effortless. We would also like to thank the Institute of Child Development, the Center for Cognitive Science, and the Department of Psychology, all of the University of Minnesota, for their financial support of the Symposium. And we are grateful for the Leveritt-Miller Fund of Vanderbilt University and the Wissenschaftskolleg zu Berlin for providing support for the volume. Additional thanks go to Linda Acredolo, Mervyn Bergman, Andy Collins, Marion Eppler (who traveled to Vermont to prepare the video tribute from Jackie Gibson), Peggy Hagen, Gordon Legge, Anne Masten, Cindy Pick, Karen Pick, Gretchen Pick, and Jerry Siegel. Finally, we must thank Anne and Herb, who have been an inspiration to all of us and to whom we present and dedicate this volume.

Jeffrey J. Lockman
Charles N. Nelson
John J. Rieser

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I

USING INFORMATION TO GUIDE ACTION

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1

Tau in Action in Development

David N. Lee
University of Edinburgh

ANIMALS ARE BORN TO MOVE

When we watch children take their first steps, a baseball player hit a home run, a pianist play Mozart, birds dive on prey, bees flit from flower to flower, we cannot help but wonder: How do they do that? Understanding movement is central to understanding development. Without movement we—by which I mean the animal kingdom—would not be able to eat, avoid harm, reproduce, or communicate by sound, gesture, or facial expression. We would not be able to perceive because perception is an active process. Consequently, we would not be able to think because there would be nothing to think about. We would not even be able to breathe or pump nutrients around the body. In short, we would be dead.

How is movement controlled and how does the ability develop? I first consider basic principles underlying animal movement. Next I outline a theory (General Tau Theory) of movement guidance based on those principles. Finally, I describe experiments testing the theory and discuss applications of the theory in the study and measurement of development of movement control.

PRINCIPLES OF ANIMAL MOVEMENT

James J. Gibson and Nicholai Bernstein never met and knew little or nothing about each other's work. However, they came to similar conclusions about the nature of animal movement. Separately they pioneered the field of perception and movement control and laid firm foundations for future research. Gibson (1966) approached the problem more from the perceptual angle, Bernstein (1967) more from the movement side. From their work, the following five general principles of animal movement may be distilled:

1. *Movement requires perceptual guidance.* The reason that this must be so is that movements are brought about not simply by muscular forces, but also by external forces such as gravity and friction. Because the external forces are not wholly predictable, they could deviate a movement from its intended course. Therefore, the progress of a movement needs to be monitored perceptually to enable appropriate muscular adjustments to be made. One or more of the perceptual systems may be involved in the monitoring. The articular proprioceptive system, comprising sensors in the joints, muscles, and skin, is constantly active during all movements. The vestibular system is active whenever head movement is part of the action, which it normally is. Hearing is active in movement monitoring whenever controlled sounds are being produced, as when speaking, singing, playing a musical instrument, and guiding movement around the world using echolocation, whether as bat, dolphin, or human. Vision can be active in a multitude of ways in guiding movement. However, one cannot be looking everywhere at once, and to pick up detailed information you need to move your gaze around in an efficient way. Learning to drive, for example, is very much about learning where to look and when. Vision also appears to act as an overseer of the other perceptual systems, keeping them mutually in tune (Lee, 1978).
2. *Movement requires intrinsic guidance.* An animal fashions movements to its purpose, and so movement must also be guided intrinsically. When singing, for example, the music that guides the voice comes from within the singer. Yet, as just mentioned, hearing is required to monitor the voice to make sure it is doing what the inner music directs. Running is another example. The running style comes from within the runner while the eyes guide the progress across the ground.
3. *Movements are prospectively guided.* They flow ahead in time like a melody. This has to be so because an animal has limited power available for making a movement. Therefore, if it does not manage its power resources prospectively, it could end up not having sufficient power available to complete a movement properly. This could have dire consequences if an animal runs out of braking power when trying to stop at a cliff edge.
4. *Movement information embraces the future.* For movements to be guided prospectively, the information guiding the movement, whether

perceptual or intrinsic, must allow adequate extrapolation of the movement into the future. Therefore, the information must have a temporal structure that extends it forward beyond the immediate present.

5. *Movement guidance is simple, rapid, and reliable—and probably follows universal principles.* That movement guidance is rapid and reliable is evident from watching the behavior of any animal. The fact that animals with small nervous systems, such as insects, perform movements with a precision comparable to our own suggests common simple underlying principles of movement guidance.

INFORMATION GUIDING HANDS AND OTHER EFFECTORS

Watching a slow motion film of a fielder catching a fast cricket ball with one hand while diving over the ground brings out two important points. First, the body can move in an indefinite number of ways when directing an effector (the hand in this case) toward something. Even in everyday activities this is the rule rather than the exception. Consider, for example, picking up a coffee cup from a desk. This can be done with equal facility when stepping over to the desk, when swiveling around on a desk chair, or when simply reaching across the desk. In short, reaching is about controlling the movement of the hand relative to the object of the reach. Depending on the circumstances, this can require a variety of different forms of body movement.

The second point concerns the connection between the hand and the object. When watching a fielder catching a ball, one can get the impression that the ball is physically connected to the hand even before the catch is made. It is as if hand and ball are connected by invisible elastic that draws them together. There is, in fact, a physical connection between the hand and the ball before contact is made. It is not, of course, a material connection like a piece of elastic. Rather it is an informational connection more like that between an operator and a radio-controlled model plane. In general, the information that prospectively guides movement is obtained through several perceptual systems. For the fielder, these at least include vision and the articulatory system of sensors in joints, muscles, and skin. For a bat catching an insect on the wing, echolocation is used instead of vision. Whatever the perceptual systems involved, a central component is the information about the changing motion-gap between an effector and its goal (hand and ball for the fielder, wing and insect for the bat) that enables the gap to be prospectively controlled. The motion-gap may be propriospecific, between an effector and part of the body, as when putting food in the mouth, or it may be expropriospecific, between an effector and an external object or surface, as in the ball-catching example (Lee, 1978).

