Chapter 10
Dimensions of Event Perception

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'The essence of rhythm is the fusion of sameness and novelty; so that the whole never loses the essential unity of the pattern, while the parts exhibit the contrast arising from the novelty of detail. A mere recurrence kills rhythm as surely does a mere confusion of differences. A crystal lacks rhythm from excessive pattern, while a fog is unrhythmic in that it exhibits a patternless confusion of detail.' (Alfred North Whitehead, 1919, *Principles of Natural Knowledge)*

'We should begin thinking of events as the primary realities and of time as an abstraction from them... It is the same with space as with time.... There is always some degree of recurrence and some degree of nonrecurrence in the flow of ecological events.' (James J. Gibson, 1979, *The Ecological Approach to Visual Perception)*

1 INTRODUCTION: ISSUES, PROBLEMS AND ATTITUDES

What makes stimulation informative? Although there is not an abundance of research on this topic, no field of perceptual psychology other than event perception addresses the issue of how we perceive change. Since the topic is essentially new, having but a few pioneers such as Michotte, Gibson and Johansson, no general terminology, principles or methodology is shared by researchers in the area. Hence, reports pertaining to event perception are often more difficult to recognize than they should be. Rarely do we find a clear statement by authors as to what they take the problem of event perception to be. Relevant reports typically must be selected by *prima facie* evidence alone.

A report may seem relevant on the surface because it purports to describe the information specifying some kind of change, such as the detection of motion, or simply because it uses the term 'event'. Such usage is rarely technically precise. We found that such *prima facie* evidence often led nowhere and sometimes was even misleading.

On too many occasions when a report seemed of obvious interest, the discussion of results would leave unanswered what conclusions the authors wished to draw about event perception. Consequently, it was left to us not only to explain the relevance and to supply such conclusions but also to fashion a framework in which relevance might be ascertained and conclusions drawn. In doing so, it was inevitable that we should have to draw on our own perspectives to do so. This, of

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course, made it impossible to keep this 'review' theoretically neutral. The reader is, therefore, forewarned.

A persistent problem encountered is that studies offering models for the detection of event-related properties typically fail to distinguish between description and explanation. Too often the only explanation given for how the event in question was perceived was to describe some hypothetical mechanism which undergoes a given state transition whenever the event undergoes a correlated transition. Clearly, nothing is gained if a theory introduces as an explanation of how some x occurs, an indicator that some y occurs (where x and y refer to different acts, experiences or processes). Such descriptive mechanisms, even if true, are not explanations but are themselves to be explained.

Clearly, nothing is gained if one attempts to explain the perception of x by describing the detection of something that is not x itself. For then we must face the conundrum of how the occurrence of one kind of thing (say, an event in the central nervous system CNS) can be taken as detection of another kind of thing (say, the causally contributing environmental event). The two may be *coextensive* (i.e. occur together) and yet not be *cointensive* (i.e. mean the same thing). Why are some state transitions informative about other state transitions? Why do they point beyond themselves rather than merely at themselves? And even if they point beyond themselves (what philosophers call their *intentionality*), of what consequence is this pointing? And for whom? The author of the model? Or the perceiver being modelled? Not only is this patently unclear, but the ambiguity goes essentially unacknowledged in the literature.

Hence, the fundamental problem for perceptual psychology is to explain how the coextensive can somehow be equivalent to the cointensive. A solution to this problem calls for a theory of perceptual information and an understanding of the nature of its specificity to the underlying environmental referents. The details of such a theory have yet to be given. Consequently, we must proceed without such help.

A related problem is recognizing that having a model for a mechanism that detects stimulation (not information) from some referent x is not equivalent to having an explanation of the perception of x, that is, how stimulation is made informative by the act of detection. It does not obviously resolve the puzzle of how a change in state of some internal mechanism, even if truly triggered by a specific change in environmental state (i.e. even if coextensive), can be informative (i.e. cointensive) about the associated environmental event. For a surrogate (e.g. a representation, a specification) to be useful, it must already be known to be a surrogate of something – to have intentionality – otherwise it is merely itself. Thus, the problem of the specificational import of information is the problem of how properties in the medium that are coextensive with the properties of the object of perception can be taken as cointensive with them. Coextensionality, say even as perfect correlation, does not logically guarantee cointensionality – having the same meaning – even if the specification is unique.

Often psychologists, following Helmholtz, will suggest that meaning accrues from stimulation by some kind of unconscious inference process. This contrasts with the view championed by those psychologists following Gibson, who claim that the relationship between the two is fundamentally noninferential – a view they call specificational. Neither of these approaches is adequate as it stands but demands clarification of its relevance to the intentionality problem. An attempt is made later to elucidate these contrasting views (see Section 1.3).

At this time, in the early development of the embryonic field of event perception, there seems to be no lucid discussion of this intentionality problem among those who evoke information or cue detection models. Coextensionality of predicates with properties referred to is addressed but their cointensionality is ignored. Smoke may be coextensive with fire but does not mean fire. Smoke is dark and billowy while fire is bright and licking. Similarly, certain cues (e.g. height in the picture plane, interposition) may accompany (be coextensive with) certain perceptual experiences of three-dimensional layout, but they are not the content of (cointensive with) the phenomenological experience of 'depth'. For instance, height in the picture plane is not 'depth'. For two objects may have different heights while being at the same distance from the observer, while two objects at different distances may have the same height. The fundamental question is: under what circumstances do physical features take on cue functions or information functions?

Attempts by Gestaltists (their principle of psychophysical isomorphism), by Wittgenstein, Russell, by Gibson and Gibsonians, and by Fodor and other contemporary correspondence theorists provide no notable help on this problem. For some of us, the coextensional aspects of stimulation with event or object properties is all that science should realistically be expected to address – leaving the cointensive aspects of information for the semanticists or philosophers. If so, then the concept of information collapses onto the concept of stimulation to which it is specific and cointension collapses onto coextension. This is like the message collapsing onto the signal in communication theory. Such reductionism makes the problem of perception a mystery rather than just a difficult problem. Gibson (1979) was quite aware of these dangers in that he emphasized the distinction between the type of change in the world (e.g. translation of one object in front of another), as the physicist might describe it, and the kind of disturbances in the optic array (e.g. certain accretion and deletion disturbances of texture) that embody the information about such changes, in the sense of being specific to them, without need of inferential enhancement.

Consequently, since this important issue is not adequately covered in the perception literature, the reader should not expect it to be laid to rest here. Instead, ecological psychologists believe the field is better served by directing its efforts toward discovering and describing the useful dimensions of stimulation for the control of action, while traditional theorists believe that perception is the having of an experience in the theater of the mind and the making of judgments thereof. The challenge of the intentionality problem is still worthy of pondering by both kinds of theorists since neither camp has a lock on the issue.

Even if there is no known solution to the recalcitrant intentionality problem, it still makes sense to ask what makes some information more informative than other stimulation. This means that in addition to showing that an event is causally responsible for a state transition in a model, one has to show how the state transition is informative – how the result not only entails the causally antecedent conditions that give rise to it but also how it does so for the agent for whom the model is intended. The key difficulty with this form of reasoning is that it is *post hoc ergo ante hoc* – meaning 'that which comes after entails that which goes before' – and is not causal since its entailment inverts the usual (chronological) order of antecedents and consequents required for them to represent a cause and effect sequence. Perceptual theory cannot avoid nor justify, under current theories of logical inference, this form of reasoning. (But see Rosen, 1991, for an interesting discussion of finality and entailment.)

Of course, perceptual psychologists are not the only theorists who have failed to resolve this thorny logical problem. But perhaps we are most guilty of ignoring it. By failure to acknowledge this problem of acausal specification (backward entailment), we imply that the perception of x might be explained by the mere existence of a putative mechanism that responds uniquely to the occurrence of x. In doing so, we are not only guilty of tolerating faulty reasoning but egregiously so. Until the hypothesized mechanisms incorporate a general theory of specificational information (i.e. includes an explanation of the backward entailment required of intentionality), then any solution to the problem of how x is detected leaves an unbridgeable gap to explaining how x is perceived.

When the general field of perception is ill-defined, it makes it difficult to delimit the scope of inquiry into a subfield. Lacking a consensus, it is nevertheless necessary to impose questions to set the bounds on the review. Consequently, we have tried to formulate these questions in such a way as to provide a generic framework to guide the selection and discussion of research on event perception. The fact that we are ecological psychologists, we hope, did not reduce our appreciation of the efforts of our colleagues of a different ilk, but no doubt has put a spin on the discussion that will not be to everyone's liking. A true review, perhaps, must be left to some later time, when sufficient consensus has been reached on the problem of intentionality and perceptual entailment to fashion a field with shared empirical and theoretical foundations. We hope the directions and dimensions of event perception discerned here help in this regard.

1.1 Stretching the Boundaries of Event Perception

More than a decade has passed since the last major review of the event perception literature (Johansson, von Hofsten and Jansson, 1980). In opening their review the authors say: '...We have broadened the term "event perception" in an important respect. The review will not be limited to perception of object motion in a passive perceiver, but will pay attention also to recent studies dealing with motion and movement perception in an active perceiver, thus motion and space perception in connection with action...' (p. 28). Johansson *et al.* point out that most traditional research had focused on static displays and emphasized the role of spatial information, such as position, shape and configuration. With the aid of certain technological advances, the field first broadened to include strobotic or cinematic sampling of motion and other forms of change. Later, by the time of their review, the field had broadened again to include real motion displays, where the change was continuously presented rather than merely discretely sampled. They were clearly justified in this extension of the topic, for it has been established that, other things being equal, the range of temporal factors for the perception of apparent motion and real motion events are quite different (Braddick, 1974); and that, in general, they have both different causes and different effects (Kolers, 1972; see below).