As a general rule, we may think of an effector as anything that is controlled to a goal. It may be a hand as in grasping, a foot as in securing footing, a mouth as in seizing food, or it may be a tool controlled by a person. When manipulating a computer mouse, one reaches with the cursor, not the hand. When holding a laser pointer, one reaches with the laser beam. When using a remote-controlled surgical instrument, one reaches with the remote instrument. In all these examples, the body movements are quite different. Therefore, *the essence of moving an effector to its goal does not reside in the pattern of limb movements that moves the effector. Rather it lies in the form of closure of the motion-gap between the effector (hand, foot, cursor, beam, instrument) and the goal.*

Controlling the closure of the motion-gap between an effector and its goal, as when reaching, is a perceptuomotor act. However, most theories of reaching have primarily addressed just the motor aspects. They have been basically concerned with explaining the dynamics of reaching with the arm and hand in terms of mathematical models of the physiconeural structure of the musculature (Bizzi et al., 1992; Feldman & Levin, 1995; Flanagan et al., 1993). The theories assume that movement of the arm and hand is directed by perceptual information—by shifting the limb's equilibrium point (see Flanagan et al., 1993, for a review of different forms of the equilibrium point hypothesis)—but no explanation of the perceptual component is considered in the theories. However, it is essential that the perceptual component is taken into account when trying to understand control of reaching or any other movement. For example, visual information picked up during reaching can guide the limb and adjust for motion of the goal (Flash, 1990; Georgopoulos et al., 1981; Péllison et al., 1986; Soechting & Lacquaniti, 1983; van Sonderjen et al., 1989).

In short, perceptual information is part and parcel of an act. Thus, if a motion-gap variable, such as its size, is being controlled, there must be a perceptual information variable (or variables) that specifies the value of the motion-gap variable. Conversely, if there is no perceptual information variable that specifies the value of a particular motion-gap variable, then it cannot be controlled. Consider, for example, moving a laser spot to a goal position across a wall that is an uncertain distance away. This can be done quite smoothly and accurately, although there is no perceptual information variable specifying the size of the motion-gap on the wall between the current position of the laser spot and the goal. Therefore, it cannot be the size of the motion-gap that is being controlled in this situation, but some other measure, X. To be sure, if, in another situation, there were perceptual information variables specifying both X and the size of a motion-gap, then the size might be controlled in this case. However, an explanation of control that applies to all situations is to be preferred to a set of ad hoc explanations. Therefore, let us see what General Tau Theory has to offer by way of providing a universal control variable for all situations.

GENERAL TAU THEORY

To summarize thus far, I have argued that an adequate theory of guidance of movement must be based on and adhere to the principles of animal movement outlined earlier. That is, *an adequate theory must explain how movements are perceptually and intrinsically guided. It must explain the form of the guiding perceptual information that enables prospective guidance of movement, and it must be biologically plausible.* So where do we start?

Motion-Gaps

A key aspect of animal movement is that it is goal-directed. Therefore, a basic concept is that of motion-gap. I introduced this concept earlier when discussing the closure of distance motion-gaps, as when catching a ball. However, the concept is more general than this. A motion-gap is the changing gap between the state the animal is currently in and the goal state that it wants to be in. When reaching for a fruit, there is the distance motion-gap between the hand and the fruit. When turning gaze to look at something, there is the angular motion-gap between the current gaze direction and the direction of the object. When thrusting off from a stair, there is the force motion-gap between the current force and the force require for satisfactory lift-off. When singing, there is the pitch motion-gap between the current pitch and the next pitch, which in turn requires controlling other motion-gaps within the vocal system. Note that the dimension of the motion-gap is different in each of these examples—namely, distance, angle, force, and pitch. Thus, the concept of motion-gap is not tied to a particular dimension.

All actions entail closing motion-gaps. Invariably, several motion-gaps need to be controlled at the same time. Running down stairs is an example. You need to coordinate the closure of gaze-stair and foot-stair motion-gaps if you want to get down in one piece. Controlling the closure of a motion-gap requires obtaining perceptual information about the gap and how it is closing. Motion-gaps come in different dimensions (distance, angle, etc.). Yet does this mean that the perceptual information about the gaps has to come in different dimensions also? At first blush, that would appear inevitable. However, it would lead to a complicated system of mixed-dimensions control. Maybe evolution has found a neater solution (it usually does) and measures all motion-gaps in the same dimension.

What might that dimension be? It is unlikely to be one of the dimensions considered so far (distance, angle, force) because that would give one type of motion-gap (distance, say) a privileged position and so would not be a symmetrical solution. Most likely evolution has used the dimension that underlies the process of change of any motion-gap—namely, time.

Tau: A Universal Variable for Controlling Motion-Gaps

Can a single type of temporal variable of a changing motion-gap provide sufficient information for controlling the closure of the motion-gap? It turns out that tau can (Lee, 1998). Tau of a motion-gap is the time to closure of the motion-gap at its current closure rate. [To express it symbolically, suppose that at time t, the size of a motion-gap is $x(t)$ and the rate of change of $x(t)$ is $\dot{x}(t)$. Then tau of the motion-gap at time t is written as $\tau(x,t)$, and this equals $x(t)/\dot{x}(t)$.] Note that tau is a measure on any motion-gap of any dimension (the dimension of x may be distance, angle, force, etc.), and the value of tau may be sensed, in principle, by any perceptual means (vision, hearing, touch, echolocation, etc.). Thus, to dispel a common misconception, tau is not the inverse of the rate of dilation of an optical image any more than gravity is the apple falling on Newton's head. The apple falling is an example of the general principle of gravity, and the image dilation is an example of the general principle of tau.