In the current review we should like to broaden once again the terrain to be covered. We should like to pay attention not only to motion and space perception in connection with action but to replace the traditional treatment of time as but an additional spatial dimension – a geometric view of time – (with a true appreciation that event perception has its referents in *space–time*. The nineteenth-century view

that change is but a sequence of static displacements in a structureless space must give way to the twentieth-century insight that change is itself a real process that acts to deform the structure of space–time (Capek, 1961). Here events replace objects and change replaces displacements. Until we psychologists master this more demanding concept of space–time and replace the less adequate and inaccurate space and time geometry, the true basis of perceptual information will no doubt continue to be elusive. This chapter is organized so as to present graded steps to this end. The reader is first introduced to space and time geometries of events and then is moved toward an appreciation of the space–time geometries of events. If the reader bears this in mind, then the motivation for the various event descriptions will be apparent.

In addition to broadening the topic from space and time to space–time, we shall introduce some refinements to help focus the field, most notably as pertains to the description of events and the information by which they are perceived. We make no pretense to offering a full review of the existing literature (but see Johansson, von Hofsten and Jansson, 1980; Warren and Shaw, 1985); rather, our main goal will be to clarify certain fundamental problems and issues that lie at the foundations of the field.

1.2 Approaches to Event Perception

It seems an incontrovertible fact that animals and humans have the general perceptual capability not only to distinguish between change and nonchange but also to classify styles of change as well as the objects that undergo change. Event perception, then, can be defined as: *the detection of information about a style of change that a structure undergoes over some determinate region of space–time.* Two fundamental aspects of event perception must be accounted for: first, how one perceives change at all; and, second, how one perceives particular styles of change as such. Pittenger and Shaw (1975a, b) introduced the terms *transformational invariant* (TI) and *structural invariant* (SI) as denoting the style of change that is perceived and that which undergoes the style of change, respectively.

Using these terms, an event (E) is said to be perceptually specified when both of these terms of invariant information (i.e. TI and SI) are available to be detected – that is, when the two-variable function E(TI, SI) can be evaluated. For instance, an event involving a bouncing ball might be denoted as E(TI = bouncing, SI = ball) = bouncing ball. A major aim of this chapter is to show how such event functions might be conveniently diagrammed and their separable space–time component functions studied.

A third corollary problem has to do with the distinction between extracting information specific to a style of change from a background of complex change, as opposed simply to detecting a style of change in an isolated context. We might ask what makes a given style of change more visibly salient, say at one scale, when other styles of change might, in principle, be informationally specified at other scales of description? To extract such information calls for some additional constraint over and beyond specification, what we might call *objectification* of the information in question. More will be said about this later.

Finally, a fourth important question that will not be considered in much detail concerns how one perceives object properties (e.g. rigidity) or properties of the layout of objects (e.g. distance, depth) under conditions of change that are not perceived under static conditions. The detection of information for structurally invariant properties (i.e. SIs) under various styles of change (i.e. given TIs) is an important related problem for event perception research without actually *being* event perception as such. For in focusing primarily on the perception of SI properties involved in an event, the TI properties play but an ancillary role. The importance of this question for event perception proper would be more assured if TIs were perceptually classified in terms of SIs, rather than the other way around which seems to be the case.

This is not, however, to overlook the fact that information for change and information for structures involved in the change often do interact. Clearly, objects must be detectable or there would be no informational support for the perception of change. Consequently, some discussion of the role that object properties (SIs) play in setting the necessary boundary conditions on event perception is unavoidable (Mark, Shapiro and Shaw, 1986).

The study of the detection (as opposed to the extraction) of information for the TI component of events can be broken down into two fundamental issues. The first issue concerns the nature of information for change (variants) as opposed to nonchange (invariants). Here, the majority of the research has addressed the distinction between real and apparent motion events. The second fundamental issue has received much less study. This issue concerns the information by which different styles of change, or categories of TIs, are perceptually recognized. Here, how one chooses to describe events (e.g. motion) is of the utmost importance.

Three event geometries are logically possible: the first approach attempts to reduce change to nonchange so that events might be spatialized. Differences in positional or configurational information are deemed sufficient to express change, with the implication that events may be captured in Euclidean space by the use of time tags. A second approach uses spatiotemporal descriptions but without restrictions on the range of values the temporal dimension might assume relative to the spatial dimension. We call this the orthogonal *space and time* geometry of events and identify it with the Galilean (space plus time) frame of classical physics. It is still Euclidean but with time treated as but another spatial dimension.

Finally, there is the possibility of a Minkowski-like space–time (event) geometry derived from special relativity which treats the two dimensions of time and space nonorthogonally and, therefore, as capable of interacting. Here, in order to keep our intuitions intact, the Minkowski space–time continuum, for convenience, is treated as embedded in Euclidean geometry (although more properly it might be treated as a separate geometry that is intrinsically hyperbolic; for a helpful introduction, see Caelli, 1981, and Caelli, Hoffman and Lindman, 1978). Over the past decade or so, there has been a growing interest in variants of such space–time descriptions of events for describing both perceptual information and action control (Adelson and Bergen, 1985; Brown, 1931; Caelli, 1981; Caelli, Hoffman and Lindman, 1978; Kugler *et al.*, 1985; Shaw and Kinsella-Shaw, 1988).

1.3 Attitudes Toward Event Information

There are three basic attitudes that one might hold regarding the origin and nature of perceptual information for change.

1.3.1 Change Inferred from Structure

The first attitude follows a Helmholtzian-like assumption that information from structural differences detected over time provides the premises, or deductive basis, by which change over time might be unconsciously inferred. It assumes that information about change involves inferences from a successively ordered sequence of samples (e.g. glimpses) of continuous motion (see Haber, 1983, for a review). Many contemporary views of cognitive science assume that change perception consists of mental representations of the successive samples that are related by computations (Fodor and Pylyshyn, 1981, 1986). Although computations, formally speaking, are not inferences, they provide a means by which the inferences are represented. Both the inferential and computational views treat such discrete perceptual samples as if they were cinematic frames. Here, change is thought to be derived from an act of cognitively comparing positional differences over successive frames while ignoring the in-between blackout interval. Perceptual persistence is typically argued to be responsible for our inability to see the blackout interval. Hence, there is no information for change as such, rather change is treated as an inferential construction. Evidence for this view is often taken from picture perception, stroboscopic and cinematic motion perception. It contrasts sharply with the noncognitive views – to be discussed next – that information for change is somehow made available by events themselves through direct (noninferential) specification.

The inferring-of-change-from-structure hypothesis suffers from three problems: first, the paradox of how change might somehow be derived from nonchange; second, how perceiving might be interpreted as inferring; and third, the need to have an internal observer that glimpses what is cinematically projected and then carries out the 'perceptual' (unconscious) inference. Since the inner observer might be the first but not necessarily the last internal observer required, the cinematic metaphor can lead to an infinite regress if not terminated by some principled final state. No one has suggested a terminating principle that is consensually accepted. Thus, the potential regress is typically ignored or, if not ignored, then terminated arbitrarily, say, by a final step that treats the static differences in position as being inferentially equivalent to the phenomenological content and ushers the experiences of change into the theater of the mind.

How this last inferential step from information to experience is made, no one knows. More is known about the first step where environmental energy from events is transduced into information events in the nervous system. Consequently, incommensurability of environmental energy distributions, physiological processes and psychological experiences is generally recognized as a serious problem for any causal chain model of perception. By using the word 'inference' to bridge the gaps, the incommensurability problem is not resolved but is compounded for two reasons.

First, and a point usually ignored that deserves careful attention, is that since computational steps may represent either valid or invalid inferences equally well, then valid inference cannot be identified with computation (e.g. as Hochberg, 1964; Rock, 1975; Ullman, 1980, do). Inferences are syntactical and truth-functional, while computations are merely syntactical. Second, it is generally agreed that to make an inference requires that the inferrer intend an inference, in the sense of recognizing the truth of the premises, following the train of reasoning, and 'seeing' that the conclusion follows. If so, then how can an inference be unconscious and intended at the same time? An unconscious inference is an oxymoron, for either it is conscious or not an inference. (For instance, the full-blown hypothesis asserts that unconscious conclusions from unnoticed sensations can be used to explain perceptual achievements; Hochberg, 1964, p. 55.)

Our point is not that no sense might be made of this hypothesis but that no sense has been made of it in the literature that uses the hypothesis or entails it. The hypothesis has often been asserted but the problem of rationalizing it has been chiefly ignored by psychologists (although Fodor and Pylyshyn's, 1986, attack on connectionism brings a variant of this issue to the forefront). Given these problems, why, then, is this a perennially favorite view?

The presumed strength of this view is that apparent motion effects and other *virtual* events can be treated as examples of *real* event perception. Given the putative role of inference or 'computation', nothing essential is assumed to be lost by studying the perception of strobotically or cinematically produced events in lieu of the more difficult-to-study real world events. If, however, real events produced in the world kinetically and virtual events produced strobotically or cinematically (and here we must also include video and computer graphics) are not essentially the same information sources, for the reasons pointed out earlier, then we have two phenomena to study that require two theories. Under the change-inferred-from-structure view both empirical research and theory construction seem to be made simpler. This feature may account for the perennial popularity of this view. Unfortunately, the difficulty of making clear, how perceiving, inferring and computing may be the same process in all relevant ways, makes this virtue more apparent than real.

1.3.2 Change Extracted from Structure

A second view, in contrast with the first view, eschews the inferential hypothesis and argues from information detection alone. This view assumes that information about change does exist and is specific to the properties of an object left invariant while undergoing a given style of change. (Recall that information about change may be conveyed by stimulation from change but is functionally and logically distinct from it.) Invariant properties are those that do not change *relative to other properties* under a given style of change. This is the inverse of the *structure-extracted-from-change* view (Cutting, 1986; Ullman, 1979), where the term extraction is used advisedly. (Here, it refers to the process by which a given property is detected among the background of other properties.)