Tau-Coupling

Let us now consider how perceiving the tau of a motion gap would benefit an animal. Here a basic concept is *tau-coupling*. Two taus are coupled over a period of time if they remain in constant proportion during that time. Expressed symbolically, the taus (τs) of two gaps, $x(t)$ and $y(t)$, are tau-coupled if

$$\tau(x,t) = K\tau(y,t) \tag{1}$$

for a constant K (the coupling constant). t stands for time. The gaps may be of different dimensions. As an example, consider a bat flying in to land on a perch (Fig. 1.1a). To land properly, the bat has to control the closure of two motion-gaps simultaneously. There is the distance motion-gap, X, between the bat and the perch and the angular motion-gap, A, between the current direction of the line between the bat and the perch and the direction that line needs to lie in during the final approach to the perch. The distance motion-gap, X, needs to be closed to zero in a controlled way to

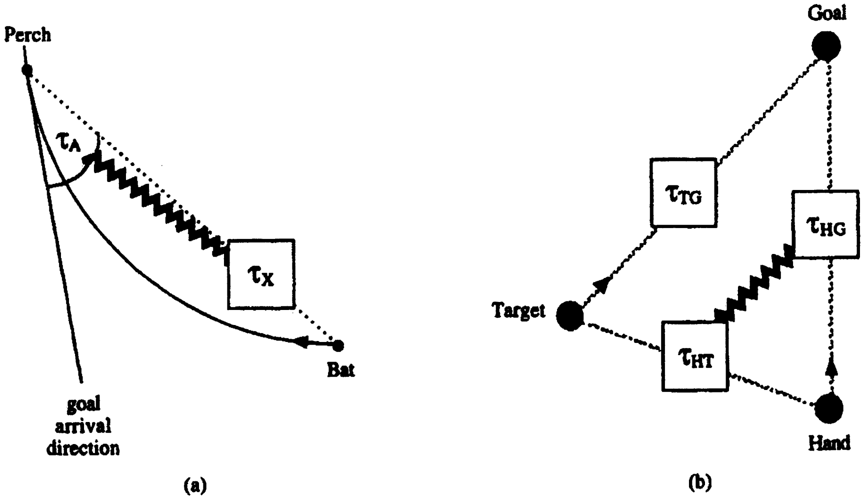

FIG. 1.1. Tau-coupling. (a) Echolocating bat flying to a perch by keeping $\tau_A = K\tau_X$. (b) Human adult intercepting a moving target at a goal zone by keeping $\tau_{HG} = K\tau_{HT}$.

avoid crashing into the perch. Simultaneously, the angular motion-gap, Y, needs to be closed to zero to approach the landing from the right direction (remember that the bat also has to somersault just before landing so that it ends up on the perch upside-down). A film analysis of a bat performing this remarkable feat indicated that it controlled its flight by tau-coupling (Lee et al., 1995). [The coupling equation was $\tau(A,t) = K\tau(X,t)$, written as $\tau_A = K\tau_X$ in Fig. 1.1a.] The tau-coupling automatically ensures that gaps A and X close simultaneously. This is because a gap reaches closure as the tau of the gap becomes zero. [As $\tau(X,t)$ becomes zero, $\tau(A,t)$ becomes zero because $\tau(A,t) = K\tau(X,t)$, and so both A and X also become zero.] However, this is not the whole story on the bat landing. The value of the coupling constant K is also important in determining the dynamics of the movement. We come to this later.

Tau-coupling also applies when intercepting something (Fig. 1.1b). In a recent experiment (Lee et al., 2001), adults had to move a hand cursor up a computer screen by means of a joystick so that it stopped in a goal zone just as a moving target cursor, moving in a straight line with unpredictable speed, reached the goal zone. The relevant motion-gaps here are between hand and goal, hand and target, and target and goal. Analysis of the movement trajectories of hand and target indicated that the participants solved the task by keeping tau of the hand-goal gap coupled onto tau of the hand-target gap [i.e., they kept $\tau(X_{HG},t) = K\tau(X_{HT},t)$, for a constant, K. The equation is written as $\tau_{HG} = K\tau_{HT}$ in Fig. 1.1b].

Tau-G

The last experiment shows how intercepting a moving object such as a ball can be achieved by coupling the tau of the motion-gap between the hand and the ball onto the tau of the motion-gap between the hand and the place of interception. Information about the ball's motion tau-guides the hand. Yet what about reaching the hand out to a stationary ball or playing a note on a piano? In these self-guided movements, again there is the tau of the gap between the effector and its goal. However, there is apparently no other tau to couple onto to guide the movement. At least there is no other extrinsic tau to couple onto. Nonetheless, self-guided movements are well formed both spatially and temporally. Therefore, there must be some information guiding them. Might the tau of the effector–goal gap be coupled onto a (changing) intrinsic tau value generated in the nervous system—by, for instance, a patterned energy flow in the brain? If so, what form might the intrinsic tau take? We might expect that, during the course of evolution, intrinsic taus will have been assimilated by animals while moving in the environment. Because gravity has a ubiquitous influence on an animal's movement, there are likely to be intrinsic taus that reflect the animal's movement under gravity. One common movement is the up-and-down motion of the body during locomotion. Therefore, there might well be an intrinsic tau that corresponds to this up-and-down motion. Such was the line of thought that led me to the tau-G hypothesis.

Tau-G is a changing tau value that, at each moment, has the same value as the tau of the vertical gap to the ground of an object, such as a ball, that is launched from the ground under gravity, reaches its zenith, and then drops down to the ground again (Fig. 1.2). Thus, tau-G is generated by, and could be sensed by, a running animal during each flight phase. Therefore, it is deeply rooted in the ecology of animals.

Let us now consider what would be the consequences of using tau-G for intrinsically guiding a movement. For completeness, we consider the tau of a motion-gap being tau-coupled onto tau-G for the full duration of tau-G (i.e., from "launch" to "landing"). In general, however, coupling may commence partway through tau-G's course. As an illustration, we consider moving a golf club relative to a golf ball. Let the motion-gap between the club-head and the ball at time t be x(t). If tau of the motion-gap is tau-coupled onto tau-G (τ_G), then $\tau(x,t) = K\tau_G(T_G,t)$, where K is a constant and T_G is the duration of tau-G. This equation can be solved to derive the dynamic equations for the motion-gap, x(t) (Appendix 1). Figure 1.3a–f shows plots of x(t) and $\dot{x}(t)$ [the rate of change of x(t)] for three ranges of K. (The plots are useful, for example, when eye-balling data, prior to a detailed analysis, to see whether the data might fit the tau-G hypothesis.) The three ranges of K give rise to distinct types of movement.