For instance, an object whose shape does not change while undergoing a rotation or translation is said to be a rigid object and the change a rigid transformation. Hence, rotation and translation are both rigid transformations. These transformations may then be distinguished from other nonrigid styles of change like compression, stretching, bending and breaking that alter the shape of the object. This approach treats information for a TI as being reducible to information for some SI.

But what invariant structural property, SI, distinguishes rotation from translation? There simply is none. For with respect to structural invariants like shape, rotating an object is no different from translating it. No change in any object property is introduced by either. Reorientation by rotation or relocation by translation involve no object properties but rather involve properties of the object's

relationship to the spatiotemporal frame in which it is reoriented or relocated. Such context-dependent properties are functionally defined, like axis points or closed circular traces (as opposed to rectilinear traces); these do indeed serve to distinguish rotation from translation. But these are not object properties (SIs): they are transformationally defined invariants (TIs). They are dynamical, existing only over time – disappearing whenever rotation stops. These properties are visible as blur streaklines when the rates of rotation or translation become too fast for the visual system to process (where rate is measured in arc units of visual angle per unit time) or when a long time-exposure photographic record is made.

Finally, the change-extracted-from-structure approach also suffers from the obvious defect that it explains the source of information for structure (e.g. rigidity) but not the source of the information for change itself (rolling versus spinning). Therefore, to argue that structural invariants extracted from the persistence of certain object properties somehow specifies change encounters the same conundrum as the change-inferred-from-structure view; namely: *how can types of spatial persistence specify types of temporal nonpersistence*? (See Ullman, 1979, for a discussion of how the extraction processes in both of these views might operate; but see Todd, 1981, for a telling criticism of Ullman's account.)

Under this extraction view the notion of specification is open to two different interpretations: a style of change can either be uniquely specified by a structurally invariant property determined under that style of change or it might be multiply specified by more than one structural property. If one invariant property can be specific to the change that revealed it, why cannot another? And if another, why not another and another and another and so forth? One would need a proof that only a single SI was associated with a given TI for uniqueness to hold. We underscore this problem but do not attempt to resolve it (see Pittenger, 1989, 1990; Stoffregen, 1990, for a relevant debate).

1.3.3 Only Change Specifies Change

Finally, there is a third alternative which might be called the *extraction-of-change-from-change* view. Under this approach events are defined in terms of invariants that are stationary over spatiotemporal dimensions. The detection of these invariants over the continuants (e.g. streamlines) of the change constitutes the direct perception of the style of change by which the event can be classified (Shaw and Pittenger, 1978). Assuming this view can be made coherent, it is very attractive. For under this view the most troublesome issues encountered under the first two views do not even arise. However, this view is less familiar than the other two; thus, we pause to place it in perspective. We do so in the next two sections.

1.4 Transformational Invariant as a Persistence Over Change

The first view considered holds that information for change can be inferred from information derived from structure. Thus, under this view change as such (i.e. a TI) is not perceived at all but is derived inferentially from positional or configurational information (i.e. from SIs). The second view is related; it holds that structural properties are informationally specified rather than inferred and, therefore, directly perceived. However, it also assumes that styles of change (TIs) do not stand on their own but are derived from structural information (SIs).

Different events may involve the same objects while the same event may involve different objects. For instance, a ball may bounce or it may spin or roll. These are not the same events simply because they involve the same object; nor are they the same events because the (elastically restored) shape of the ball is shared as a structural invariant. Rather, bouncing, spinning and rolling are three different events because they involve three different transformations, or styles of change, each characterized by its own distinct TI.

Conversely, a ball may roll smoothly down an inclined plane or a rock may roll erratically down a bumpy hill. In both cases, the verb tells us what *kind* of event it is – that the general style of change is rolling, while the adverbial modifier tells us what particular *manner* of that style of change is involved – that the manner of rolling is smooth or bumpy. There is no difficulty in speaking of variants of the same transformational invariant, nor is this to change the accepted mathematical meaning of the terms *transformation* and *invariant* as has been claimed (Cutting, 1986). Transformations may undergo a change in parameters without the change destroying the dynamical invariants that specify their identity. For example, let x be an object, R a rotational transformation applied to x, and k the number of rotations applied, then kRx expresses the rotation of the object x k times (say, in radians). It is clear that k is a parameter whose value might change without changing the definition of the style of change, R. This important point is further elucidated below.

Under the first two views a recalcitrant puzzle is encountered if we assume that information for change comes from the persistence of structural properties *under* the same styles of change. But now we see no such puzzle is encountered if we assume that information for change comes from the persistence of dynamical properties *over* different manners of the same style of change. If object-specific information corresponds to invariants extracted from structural properties that persist *under* a transformation, then change-specific information must correspond to invariants extracted from dynamical properties that persist *over* different transformations. The *under* and *over* relationships are important here, logically carrying the sense of being an SI or a TI, respectively. In another context, we have spoken of this as 'change constancy' and offered it in counterpoint to 'object constancy' (Mark, Todd and Shaw, 1981). This argument has implications for resolving the so-called *multiple specification controversy* (Bruno and Cutting, 1988; Cutting and Bruno, 1988; Massaro, 1988; Pittenger, 1989), but we shall not pursue this issue further.

1.5 Is the Concept of Transformational Invariant an Oxymoron?

Does the only-change-specifies-change view also have shortcomings? At least one leading psychologist thinks so, for he argues that the notion of a transformational invariant is self-contradictory – an oxymoron (Cutting, 1983, 1986). Presumably, the complaint is that transformation is synonymous with change and invariant with nonchange. Therefore, under this interpretation, a transformational invariant would refer to a *changing nonchange*, which is indeed an oxymoron. But this objection rests on a misunderstanding – on confusing the notion of something being relatively invariant with that of it being absolutely changeless.

As defined earlier, invariant means relatively unchanging with respect to other things *which change in the same way*, not absolutely unchanging with respect to things that do not change at all. To determine that two things change in the same way already presupposes that there is information for distinguishing one style of change from another. Thus, to be invariant does not necessarily mean to be static; rather, it means to be stationary in the sense of relatively unchanging. Mathematics is explicit on this issue.

Stationarity is the property of a function (or functional) that equals a constant for some values in its domain. It is not required that it do so for all values. Nor is the constant required to be zero – so long as it can always be rescaled to zero. More explicitly, a differentiable function is said to be stationary if its first derivative is zero and, correspondingly, an integrable function if its first variation is zero. A curve plotting a function (or a transformation) is stationary if it does not move in the space in which it is plotted under a change in parameter evaluation. Whether such functions are plotted over time, over space or over space–time dimensions the definition still holds. Under our usage, *transformational invariants are functions or functionals that are stationary over time while structural invariants are those stationary over space*. Thus, mathematically they have equal status although they are not intersubstitutable.

For instance, two or more things might be comoving and therefore be stationary relative to each other. This shows up in their relative plotting if the origin of the coordinate system is initialized with respect to either one. Consider the relative stationarity of individual geese in a migrating flock (defined by placing the origin of the coordinate system on one of the birds in the flock in question). The flock may be moving, or nonstationary, with respect to another flock of geese floating below it on a pond. However, assuming their behaviors are perfectly coordinated, a velocity function for each bird in the same flock will have first derivatives equal to zero since they share the same velocity vectors. The space–time path integrals (i.e worldlines) of each bird likewise have first variations that are equal to zero since they covary. Here, the structural invariants are the same – geese are geese – but the transformational invariants between flocks are different – for flying is not floating. The Gestalt 'law' of common fate expresses what it means for more than one object to share the same transformational invariant. In waltzing, the couple must share the same TI or they would not stay together on the dance floor.

The notion of covariant functions (e.g. her waltzing versus his waltzing) can be made explicit under various mathematical descriptions. For two or more objects to share the same TI means their covariant derivatives are symmetrical (differential geometry; Burke, 1987) or that their Lie brackets equal zero (continuous group theory; Belinfante and Kolman, 1972), thereby expressing the fact that no linear deficiency exists in their shared forms of relative change. Using these latter descriptions, it is important to note that departures from symmetry by their covariant derivatives, like departures from zero for their Lie bracket commutators, can be measured (Arnold, 1978). Hence, the degree that transformations share a transformational invariant may be measured.

Consider the Lie bracket commutator for the operator description of two styles of change, where Tx and Ty represent the quantitative descriptions of the space–time path followed by each style of change (e.g. the man waltzing and the woman waltzing). Their bracket product is written as $[Tx, Ty] = (TxTy - TyTx) = k$, where k is a measure of the linear deficiency of the two styles of change – that is, their degree of asymmetry (arising from the dancing couple being out of step). If $k = 0$, then the two styles of change share the identical TI (and the couple is in step). On the other hand, if $k \neq 0$, then they do not share the same TI but differ by the amount designated by the number k. Event descriptions, then, are not restricted to ideal invariances but may approximate them within some tolerance measure $\alpha_1 < k < \alpha_2$, where α_1 and α_2 specify the lower and upper 'threshhold' limits, respectively (say, as given by the resolution of the perceptual system) (Shaw, Kugler and Kinsella-Shaw, 1990). Imperceptible differences are sufficiently small differences, namely, those differences that are less than a *jnd* (a 'just noticeable difference'). A difference in k greater than a jnd between two TIs would allow them to be perceptually discriminated.

Take another example: in classical mechanics the concept of the total energy of a conservative system, the so-called *Hamiltonian action function*, is stationary over time. The components of total energy, the potential and kinetic energy of the system, are not, in general, stationary functions. The Hamiltonian is said to be a motion invariant or a dynamical invariant. Likewise, any quantity that covaries with it (i.e. defined by a Poisson bracket, used analogously to a Lie bracket) is also said to be a dynamical invariant (Goldstein, 1980). Hence, there is nothing unusual in talking about transformational invariants if by that one means dynamical invariants. Under this view a TI is definitely not an oxymoron. Notice also that because we may in general be talking about energy or information flows, no reference need be made to structural invariants at all.

The Gestaltists recognized that symmetry of motions ('common fate') may be as important to perceptual theory as symmetry of forms ('good form'). We would be wise to do likewise. We turn next to the important question of how symmetry theory might be used to describe both structural and transformational invariants.

2 SYMMETRY THEORY OF EVENT INFORMATION

In this section we attempt to formulate an event perception hypothesis whose ramifications will be pursued throughout the chapter. A decision is made to view events as physical objects in their own right, rather than as cognitively constructed fictions. This working hypothesis has enormous implications for perceptual theory, for it suggests that what might require a complicated and yet undiscovered mechanism of cognitive mediation might be more simply handled by an information detection mechanism. Philosophically, this will be recognized as a move from a cognition-based phenomenalism (an indirect theory of perception) to a perception-based realism (a direct theory of perception). (For a defense of the former, see Fodor and Pylyshyn, 1981; and for a defense of the latter, Turvey *et al.*, 1981.)

2.1 The Event Perception Hypothesis: Generative Specification

The notion of invariant is synonymous with the concept of symmetry. As argued earlier, events involve two kinds of symmetry: successive symmetry expressed by the transformational invariant and adjacent symmetry expressed by the structural invariant. Events are not unextended instantaneous points in a space–time but occupy a 'window' which extends beyond the *here and now* continuously, both

backward and forward to the *there and then*. Events, therefore, are sources of retrospective, perspective and prospective information because the 'current' state of an event is spatiotemporally extended from the past through the present to the future. There is no cutting edge to time that is the specious moment so that perception takes place instantaneously (Gibson, 1975). Consider: a redwood forest grows for centuries; it rained all day over the whole state; the tennis game lasted for four hours; the ball bounced fifty feet in thirty seconds; the lightning flashed from the cloud to the flagpole in a fraction of a second; the particle track indicated a half-life of only a few billionths of a second.

Real events must be thought of as being both spatially and temporally extended while at the same time being limited in their extent. They cover places and have durations. Hence, they occupy a 'window' in space–time. Perception is the process that connects information samples that fill the window. The window expands or contracts depending on the nature of the event. Under this view, since perception shades off into cognition, it cannot be mediated by cognition – for this would be to be mediated by itself.

Because information is symmetry based, it is abstract. Thus, it matters not one whit whether the event is fast or slow so long as the detection mechanism is capable of somehow regenerating the event's symmetry structure (Shaw and Pittenger, 1978; Shaw and Wilson, 1976). Gestaltists recognized the need for this redintegrative process in the application of their so-called 'laws' (e.g. continuity, completion, good form) to patterns or events transposed or fragmented over space and time. Feature theories, on the other hand, fail to acknowledge this requirement for perception because of their strong locality assumption. The mere fact that we can recognize transposed events attests to the need for an abstract basis to event information that treats events as objects of perception *per se* with differentiable features (e.g. symmetries) rather than as featural differences over static spatial compositions.

After a century of fruitless scientific debate, perhaps, it is not imprudent to suggest that the proponents of these opposing views are philosophically incorrigible in the sense that no argument is likely to dissuade them from their position or to move them closer together. Believing this to be so, further polemics will be eschewed in this chapter in favor of a positive statement of the event perception hypothesis. (For the polemics one might see, for instance, Carello *et al.*, 1984; Fodor and Pylyshyn, 1981, 1986; Gibson, 1979; Hochberg, 1986; Shaw and Turvey, 1981; Shaw, Turvey and Mace, 1982; Turvey and Shaw 1979; Turvey *et al.*, 1981).

If we accept this view of event information as specifying a restricted spatio-temporal continuant (i.e. a spatially 'fat' temporal trace of limited duration), then a hypothesis is required to explain how the present information about an event can also entail information about its past and future. From an information sample of an event over the extended present, we perceive where something most likely came from and where it is most likely going. Perhaps, event perception involves a mechanism of generative specification (Shaw and Wilson, 1976) – a recursive application of a rule or operator to a base structure.

Generative specification requires two things: a set of connectable elements and a generator that can connect them. More precisely, a generator is one of the set of elements of an algebraic structure, such as a group, ring or module, which determines all other elements belonging to that structure when all admissible operations are performed upon them. Assume that an event continuant is an algebraic structure and that current information for the event continuant is an element of that structure. Further assume that the operation of detecting the perspective information acts as a generator of the whole structure – that is, as a specification of how the perspective portion of the event connects its retrospective and prospective portions. For instance, an expert batter can anticipate where the pitched ball is going to be so as to start swinging the bat early, in time to connect. Drivers in traffic repeatedly use *time-to-contact* information to brake their cars to avoid the prospects of colliding with another car. One has a natural tendency to look in the direction from which a snowball was thrown to detect the culprit. Numerous studies have been directed at determining the visual information for time-to-contact (Lee, 1976, 1980). Consequently, one can likewise imagine a complementary set of studies to determine the retrospective optical or acoustic information for the source of an event.

The set of graded examples presented below are designed to illustrate the use of the symmetry properties of algebraic structures to describe how event information (TIs and SIs) might be generatively specified. From a mathematical point of view, symmetry theory provides the most natural expression of invariant event information (Shaw and McIntyre, 1974; Shaw, McIntyre and Mace, 1974). However the perceptual mechanism is designed, a minimal requirement is that it be able to detect such symmetries. Let us consider a few simple examples of such symmetries that underlie TIs and SIs.

A light on a disk rotating in the dark when viewed edgewise will project a harmonic motion whose spatiotemporal continuant is a sinusoidal trace (Figure 10.1). The amplitude of the sine wave generated by the rotation will be the diameter of the disk and the period of one cycle of the sine wave is equivalent to the length of the disk's circumference stretched out over time. A double rotation of the disk determines two cycles of the sine wave, a triple rotation, three cycles, and so forth. These cycles are *isometries*, that is, segments of the trace that exhibit recurrent self-similarity (e.g. self-congruence). In real events these isometric periods are not perfectly recurring but do so only within some tolerance range. Structural properties that belong to the object generating the trace, such as size and shape, may also exhibit isometries over spatially adjacent relationships rather than over temporally successive relationships.

Intuitively, such orthogonal isometries comprise the SI and TI of an event. Hence, to change size or shape is to change a parameter on the SI of the event trace, while to change period or wavelength is to change a parameter on the TI of the

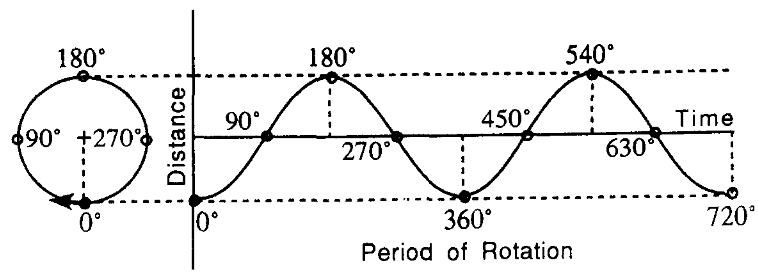

Figure 10.1. *The sinusoidal trace of a rotation event.*

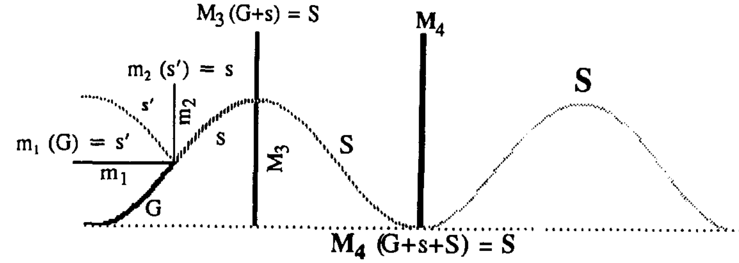

Figure 10.2. *The symmetry analysis of a rotation event trace.*

event trace. Since these SI and TI event components are based on isometries, they intrinsically scale the size of the spatiotemporal window within which perception operates.

The generator for this harmonic motion is a sequence of reflections of element G over the mirrors $[m_1, m_2, M_3, M_4]$ (Figure 10.2). This reflective sequence defines the successive symmetry, or TI, of any rotation event. Clearly, the generating element G could be chosen from any elemental portion of the symmetric spatiotemporal trace. For instance in Figure 10.1, if G were the trace element selected over the period [0–90°], then *prospective* generation forward in time would specify the completion of the trace over [90–360°] via the successive reflective symmetry. Likewise, if G were the trace element selected over the period [360–270°], then *retrospective* generation backward in time would specify the completion of the trace over [270–0°] via the successive reflective symmetry. Finally, given a middle portion of an event as a generator, say G = [180–270°], then *perspective* generation would specify the impletion of the trace in both the forward and backward temporal directions via the successive reflective symmetry.

For an asymmetric event trace the only generator, of course, would be the whole trace itself. But in all those cases where the event has nontrivial symmetry, then the perceptual sample that acts as a generator is necessarily some portion of the event smaller than the window.

While a rotation viewed edgewise (a linear event) can be depicted in two dimensions – one of space and one of time – a rotation viewed perpendicularly in the frontal plane requires three dimensions – two of space and one of time. Here, instead of a harmonic motion trace, there would be a helical trace wrapped around the rectilinear trace of its fixed axial point (like a coil spring surrounding a thin stiff rod).