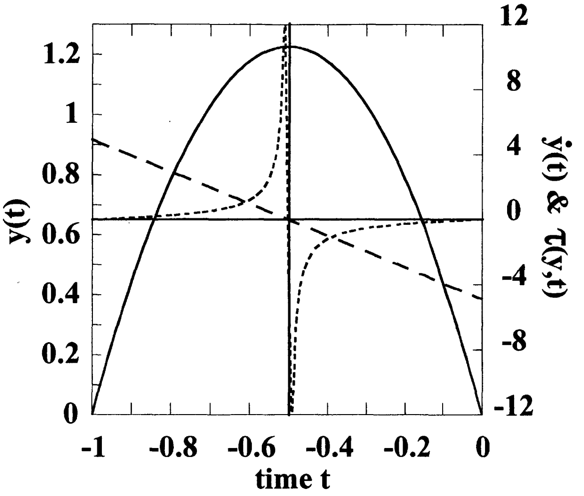

FIG. 1.2. The tau-G guide, $\tau_G(T_G,t)$. Illustrating how the equation for the guide (Appendix 1) would be generated by a ball that is launched from the ground under the gravitational acceleration of $9.81ms^{-2}$, rises to its zenith, and then falls back to the ground. The ball is launched at time t = –1s and lands at time t = 0s. Thus, the duration, T_G, of the tau-G guide is 1s. The solid line represents the height, y(t), of the ball at successive times, t. y(t) increases from 0m at t = –1s (the launch), reaches its maximum of 1.23m at t = –0.5s (the zenith), and then decreases to 0 at t = 0s (the landing). The dashed line represents the vertical component of velocity of the ball, $\dot{y}(t)$. This starts with a value of $4.9ms^{-1}$ at t = –1s, decreases to zero as the ball reaches its zenith at t = –0.5s, and then becomes negative as the ball drops, reaching a value of $-4.9ms^{-1}$ as it hits the ground at t = 0s. The curves for y(t) and $\dot{y}(t)$ are calculated from Newton's equations, ignoring air resistance. The dotted line represents $\tau(y,t)$, the τ of the gap between the ball and the ground. $\tau(y,t)$ is calculated from y(t) and $\dot{y}(t)$ using the formula $\tau(y,t) = y(t)/\dot{y}(t)$. Like time, t, $\tau(y,t)$ is measured in seconds. $\tau(y,t)$ starts at a value of zero as the ball is launched at t = 0s. It then increases steadily to positive infinity as the ball climbs to its zenith at t = –0.5s. Immediately thereafter, its value switches to negative infinity, and then decreases steadily to reach zero as the ball lands at t = 0s. The plot of $\tau(y,t)$ is the same as that of a general gravity τ_G-guide, $\tau_G(T_G,t)$, of duration T_G = 1s. Note that when a motion-gap, x(t), is τ-coupled onto a gravity τ_G-guide through the equation $\tau(x,t) = K\tau_G(T_G,t)$ for different constants, K, the plots of $\tau(x,t)$ (Fig. 1.3g–i) have the same general shape as the plot of $\tau(y,t)$ (Fig. 1.2). The $\tau(x,t)$s are simply scaled versions of $\tau(y,t)$, the scaling factor being the coupling constant, K. The value of K has a more dramatic influence on the plots of $\dot{x}(t)$ (Fig. 1.3d–f). These vary as a function of the value of K and are quite different in shape from the plot of $\dot{y}(t)$ in Fig. 1.2 (except for the straight line plot in Fig. 1.3f, which corresponds to K = 1).

For all values, K, the club-head starts in contact with the ball [at $x(-T_G) = 0$]; it then recedes from the ball until it reaches the end of the backswing [at $x(-T_G/2) = -1$]; finally, it moves forward and contacts the ball [at $x(0) = 0$]. Differences between the three ranges of K occur in the vicinity of the ball [i.e., when $x(t)$ is close to zero].

When $0 < K \leq 0.5$ (Fig. 1.3a & 1.3d), the club-head starts at rest at the ball and moves away with increasing acceleration from a zero value; it then decelerates, reverses direction at the top of the backswing, and accelerates back toward the ball; finally, it decelerates at a decreasing rate and stops at the ball. Thus, when $0 < K \leq 0.5$, the movement ends with touch contact, as when reaching for something light and small. As K increases from 0 to 0.5, the mean absolute force and power involved in moving the club-head increases (Fig. 1.3j & 1.3m) and the maximum velocity of the club-head decreases (Lee, Grealy, Pepping, & Schögler, 2004).

When $0.5 < K < 1$ (Fig. 1.3b & 1.3e), the club-head starts at rest at the ball and moves away with a high initial acceleration (infinite, in theory), which decreases to zero; the club-head then decelerates, reverses at the top of the backswing, and accelerates toward the ball; it then decelerates at an increasing rate until it reaches its maximum deceleration, which is maintained until the ball is hit. Thus, when $0.5 < K < 1$, the movement ends with hard contact with the ball, with the club-head decelerating. The mean absolute force and power involved in moving the club-head are both lowered by increasing K (Fig. 1.3k & 1.3n). The velocity at contact is raised by increasing K (for any given maximum deceleration) or decreasing maximum deceleration (for any given K), and the maximum velocity of the club-head decreases as K increases from 0.5 to 0.66 and then increases as K increases further (Lee, Grealy, et al., 2004).

When $K = 1$, the club-head starts moving away from the ball at speed, decelerates at a decreasing rate (at constant rate when $K = 1$), reverses at the top of the backswing, accelerates at an increasing rate (at constant rate when $K = 1$) until it reaches its maximum acceleration, and finally hits the ball at high velocity. Thus, when $K = 1$, the movement ends with hard contact with the ball, with the club-head accelerating. The mean absolute force and power involved in moving the club-head are both raised by increasing K (Fig. 1.3l, 1.3o). The velocity at contact and the maximum velocity of the club-head are the same when $K = 1$; they are each raised by increasing K, for any given maximum acceleration, or by increasing maximum acceleration, for any given K (Lee, Grealy, et al., 2004).