It is important to note that the successive symmetry underlying the TI of any event trace is abstract in the sense of being independent of the object involved in the event. All points on any rotating object would trace out the same helical successive symmetry in three-dimensional space–time when viewed frontally, or the same sinusoidal successive symmetry in two-dimensional space–time when viewed edgewise. The successive symmetry achieved by application of an event generator is the basis of generative specification and provides an abstract informational basis for detecting events and classifying them according to their distinctive TIs. In Gestalt terms, however, we recognize that the TI is not only transposable over time (retrospective, perspective and prospective) but transposable over space as well (i.e. over different adjacent structures that are involved in the same event type) This is the basis of the Gestalt law of 'common fate'.

If the sample detected is a generator, then the whole event is redintegrated to fill the window's symmetry-specified dimensions. A repeating event defines a sequence of such windows. Under this view, whether the event is slow (like growth or the motion of the hour-hand) or fast (like locomotion or the motion of the second-hand) does not matter so long as the generator information for the event can be detected (Shaw and Pittenger, 1978). The generative specification approach to event perception depends on the logically prior noticeability, or perceptual saliency, of the generator samples as opposed to the perceptually inert samples. If the generator samples are not more likely to be attended to than other inert samples – in the sense of standing out like figure against ground – then there would be no way to get the act of event perception started.

The hypothesis for event perception start-up rests on the assumption that *the more invariant the property in the stimulation, then the more available it is to be noticed* – hence its greater perceptual salience (its *attensity*; Shaw and McIntyre, 1974). Many studies show that subjects tend to become selectively attuned to systems of invariant properties even when these properties are nested among noninvariant ones. Invariance seems to carry its own built-in noticeability quotient. After reviewing a variety of such studies investigating event perception, Johansson (1985) concluded that 'what the visual system evidently records are not absolute measures but instead hierarchies of certain spatial relations which stay invariant under change' (p. 51).

Objects with different shapes generate distinct spatial complexes of successive symmetries that intertwine over time in ways specific to their respective shapes. The abstract basis for structurally invariant information specifying the objects that undergo change can therefore be found in the phase relationships (i.e. adjacent symmetries) that hold under the successive symmetries. This can be seen by studying the phase relationships among the successive symmetry complexes peculiar to objects of different shapes (as shown in Figures 10.3–10.5).

For simplicity of graphical presentation, the shape of an object can be represented by certain selected points of high information. For polygons, vertices are useful choices. In Figures 10.3 and 10.4 we see the event traces for a rotating equilateral triangle and a square. The sinusoidal shape of each point trace specifies that these

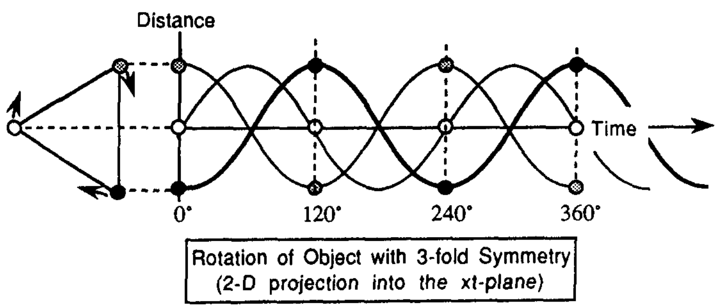

Figure 10.3. *The 3-fold symmetry of the trace of a rotating triangle (2-D projection into the* xt *plane).*

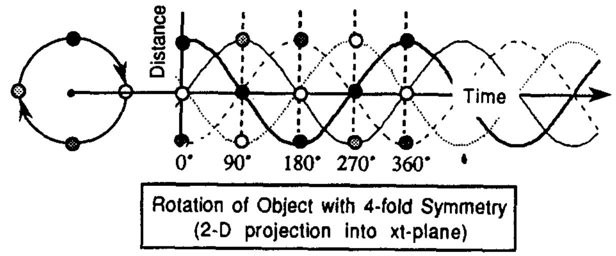

Figure 10.4. *The 4-fold symmetry of the trace of a rotating squares (2-D projection into the* xt *plane).*

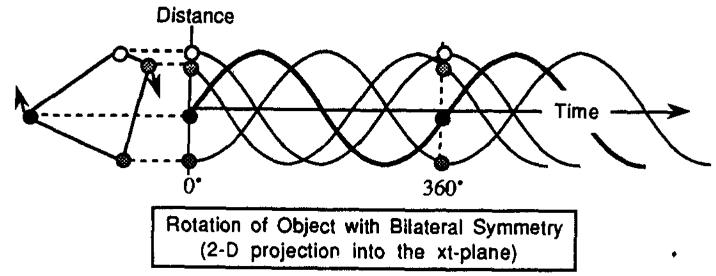

Figure 10.5. *The 2-fold symmetry of the trace of a rotating trapezoid (2-D projection into the* xt *plane).*

points, regardless of the overall shape of the object, are involved in events that share the same TI characteristic of its harmonic motion. The degree of regularity of the phase angles apparent among the individual point-generated sinusoidal traces specifies the symmetry, SI, of the object to which the common TI is applied. It is this information that specifies that the rotary object is an equilateral, isosceles or scalene triangle, or a square or trapezoid.

The beauty of event diagrams is that they can disambiguate over time those objects whose static perspective forms are spatially indistinguishable. For example, at an appropriately selected distance, a static square viewed from an oblique perspective may be indistinguishable from a selected trapezoid viewed in a frontal perspective. Yet, as we can readily see from comparing the event traces depicted in Figures 10.4 and 10.5, dynamical information for rotating square objects is quite different from that made available by rotating trapezoidal objects. The event approach rids us of the troublesome ambiguity allowed by the classic projective geometry of static retinal image samples.

Thus, the SI information for distinctly shaped objects is itself distinct, namely, the phase angles between sinusoidal traces determine different spacing and the periods of their successive isometries are also different. One merely has to see the rotation of the different objects to break the perspective symmetry. No taxation need be placed on memory or cognition to achieve a feature-by-feature image comparison of each object. If events are themselves objects of perception, then period and phase can be considered complex features (i.e. event information). For the properly designed and attuned perceptual mechanism (e.g. a Grossbergtype neural network; see Marshall, 1990), such global patterns of information can be assumed to be picked up as directly as any local feature.

To summarize the argument so far: a transformational approach can be used to express the successive symmetry exhibited by an event. A transformational description of this symmetry is synonymous with the concept of transformational invariant and expresses mathematically the intuitive content of the phrase 'style of change'. The detectable optical disturbances that emanate from the event source and that express the relevant TI comprise the perceptual information for the *event-type*. Likewise, the same optical disturbances convey information for size and shape and other structural properties. Information samples that are generators, in the technical sense, generatively specify the event. The spatiotemporal windows for such events are intrinsically scaled by their SI and TI isometries. The dimensions of phasing, amplitude and number of traces generated by feature singularities (e.g. vertices for polygons) express the relevant SI and comprise the perceptual (generative) information for the *object-type* to which the TI is applied. The specific values of manner parameters on the TI (e.g. its rate, number of iterations on its period, smoothness in its application) comprise the perceptual information for the *event-token*.

The hypothesis that event perception has a generative basis as explained by symmetry theory suggests an alternative to the cognitive hypothesis that events are constructed rather than perceived: consider the following line of argument. Traditionally, animal gaits have been given symmetry analyses (Gambaryan, 1974; Hildebrand, 1965). Recently, the hypothesis of cognitive programs that mediate locomotive pattern generation has been theoretically challenged by the assumption of central pattern generators. These pattern generators are treated as CNS-based oscillators that are coupled by information rather than being neurologically 'hard-wired' (Cohen, Rossignol and Grillner, 1988; Schöner, Jiang and Kelso, 1990). Here, recurrent gait isometries of animals are not cognitively mediated in the traditional sense of motor programs nor cognitive rules but are governed by natural law (Kugler and Turvey, 1987).

Analogously, we might assume a noncognitive perceptual mechanism that generatively specifies the impletion or completion of events according to their intrinsic isometries. If, on the other hand, we choose to think of visual information as 'cognitive' by definition (which broadly speaking it must be), then the coupling of elemental pattern generators by information in action theory (Schmidt, Carello and Turvey, 1990), and a similar coupling of central pattern generators by information in perceptual theory is not so strange a cognitive assumption.

Finally, under this event perception hypothesis, we need not know the details of the functional architecture of the CNS-based perceptual mechanism before we determine the informational basis of an event and, thereby, describe the functional requirements of the job that the stipulated mechanism must perform. It will be useful to examine the event perception hypothesis in the context of a well-known example. We do so next.

2.2 Perceiving a Rolling Wheel Event: An example

When a distinguished point on the rim of a wheel is rotated around a fixed axis point, it generates a highly symmetrical trace in the xy-plane: a circle (Figure 10.6). By plotting the circular motion over time, some of the symmetry is broken and more structure of the event is revealed. Recall that in the three-dimensional

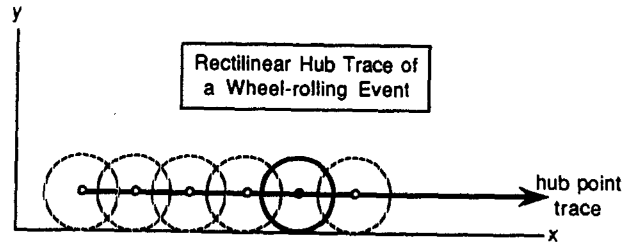

Figure 10.6. *Trace of the hub point of a rolling wheel.*

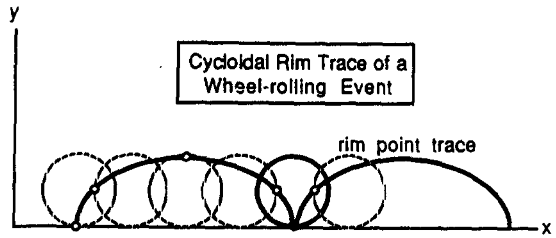

Figure 10.7 *Trace of the rim point of a rolling wheel.*

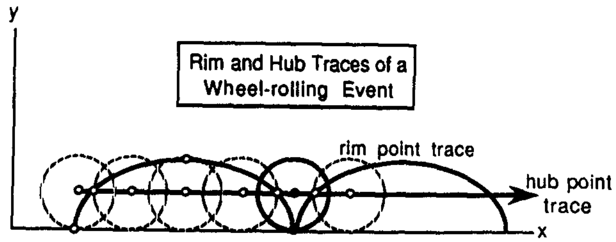

Figure 10.8. *Hub point and rim point traces of a rolling wheel.*

space–time we would see a helical trace coiled around a line of axial points – like a spring coiled around a straight wire. However, when we view the projection of this dynamical three-dimensional trace in the xt-plane, we see a sinuoidal shadow of the event trace indicative of a rotational TI – its harmonic motion. Rolling events have a related but more complex space–time structure.