The duration (T_G) of tau-G and the amplitude of the movement also affect the dynamics of the club-head. (Duration and amplitude were assumed constant earlier.) As duration, T_G, decreases and/or movement amplitude increases, velocity at contact increases, as do absolute force and power involved in moving the club-head (Lee, Grealy, et al., 2004).

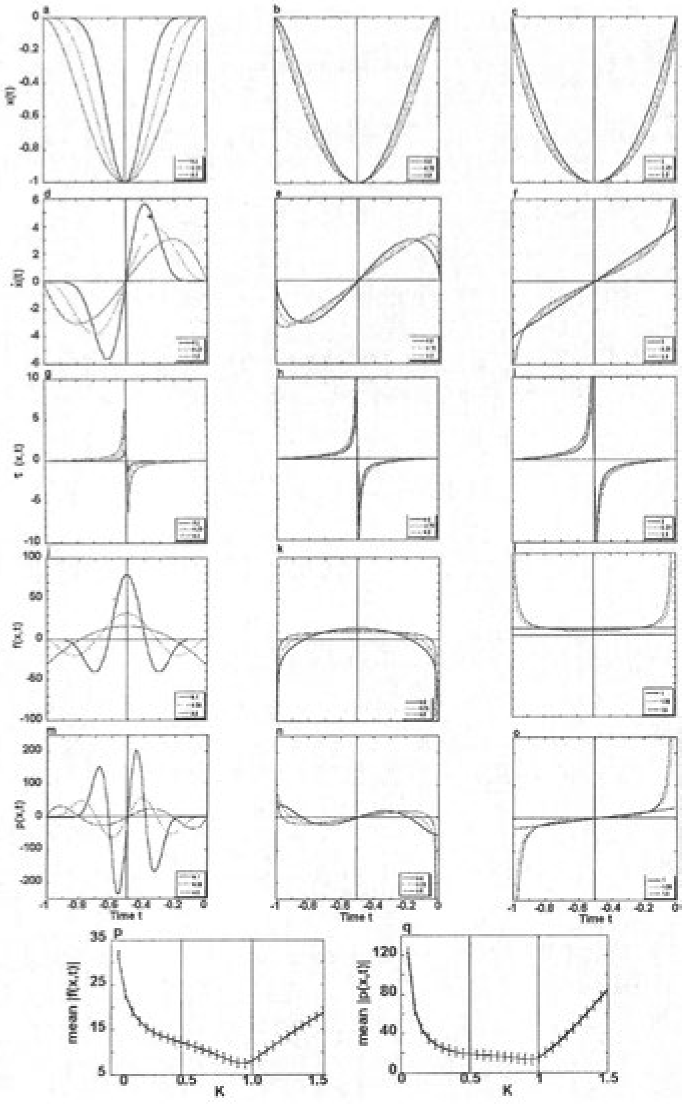

FIG. 1.3. The dynamics of motion-gaps generated by coupling onto a tau-G guide. Three ranges of value of the constant K in the coupling equation $\tau(x,t) = K\tau_G(T_G,t)$ are illustrated. Col. 1: $0 < K \leq 0.5$. Col. 2: $0.5 < K < 1$. Col. 3: $1 \leq K$. At time t, $x(t)$ = size of the motion-gap (m), $\dot{x}(t)$ = the rate of change of the size of the motion-gap (ms^{-1}), $\tau(x,t)$ = τ of the motion-gap (s). $|f(x,t)|$ (N) is the absolute force, and $|p(x,t)|$ (W) is the absolute power required to move a mass of 1kg and generate the motion-gap. The equations generating the curves are given in Appendix 1. The bottom two plots (p, q) show how the mean absolute force (N) and power (W) required to move a unit mass and generate the motion-gap varies as a function of K. Standard deviation bars are shown.

In summary, if the tau of the motion-gap between an effector and its goal is tau-coupled onto an intrinsic tau-G, the time courses of the velocity, force, and power of the movement, and the velocity of contact at the end of the movement, are all determined by the values of three parameters: the coupling constant (K), the duration of tau-G, and the amplitude of the movement.

Tau-g

An earlier hypothesis about intrinsic guidance of movement from rest postulated that the tau of the motion-gap is tau-coupled onto an intrinsic tau, designated τ_g (Lee, 1998). τ_g corresponds in value to the tau of the motion-gap to a goal of an object accelerating at a constant rate from rest to a goal. Thus, a τ_g corresponds to the second half of a tau-G. Whereas tau-G is generated by both the upward and downward motion of a ball under gravity (Appendix 1), τ_g is generated by just the downward motion. Thus, the τ_g hypothesis is but a special case of the more general tau-G hypothesis. The formula for τ_g is the same as for tau-G (Eq. 1, Appendix 1) except that τ_g only extends over the second half of a tau-G. This means that experiments supporting the τ_g hypothesis also support the tau-G hypothesis. There are a number of such supportive experiments spanning a wide range of activities (Lee, 1998). They indicate, for example, that newborn babies control their suction when feeding from a bottle and golfers control their swing when putting in a similar way by using an intrinsic τ_g or tau-G (Craig & Lee, 1999; Craig et al., 2000).

Tau-Dot

The earliest hypothesis about the use of tau in controlling the closure of a motion-gap was formulated in the context of braking a vehicle to stop at an obstacle (Lee, 1976). The hypothesis is that, during the deceleration phase to an obstacle, the time derivative of the tau of the motion-gap to the obstacle (tau-dot or $\dot{\tau}$) is kept equal to a constant, k. If k is less than or equal to 0.5, this would ensure stopping at the obstacle. Unlike the τ_g hypothesis, the tau-dot hypothesis is not a special case of the tau-G hypothesis. However, it turns out that the two hypotheses make numerically rather similar predictions about the final deceleration phase of a movement to the goal, which is the only phase to which the tau-dot hypothesis applies. Consequently, evidence for the tau-dot hypothesis is also evidence for the tau-G hypothesis. Such evidence spans a wide range of behaviors, including hummingbirds docking on a feeder (Lee, Reddish, &

Rand, 1991), trampolinists somersaulting (Lee, Young, & Rewt, 1992), and drivers braking in a simulator (Yilmaz & Warren, 1995).