If a wheel with a hub light is rolled over a flat surface in the dark, we see a rectilinear trace that maintains a constant radial distance from the surface. However, if – as Duncker (1929) showed – we view the rolling wheel with only a rim light, then we see a more complex trace in the frontal plane known as a cycloid (Figure 10.7). Apparently, an event TI can have more than one trace. How many?

Following Johansson (1975, 1985), one might hypothesize that the number of isolatable distinct traces should correspond to the number of component vectors associated with the event's resultant TI vector. Two component trace vectors are shown together in Figure 10.8. This depicts a wheel rolled as before but this time with a hub light and a rim light. Both a cycloidal and a rectilinear trace vector are generated simultaneously. Surprisingly, what is seen is neither of these isolatable trace vectors but rather a composite event vector that is quite different from either.

What is seen is a rotating object undergoing rectilinear translation. The invariant center of rotation perceptually anchors the event information because it maintains a constant radial distance from the horizontal surface over which the wheel rolls. Consequently, the most stationary motion trace is generated by the hub light. The next simplest motion trace is the circular orbit of the rim light which maintains a constant radial distance from the moving hub light. The least stationary motion trace is the rim light which follows a complicated nonlinear trace as defined relative to the surface of support. Hence, if we assume that the decomposition of the resultant event proceeds from the most invariant to the least invariant (a principle of minimal change), then there is no real surprise that we see the event as being organized as we do (Cutting and Proffitt, 1982; Proffitt and Cutting, 1980; Shaw and Verbrugge, 1975). This fact provides important support of the event perception hypothesis, for the event is seen as consisting of a rotation TI (i.e. motion around a center) and a translation TI (i.e. the rectilinear motion of that centered motion). How does the TI of the cycloidal trace relate to the TI of the rotation trace and the translation TIs?

Figure 10.9 shows how a perceptually persistent (spatially stationary) cycloidal trace is smoothly related to a rotation-only sinusoidal trace. The sequence of sinu-cycloidal traces represents rotating systems that have various degrees of translatory velocity, indicated by the slope of the hub trace in the xt-plane. These dynamic traces define a *homotopic* (topologically smooth) sequence (i.e. a coordinate transformation) that is interpolated between the pure adjacent symmetries (projection of the event's SI into the xy-plane) and the pure successive symmetries (projection of the event's TI into the yt-plane). Before, we argued that perception, construed formally as generative specification, operates to complete (or implete) a whole event (one that fills the space–time window) from smaller samples (that do not fill the window). Now we extend the argument to a higher level of generative specification.

Recognizing an event-token as belonging to an event-type (i.e. a class) is tantamount to perception involving a mechanism for extrapolating (or interpolating) homotopically from one token to another token, say, from a cycloidal trace to a sinusoidal trace. This homotopic relation can be seen in the event-token sequence (the sinu-cycloidal traces) that connects the SI boundary condition to the TI boundary condition. Moreover, slow events may be homotopically (transformationally) related to fast events (i.e. $dx/dt = 0$ may be related to $dx/dt = \infty$ by $dx/dt > 0$, as shown in Figure 10.9), because they lie on the same manifold whose local structure generatively specifies more remote structures. Thus, by assuming that event perception is generative, the Gestaltist's transposition problem receives a reformulation that implies a potential solution (Boring, 1942; Köhler, 1917).

The transposition problem is reformulated as the problem of explaining how one recognizes the common structure shared by event-tokens that have been transposed to different locations on their event-type manifold (e.g. like a melody played on different but related instruments). The solution is to recognize that this problem is now synonymous with discovering a manifold on which the event-tokens can be defined. This manifold must possess an information function that specifies a generative (homotopic) connection among the event-tokens corresponding to how they are perceived. Under this view, information as specification might be

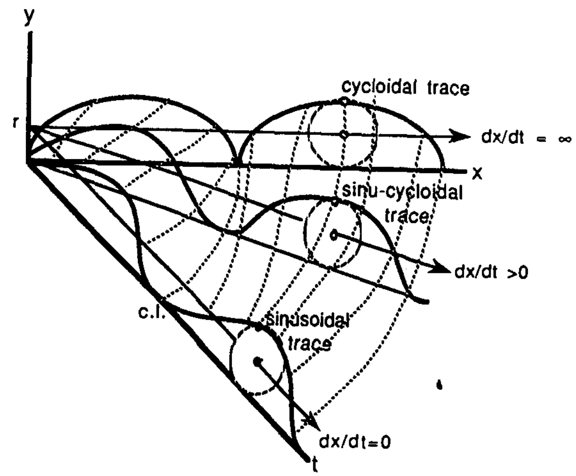

Figure 10.9. *Dynamical traces of a wheel rolling event. Here, r is the radius of rotation and c.l. is the circumferential length. The information specifying the TIs for such events clearly has an intrinsic scale.*

given a precise interpretation (Kugler and Turvey, 1987; Turvey, 1990; Turvey *et al.*, 1981).

In general, for event perception to be generative requires that there be the detection of event information intrinsic to a space–time geometry (e.g. window) for which the neural architecture that underlies detection is appropriately attuned. Specifically, it must be attuned to the homotopic sequences that dynamically relate an adjacent symmetry boundary (SI) condition to a successive symmetry boundary condition (TI). Again how such event traces are set up in the CNS, of course, needs to be explained, but the job putatively performed by such mechanisms can be made quite clear at an abstract level of description.

Consequently, this interpretation of Duncker's (1929) results supports the event perception hypotheses that the successive symmetry exhibited by an event is synonymous with the concept of transformational invariant. It also suggests a way that information for event-types may, indeed, be a form of generative specification in the sense discussed above. Adoption of the event perception hypothesis requires justification for believing that perceptual information exhibits spatiotemporal dependencies and that TIs and SIs are orthogonal dimensions of event space. These issues are addressed in due course.

2.3 Do Transformational Invariants Depend on Structural Invariants?

The evidence for the relative independence of TI from SI is mixed. Wertheimer's (1912) experiments on phi movement suggest independence, while Wallach's (1976) research on viewing motion through a rectangular window suggests dependence. These contrasting cases are considered next.

Wertheimer (1912) discovered a form of objectless motion that he called *phi movement*. As the interstimulus interval (ISI) is increased beyond that required for optimal motion, a ghostly motion is seen to pass between the two successively illuminated stimuli (see Figure 10.14 below). Wertheimer took the phi motion effect to be evidence that motion information is detected as such without any admixture of object information. G. H. Schneider (1878; cited in Boring, 1942) found that a shadow, too faint to be perceived at rest, becomes noticeable when it moves. Similarly, an object that is invisible in peripheral vision becomes visible when it moves.

Reversal of motion after-effects, like the so-called *waterfall illusion* or the *spiral illusion*, provide evidence that motion (TI) and spatial structure (SI) are independent. Stationary objects are seen as moving in a direction opposite to the direction of apparent (spiral after-effect) or real motion (waterfall illusion) of previously viewed objects (Boring, 1942). Phenomenological reports typically include a rather startling experience. During the after-effect the apparent counter-motion of a target object seems to become dissociated from that object's position. Such objects are sometimes claimed to be moving or changing size, even though they keep their place or size relative to other objects. This is a paradox unless one regards motion information (TI) and position information (SI) as having some independence (Gregory, 1966). Like Wertheimer's (1912) phi motion, this odd motion also seems objectless (see below).

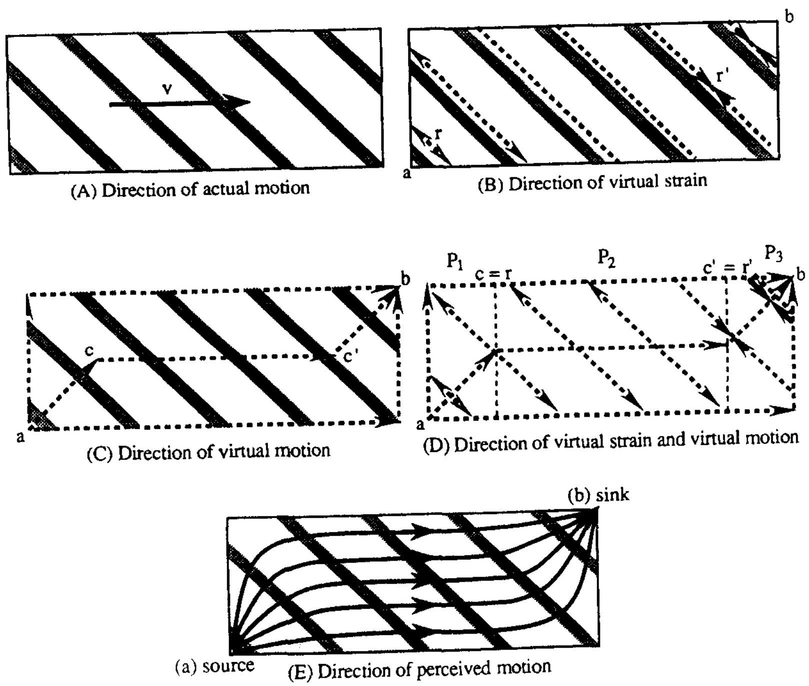

Figure 10.10. *Perception of apparent direction.*

Wallach (1935) developed a set of displays where subjects viewed stripes that moved behind a window in a direction specific to the interaction of the slant of the pattern to the window's shape (e.g. rectangular) (see Figure 10.10A–E). For example, the perceived motion, as depicted in (E), undergoes three directional phases: in phase 1 the motion is directed diagonally, in phase 2 horizontally, and in phase 3 diagonally again. Each stripe undergoes a positive (virtual) strain in phase 1, no strain in phase 2, and negative strain in phase 3. This phenomenon poses a significant problem for any local property approach to perception, whether it be an ecological approach aimed at describing the information made available by such events or a cognitive science approach aimed at modelling the mechanism by which such information is detected.

In Figure 10.10 the following holds: in (A), velocity vector v specifies left-to-right horizontal direction of real motion of the striped pattern. Figure (B) depicts the striped pattern emerging from a source-point singularity at a (lower left corner) and disappearing at a sink-point singularity at b (upper right corner). These dynamically specified initial and final conditions along with the spatial boundaries determine the perceived direction motion. As the stripes emerge and disappear, they undergo a positive and negative strain, respectively, which specifies a *relatively fixed-point property* (r.f.p.p.) on each stripe, represented by r and r'. Figure (C) shows the analytically defined motion vectors: on the one hand, the shearing of the stripes on the spatial boundary condition (perimeter motion vectors) defines the direction of motion as a function of edge-rate while, on the other hand, the connected flow of r.f.p.s defines a central motion vector with critical points (point-nonlinearities) at c and c'. Figure (D) combines the lateral strains with the edge rates due to the actual motion vector. Figure (E) shows the smooth continuous motion that is actually perceived. How do we explain the disappearance of the nonlinearities (e.g. critical points) generated under the vectorial description?

The perceptual information for aperture shape-directed motion events cannot be explained by local properties of neural networks or by information specific to local properties of the display that stimulates such networks (Marshall, 1990). The receptor network must be sensitive to both the changing local boundary conditions (the ends of each stripe) and the fixed nonlocal boundary condition (the aperture's overall shape). Each local boundary condition adjusts to satisfy the fixed nonlocal boundary condition, that is, the stripes increase or decrease continuously in length to fill the aperture's shape while moving continuously over the aperture's length. The relationship of the angled stripes to the shape of the window cannot be encoded into independent receptors but require global distributed attunement over the distributed receptor array (Marshall, 1990).

How does the shape of the window determine the trajectory of the motion event? It is one thing to explain how the information for such events is detected as a proximal stimulus but another to explain how that information is determined as a distal stimulus. Clearly, the design of the perceptual mechanism must conform to the TI for the event perceived. Let us consider how the TI for these events might be formally described.

A mapping from one set of points to another that leaves at least one point fixed is said to have a *fixed-point property* (f.p.p.). One-dimensional strains that operate in opposite directions on the ends of the stripes leave a point fixed at the center of the stripe. Since the direction of strain reverses in the neighborhood of such fixed-point properties, they may be called *reversal points*. Examples of reversal points are denoted by r and r' as shown in Figure 10.10B, D. But because these reversal points translate with the stripes, they are only relatively fixed-point properties (r.f.p.p.)

The r.f.p.p. of a given stripe is determined by the contravalent strains that act on the stripes toward the beginning (phase 1) and the end (phase 3) of the window. A reversal point is mathematically determined at the midpoint of each stripe as a function of the counter-directional strains at the end-points. The motion trajectory follows a direction mathematically defined as a path integral over the spatio-temporal interval from the initial condition a to the final condition b. The direction of the motion path is defined successively from the reversal point of one stripe to another. But what defines the motion path in the middle of the window (phase 2) where there are no contravalent strains, and hence no reversal points?

Another problem that must be resolved is why the TI for the event is smooth rather than jerky at the nonanalytic critical points, denoted by c and c', where the direction of motion abruptly changes. Is there some way to temper the stringency of the mathematics? The nonlinear abruptness arises mathematically because the path of motion is not integrable in the region of these singular (nonanalytic) points – that is, the vertices of the flow vectors at the phase transition boundaries. If these critical points are identified with the last reversal point in phase 1 and the first reversal point in phase 3, then a line of moving points is defined from $r = c$ to $c' = r'$. In this way the continuity of rectilinear flow across phase 2 is specified and our first problem is resolved.

In formal models of the CNS (e.g. neural networks or connection machine models), perceptual integration of contours and trajectories is likened to mathematical integration. Hence, we must take seriously the mathematical problems that arise in representing formally the process of integration. For instance, singular points that are not integrable by mathematical techniques cannot be blithely assumed to be integrable by perceptual techniques inherent in the CNS. Under either view, vertices of angles pose a problem. They act as critical points that are nonintegrable because they interrupt the continuity of a curve or the smoothness of a trajectory of flow. One can integrate up to but not including a vertex point. Such points constitute jump discontinuities and therefore are only piecewise integrable. Furthermore, the singularities at the vertices, through vectorial superposition effects, convolve to create the critical points (c and c') inherited by the flow in the middle of the window as well. On the other hand, if vertices can be slightly rounded off by perception, the trajectory of flow passing through their neighborhood could then be made smoothly integrable.

One way to smooth over nonlinear kinks in curves or trajectories is to reduce the precision of the mathematical description of the vertex singularity. Let the length of a chord be the minimum length that can be perceptually resolved. We do not care what the length is but only that it be realistically finite rather than ideally infinitesimal. Next, assume that the distribution of these short chords of equal length subtend the two sides of the angle in question. This distribution then defines an envelope of tangents to a curve generated by rolling a circle with a radius of $1/4R$ inside a circle with radius R. Figure 10.11 shows this curve stretching from T1 to T2 at a distance of $2R$ from the vertex point of the angle.

'The only thing that distinguishes one potential flow from another is the shape of the boundaries' (Gerhart and Gross, 1985, p. 590) . Because flowlines of a medial trajectory deform continuously onto the boundary of the flow (e.g. the aperture window), this guarantees that the smoothness of medial flow must be preserved in

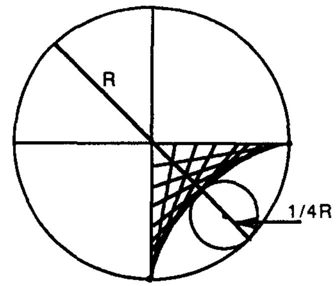

Figure 10.11. *A chord distribution geometry. An integral geometry based on chord-sets rather than point-sets provides one way of smoothing out discontinuities (Moore, 1971, 1972) (see text for details).*

the boundary flow, and vice versa. Likewise, vertex singularities that create nonlinear flow on the boundaries would promulgate as nonlinearities into the medial flow and be perceived. But they are not. Consequently, smoothness on the boundary is both a necessary mathematical and perceptual assumption of the Wallach aperture viewing situation.

Perhaps, then, boundary flow around sharp corners is perceptually abraded because the space of perception is based on a set of minimally discriminable lengths (e.g. chords) rather than on real points (Shaw and Cutting, 1980). Perhaps, also, the curve is smoothed by considering c and c' perceptually to be fuzzy set distributions (Kaufmann, 1975) of flow vectors that satisfy some tolerance limit (e.g. a perception of length threshold) rather than as topological neighborhoods of single points. The perceived flowfield characteristics would then be the result of the TI of the motion being the mean free path through these regions of fuzzy set distributions.

The Wallach aperture viewing case raises several questions regarding the relationship of apparent motion events to real motion events. Are they informationally equivalent or disequivalent? We turn next to the so-called *equivalence thesis* which asserts that since real motion and apparent motion have equivalent perceptual effects, then they must have equivalent underlying information and/or mechanisms. Both the antecedent and the consequent of this proposition have been challenged.

2.4 Is the Perception of Apparent Motion Equivalent to the Perception of Real Motion?

Is it a fallacy to assume that real motion and apparent motion are the same in some or most essential ways? A surprising number of first-rate thinkers have strongly disagreed on this question. Some have begun with the affirmative opinion and later switched to the negative one as evidence accrued. Others have staunchly maintained their respective attitudes toward this issue despite evidence to the contrary. Perhaps the most persuasive evidence that the equivalence thesis must be weakened comes from the important discovery that distinctions exist between apparent and real motion events (Kolers, 1974).

The equivalence hypothesis is a logically tenuous claim at best. For even if pparent and real motion events appeared identical under all parametric conditions which of course they do not), it would still be fallacious to argue from the ›resumed equivalence of two effects that the underlying mechanisms were necesarily the same. This would be to commit the well-known fallacy of affirming the :onsequent. Let x be the premise that similar mechanisms produce similar effects, ınd let y be the observed equivalence of the phenomenal attributes of real and ıpparent motion. The equivalence thesis has the form: *if x, then y. Given y. Therefore* ɛ. The only way that the equivalence thesis could be valid is if mechanisms had ınique effects, that is, if a given mechanism were the only possible cause for ɜxplaining the occurrence of the observed effects. Consequently, we should not be surprised to find that distinctions exist between apparent and real motion events. But do these differences make a perceptual difference?

Among the most important of these distinctions is that between 'short-range' and 'long-range' information detection. Braddick (1974) presented evidence for the existence of two kinds of information in apparent events: low-level information for a *short-range process* that detects information over relatively short durations and short distances and a higher-level information for a *long-range process* that detects information over relatively long durations and long distances. Given this evidence, it now seems unwarranted to hold to the strong form of the equivalence thesis, although expert opinion in the field is still mixed. Let us consider examples of the most polarized opinion on this issue.