Perceiving Tau

Tau-coupling requires perceiving tau: tau is perceptible through tau-coupling. Let me elaborate on this interesting duality. It would be very useful for an evolving organism. For an animal to tau-couple the tau of a motion-gap onto the tau of another motion-gap, or onto a tau-G, it needs to perceive the tau of the motion-gap. Fortunately for the animal, there are naturally occurring tau-couplings that make the perception of tau a relatively easy matter. This is because power laws abound in nature and there is a simple theorem relating power laws and tau-couplings (Lee et al., 1992). For example, suppose we have a motion-gap, $Z(t)$, between a person and a frontal plane containing a tree of height, D (see Fig. 1.4a, bottom). The sensory gap, $r(t)$, corresponds to this physical gap, $Z(t)$. As $Z(t)$ shrinks, $r(t)$ expands. In fact simple geometry reveals that $r(t)$ is a power function of $Z(t)$—namely, $r(t) = DZ(t)^{-1}$. The final step, involving simple calculus, shows that if $r(t) = DZ(t)^{-1}$, then $\tau(Z,t) = -\tau(r,t)$. Thus, the physical tau, $\tau(Z,t)$, is perceptible through the sensory tau, $\tau(r,t)$. Figure 1.4b (and caption) also shows how the tau of a motion-gap in a frontal plane is perceptible through a sensory tau by virtue of the taus being coupled. The general power-law, tau-coupling theorem is this. If a sensory gap, $r(t)$, corresponds to a motion-gap, $Z(t)$, and $r(t) = CZ(t)^{\alpha}$ for constants C and α, then $\tau(Z,t)$ and $\tau(r,t)$ are tau-coupled by the equation $\tau(Z,t) = \alpha\tau(r,t)$. Note that the exponent, α, in the power law relation, $r = CZ^{\alpha}$, becomes the coupling constant, the multiplier in the tau-coupling equation, $\tau(Z,t) = \alpha\tau(r,t)$.

In summary, whenever there is a sensory variable, $r(t)$, that is a power function of a motion gap, $Z(t)$, with exponent, α, the tau of the motion-gap, $\tau(Z,t)$, is, in principle, directly perceptible from the tau of the sensory variable, $\tau(r,t)$, because $\tau(Z,t) = \alpha\tau(r,t)$. Examples of how tau of a motion-gap could be perceived via tau-coupling in echolocation, electrolocation, and other sensory modalities are given in Lee (1998). Examples of experiments showing that tau of a motion-gap can be directly perceived visually from the planar projection of the motion-gap—and therefore without information about the size or rate of change of size of the motion-gap—are given in Yilmaz and Warren (1995) and Lee et al. (2001).

Distance From Tau and Direction

Tau is not everything by way of information needed by an animal to get around in the world, but it is almost everything. Color apart, the other information required is directional information. An animal needs to be able

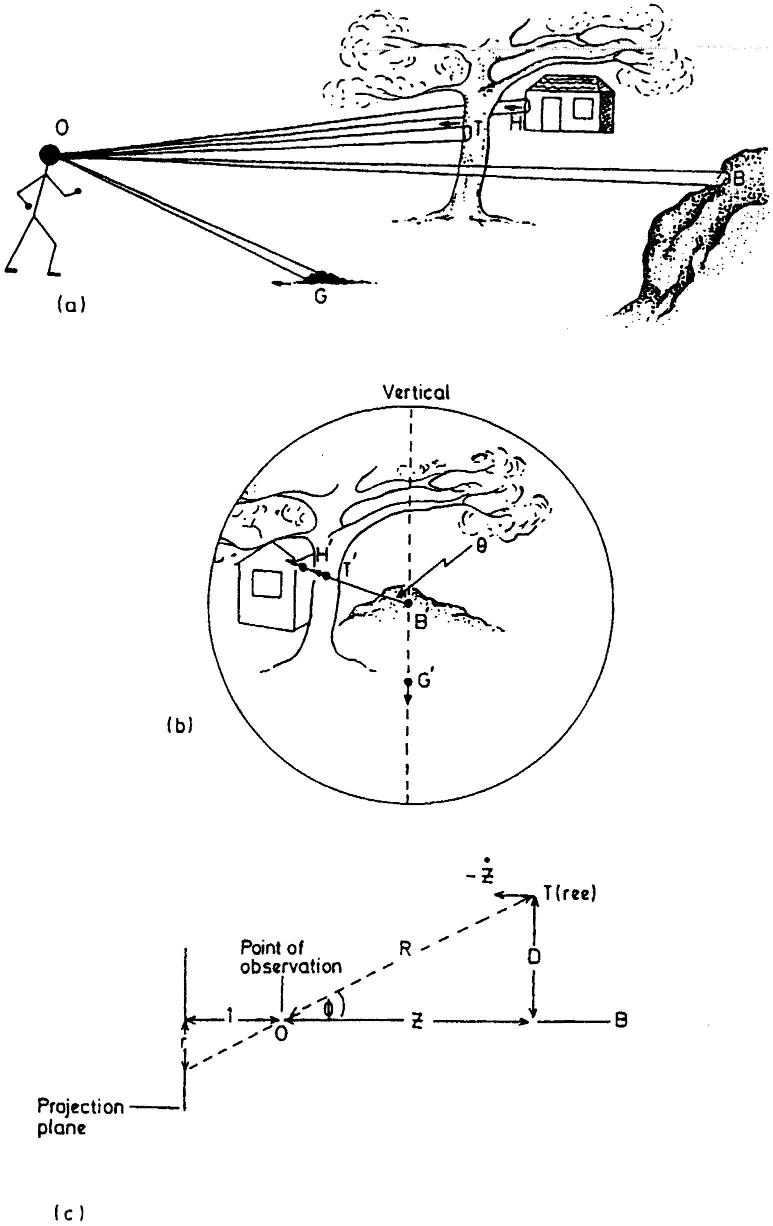

FIG. 1.4. *(Continued)*

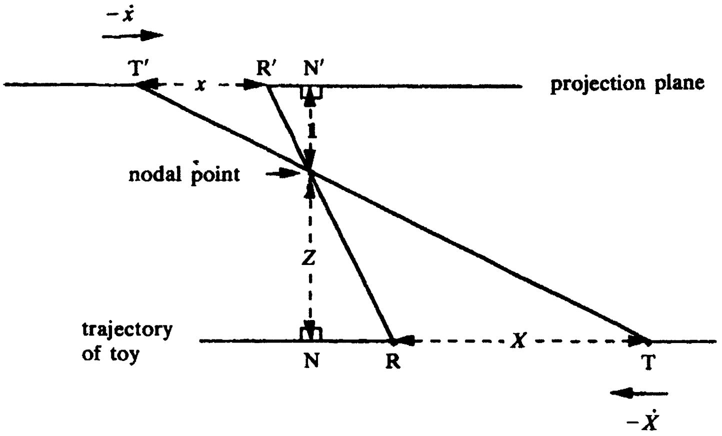

FIG. 1.4. How the tau of a motion-gap is specified optically through tau-coupling. (a) Forward relative linear movement of point of observation. Upper diagram (a): the optic flow field portrayed as a bundle of narrow optic cones each with its apex at the eye and its base on a surface texture element in the environment. As the eye moves forward, the cones fan out. Middle diagram (b): the optic flow field portrayed as the intercept of the bundle of optic cones with a projection plane in front of the eye and perpendicular to the line of locomotion. Bottom diagram (c): A slice through the optic cone bundle containing the line of locomotion, OB, and the line, OT, to the texture element on the tree. A projection plane perpendicular to the locomotor line is added at unit distance behind O, onto which the image of T is projected, at distance r from the image of O. Tau of the motion-gap Z(t), $\tau(Z,t)$, is specified by $\tau(r,t)$ through the coupling equation $\tau(Z,t) = -\tau(r,t)$. [Proof. From similar triangles, $Z(t)/D = 1/r(t)$. Differentiating with respect to time, t, $(dZ(t)/dt)/D = -(dr(t)/dt)/r(t)^2$. Eliminating D from the two equations, $Z(t)/(dZ(t)/dt) = -r(t)/(dr(t)/dt)$, i.e., $\tau(Z,t) = -\tau(r,t)$.] (b) Sideways relative linear movement of point of observation. x(t) is the projection of the motion-gap X(t). From similar triangles, $X(t)/Z = x(t)/1$. Hence $\tau(X,t) = \tau(x,t)$.

to perceive the direction in which something lies relative to the body to be able to move toward it. Directional information is available visually by virtue of the spatial layout of the retina, acoustically through the time and intensity differences at the ears and the multiple sound reflections in the pinnae, and haptically through the articular receptors in the joints muscles and skin.

Yet surely, you may ask, doesn't an animal also need distance information—about the distance of a surface, the size of an object, its speed of movement, and so on—to judge how hard to thrust to jump over a ditch, how wide a grasp is required to pick something up, or how hard a cross-ball needs to be hit to deflect it into the net? It is true that distance information is needed, but an animal does not require a different form of sensory information for this. Information about tau and direction are sufficient

(Lee, 1980; von Hofsten & Lee, 1994). The basic argument is this. Distance information is necessarily relative. There is no such thing as absolute distance. For distance information about the environment to be useful to an animal (whether in perceiving distance, size, or speed), it has to be scaled relative to the body in some way. This means that perceiving body-scaled distance (e.g., of a surface) requires picking up information about two relative distances: the objective-distance of the surface and a bodily-distance, such as eye-height or stride-length. The ratio of the relative objective-distance to the relative bodily-distance gives the body-scaled distance. Information about tau and direction is sufficient for perceiving both the relative objective-distance and the relative bodily-distance. Thus, body-scaled distance is derivable from information about tau and direction.

Synergic Tau-G Guidance

Suppose you are guiding your gaze toward an object. In general, this involves rotating your eyes in your head and rotating your head on your shoulders, as well as twisting your trunk and maybe shifting your feet. The question is: How do you manage to accurately guide your gaze to the target when it involves so many component movements? The same basic question as to how component movements are organized into a synergy to guide an effector to a goal applies to virtually all movements. This central question has never been satisfactorily answered, however. I propose an answer, or partial answer, by applying General τ Theory to the problem.

According to General τ Theory, the focal aspect in shifting gaze, for example, is tau-G guiding the closure of the angular gap between the current direction of gaze and the direction of the object. This tau-G guidance of gaze is achieved through the combined movements of eyes, head, and so on. However, each of these components also has its own agenda to follow: it has to abide by particular bodily constraints. The eyes and head, for instance, have to be turned in such a way that the muscles and joints are not strained by too abrupt accelerations or decelerations. My suggestion is that this is achieved by independently tau-G guiding the movement of each component (eye, head, etc.) to a goal position lying within the bodily constraints while also tau-G guiding their combination (gaze) to its goal. I refer to this as the tau-G synergy hypothesis. In the tau-G synergy, the movements of the eyes-in-head, head-on-shoulders, and so on may or may not be tau-coupled to the gaze movement or to each other, and the movements may or may not occur over exactly the same time period. What defines a tau-G synergy is simply that all the movements involved in the synergy are tau-G guided. Later, I present evidence in support of the tau-G synergy hypothesis when discussing guidance of gaze. However, before going on to the next section, I should add a caveat. I am not proposing that the component movements that move a bodily effector are invariably accurately tau-G guided any more than the effector is accurately tau-G guided in every instance. Biological control is not perfect, although it can be honed with practice. Even then errors can occur, as in the famous case of the baseball pitcher who snapped his arm by hurling too hard. Indeed it seems likely that many sports injuries are due to errors in tau-G guiding component movements within their bodily constraints.

Stabilizing With a Tau-G Guide

Let us now consider the common problem in movement control of stabilizing an effector within a goal zone. By this I mean keeping the effector within the boundaries of the goal zone. For instance, the effector may be your gaze and the goal zone a moving object that you are inspecting, the effector may be your vehicle and the goal zone the traffic lane you are driving along, or the effector may be the vertical projection of your center of gravity and the goal zone your base of support when you are trying to stand still. Whatever the effector, stabilizing it within a goal zone could be achieved by repeatedly tau-G guiding the gap, X, between the boundary of the effector and the boundary of the goal zone [such that $\tau(X,t) = K\tau_G(T_G,t)$, for $0 < K < 1$], with the tau-G guidance including some bounce-back. This would cause the effector to stop momentarily within the goal zone and then reverse direction. At this point, another tau-G would guide it to another momentary stop within the goal zone, followed by reversal, and so on. Later I present evidence for this with regard to stabilizing gaze on a moving object.

Tau-G Guidance in Developing Skill

Skilled movement requires controlling the closure of a set of motion-gaps in a concerted manner. My hypothesis is that this is attained by coupling the taus of the motion-gaps onto the taus of other motion-gaps and onto tau-G guides. Thus, skilled movement comprises a balanced ensemble of tau-couplings. Controlling a tau-coupling requires constantly determining the power that needs to be pumped to the muscles to regulate the closure of the motion-gaps involved in the tau-coupling. For example, if you follow an object with your eyes, you not only need to sense the motion-gap between your gaze and the target, you also need to know how to adjust the power to your muscles to move your gaze back onto the target when it wanders off. Thus, calibrating the process of regulating power to the muscles on the basis of prospective sensory information about the taus of motion-gaps is an essential aspect of learning to move skillfully. Because of changing dynamical circumstances (growth, joint stiffness, injury, wearing new spectacles, etc.), the calibration needs to be constantly adjusted. Recalibration experiments (e.g., Hay & Pick, 1966; Pick et al., 1999; Rieser et al., 1995) indicate that calibration takes place in both sensory information pick-up and the regulation of power to the muscles.

Tau Within and Without

I conclude this introduction with a summary of some of the main points of General Tau Theory and then briefly discuss how tau might be embodied in the nervous system. As an illustration, consider someone playing a tune from memory on the piano. This clearly involves both intrinsic and sensory guidance (Fig. 1.5). According to General Tau Theory, controlling the finger movements to play expressively requires guiding the closure of the motion-gaps between the fingers and keys using information about the tau of the motion-gaps. This tau information is picked up by the perceptual systems by detecting corresponding taus in the patterns of sensory input to the eyes and/or ears and/or skin. The perceptual systems translate this tau information into neural tau information in the nervous system. Using the principle of tau-coupling, whereby one tau is kept proportional to another, this tau information, together with intrinsically generated neural tau information in the form of tau-G guiding functions, directs the muscles to change the taus of motion-gaps in the desired way.

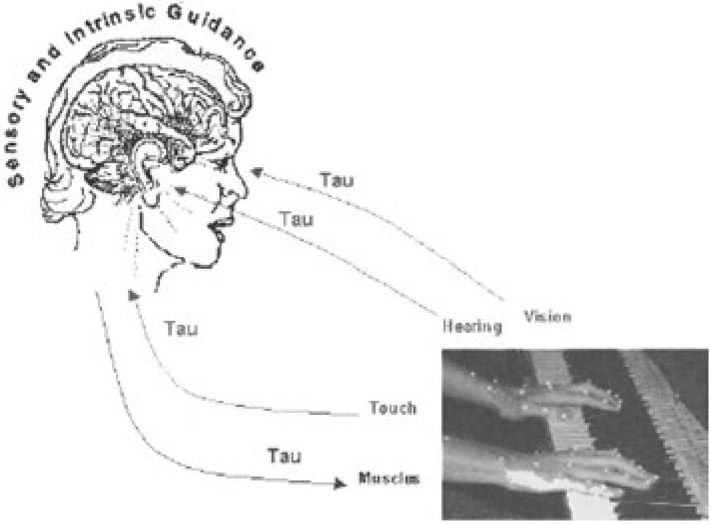

FIG. 1.5. Tau information flowing around a perceptuomotor cycle and coupling with intrinsically generated tau information.

These changes are detected by the perceptual systems and provide feedback, and so the cycle continues.

What form does tau information take in the nervous system? It must be some function of the rate of flow of electrical energy in ensembles of neurons. I refer to this rate of flow of energy as *neural power*. (In the mammalian central nervous system, neural power flows as trains of homogeneous electrical pulses [spike trains] and is often referred to as *neural spike-rate*. I think the term *neural power* is better because it is more general and can be applied to any form of flow of information as electricity within an animal, whether continuous or discontinuous.) However, tau cannot correspond to neural power as such because the dimensions do not match—tau is measured in time units, whereas neural power is measured in power units. However, tau could be specified neurally by the *tau* of the neural power (measured relative to a base level) flowing through ensembles of neurons in the brain. We tested this hypothesis by analyzing neural power data collected from monkey motor cortex and parietal cortex area 5 during a reaching experiment (Lee, Pepping, Lee, & Georgopoulos, 2004). We found that the tau of the motion-gap between the monkey's hand and the target stayed in constant proportion to the tau of neural power in motor cortex and parietal cortex. The tau in motor cortex preceded the motion-gap tau by a few milliseconds, whereas the tau in parietal cortex followed the movement by a few milliseconds. This indicates that the tau of neural power in the motor cortex prescribed the hand movement, whereas the tau of neural power in the parietal cortext monitored it. The tau of the motion-gap and the taus of neural power in motor and parietal cortex each stayed in constant proportion with a tau-G guide, suggesting that the tau-G guide was the underlying base of the movement.

TAU IN DEVELOPMENT

In the remainder of this chapter, I consider how General Tau Theory might help in understanding the development of some basic skills—feeding, breathing, vocalizing, guiding the head and gaze, guiding the hand, and guiding the feet when walking and running. For the most part, each section starts with an analysis of adult skill and moves on to consider how the developing child progresses toward the adult level.

Feeding, Breathing, and Vocalizing

Fueling the body is essential for movement and involves skilled movement. Therefore, it is not surprising that most skilled actions of young babies center around the mouth and nose. Infants start their life outside the womb with a controlled gusty outflow of air with which they announce