Some of the most notable psychologists who have maintained that apparent motion events are equivalent in essential ways to real motion are Gibson (1968), Gregory (1966), Hochberg (1987) and Wertheimer (1912). For instance, Gregory has likened their equivalence to a loosely fitting lock and key; Gibson once remarked that it was unfortunate that a distinction had ever been drawn between veridical and illusory motion – a sentiment he later recanted (see below). The most notable exceptions to the equivalence hypothesis have been taken by Gibson (1979), Haber (1983), Johansson (1975) and Kolers (1964). After nearly a decade of research on the topic, Kolers (1964) summarized his findings as follows:

> 'In sum, what our experiments reveal, in addition to several behavioral criteria that distinguish real and apparent movement, is that the "mechanism" for illusory movement has more in common with the "mechanism" controlling the formation of simple visual figures than it has with real movement. What one sees "moving" in an illusion is the result of an impletion, but the impletion occurs only at rates of stimulation associated with forming the perception of simple visual figures. The more difficult problem remaining is to elaborate the rules that govern impletion.... Experiments of this kind also support a hypothesis that has been advanced tentatively in the past few years. It is that perceptions are constructed by means of a number of different operations occurring at different times and places in the nervous system.' (p. 323)

Johansson (1975) voiced his dissent from the equivalence thesis as follows:

> 'The eye is often compared to the camera, but there is one enormous difference between the two. In all ordinary cameras a shutter "freezes" the image; even in a television camera, which has no shutter, the scanning raster of an electron beam serves the same purpose. In all animals, however, the eye operates without a shutter. Why, then, is the world we see through our eyes not a complete blur?... Whether we are standing still or moving through space the eye effortlessly sorts moving objects from stationary ones and transforms the optic flow into a perfectly structured world of objects, all without the benefit of a shutter.... Thus, the eye is basically an instrument for analyzing changes in light flux over time rather than an instrument for recording static pattern.' (p. 67)

A decade after Kolers' monograph seemed to have established the counter-thesis, Haber (1983) thought it still worthwhile to argue against the equivalence thesis. In arguing for a 'natural ecology of vision', he summarizes his remarks as follows:

> 'I described the most typical instances of how we perceive in terms of our movements and the movements of objects in the scene. I argued that all such combinations of perception could easily be explained if the stimulus for vision is conceived of as dynamic change. Conversely, if the *stimulus* is conceived of as an initial static picture, explaining perception is inordinately difficult, implausible, and often impossible.' (pp. 49–50)

The only context in which perception might be legitimately treated as static persisting glimpses is, perhaps, when brief flashes of lightning during a stormy night are the only sources of illumination, or when searching a dark room one uses brief intermittent illuminations by a flash-light. However, it is worth noting that out of the nearly three dozen leading psychologists who offered peer commentaries on Haber's arguments, only three saw fit to agree with his view that perceptual information is a dynamical abstraction from stimulation whose source is change itself – a change whose information we have sought to construe formally as generative specification.

Still more recently, as notable of a figure in perceptual psychology as Hochberg (1987) still gamely expressed support for the equivalence thesis, although certain notable differences were duly recognized (Hochberg and Brooks, 1978):

> 'Some of these mechanisms and processes must also be engaged when we build up a continuous percept of our physical environment by taking successive discrete and discontinuous glances at it.' (Hochberg, 1987, p. 604) '... Research in this area has barely begun. The cognitive skills by which the information from successive glances is integrated – skills that are of the utmost importance to perceptual theory that aspires to apply beyond the momentary glance – are open to study through the medium of motion picture cutting.' (p. 608)

Thus, despite mitigating evidence the equivalence thesis seems atavistically healthy.

The cognitive approach to event perception opposes the direct pick-up of information for change and treats change as a representation constructed by inference. This view is exemplified by Oatley (1978). He asserts that the problem of perception is to understand:

> '... the processes that von Helmholtz (1866) called unconscious inference that allow us to create in our minds a representation which we experience of what it is like out there, given a fragmentary, changing two dimensional set of receptor excitations.' (p. 167)

The constructive view requires memory so that the positional and configurational information that act as 'premises' might persist long enough for the inferences to 'change' to be drawn, presumably, as mental computations. If one is willing to allow 'unconscious inference' mechanisms to construct more elaborate perceptions than given in the stimulus information, then why not begin with static snapshots of events? Consequently, it is often (although not always) the case that those who accept the Helmholtzian thesis also have no qualms in accepting the strongest form of the equivalence thesis.

On the other hand, if generative information for change is available in the stimulation, then neither of these theses are required. Thus, the counter-Helmholtzian thesis asserts that the problem of event perception is to understand how we perceive events from the information for change *per se* without need of cognitive elaboration. Is there any evidence to favor this counter-thesis?

In a recent, thorough review of evidence for mechanisms proposed to explain visual processing of real and apparent motion, Nakayama (1985) evaluates the thesis that motion perception requires memory or persistence of position information over time (Dimmick and Karl, 1930; Kinchla and Allan, 1969):

> 'It is likely that the appreciation of motion as a fundamental sense was retarded by these alternative interpretations. Mounting evidence, accumulated over the past century and especially of late, however, leaves no doubt that motion is indeed a fundamental visual dimension.' (Nakayama, 1985, p. 626)

After reading Hochberg and Brooks (1978), what he called the only serious account of motion picture perception, Gibson (1979) expressed the ecological psychology thesis that runs counter to both the Helmholtzian and the equivalence thesis as follows:

> 'The artificially produced *glimpse* is an abnormal kind of vision, not the simplest kind on which normal vision is based.... If perception of the environment is truly based on glimpses, it *has* to be a process of construction. If the data are insufficient, the observer must go beyond the data. How? Some of the greatest minds in history have undertaken to answer this question without success.' (p. 304)

He goes on to say that explanations of perception based on discrete sensory inputs fail because they all come down to this:

> 'In order to perceive the world, one must already have ideas about it. Knowledge of the world is explained by assuming that the knowledge of the world exists. Whether the ideas are learned or innate makes no difference; the fallacy lies in the circular reasoning.
>
> But if, on the other hand, perception of the environment is not based on a sequence of snapshots but on invariant-extraction from a flux, one does not need to have ideas about the environment in order to perceive it.' (p. 304)

These represent the primary opinions of the field toward perception in general and event perception in particular. Event perception is either a cognitive construction from impoverished stimulation or it is the detection of information that generatively specifies exactly what is seen. If the observer perceives by going beyond the data, then perception is a constructive process that adds something to the event data that was not there. But if, as the event perception hypothesis purports, the observer perceives by extracting invariants from the event data, then perception is an extraction and generative completion (or impletion) process that adds nothing to the event data that was not already there. If so, then this is the basis for a realism rather than a phenomenalism regarding perception.

So far our concern has focused primarily on linear descriptions of event information. However, there are important nonlinear issues to which we now turn.

3 PHASES OF MOTION EVENTS

One of the most perplexing aspects of event perception is that a continuous change of an extensive parameter can lead to discontinuous intensive effects. One style of change can make an abrupt transition to another style of change so that: f: $TI_1 \rightarrow TI_2$ may be a nonlinear function even though the controlling independent variable undergoes only smooth linear change. The issue is whether such differential 'thresholds' in perception can be explained in terms of the information made available by the event or whether some cognitive construction or 'inferential' activity must be postulated. In other words, can the perception be direct in the sense of generative specification, or must it be indirect and go beyond the information given? This issue is addressed next.

3.1 Slipping, Rolling and Sliding

A real world rolling event is rarely perfect. Usually the traction of objects rolling over a surface varies as a function of changing coefficients of friction so that the object may slide or slip to some extent instead of rolling. These three event phases can be graphed in such a way that they are shown to be homotopically related and therefore lie on the same manifold. A generative specification of how these phases relate can be given by changing the value of a free parameter, called a *control parameter* (R or T as discussed below) which then determines the value of an *order parameter* (R/T). A control parameter is a variable in an equation that describes the order parameter of a dynamical system such that changing it gives rise to a successive order of distinct but related phases of a given phenomenon. An order parameter is a measure of, and determiner of, the phases of orderliness that the dynamical system moves through when the control parameter is manipulated (Bruce and Wallace, 1989; Haken, 1977; Landau and Lifschitz, 1985). Here, the order parameter is the ratio of the amount of rotation to the amount of translation, as measured in circumferential distance units of $2\pi r$. Notice in Figure 10.12 that the slip phase graph is for the case where the rotation R is greater than the relative translation T, that is, $R > T$ (as measured in circumferential units of distance); the roll phase graph depicts the case where $R = T$; and the slide phase graph the case where $R < T$. The entire event is comprised of three phases that show up as distinct segments satisfying different transformational invariants – ranging from pure slipping (where $T \rightarrow 0$) through pure rolling (where $R = T$) to pure sliding (where $R \rightarrow 0$). Hence, the complex event depicted satisfies the transformational invariant with the boundary conditions $0 \leqslant R \leqslant 2k\pi r$ and $0 \leqslant T \leqslant 2k\pi r$ – where k and r are constants specifying the number of periods through which the event cycles.

A real world event to which this complex event might correspond is a car slipping its wheels in mud as it attempts to go up a hill (slip phase), rolling with good traction on dry pavement (roll phase), and sliding across a wet pavement as the wheels lock-up under heavy braking (slide phase). These three phases comprise three different lower-order transformational invariants that belong to the same higher-order transformational invariant; namely, although they specify three distinct styles of rolling, they are all cases of rolling (except at limit). Here, the order parameter implicated is *degree of rotation/unit distance translated*. Degenerate cases of

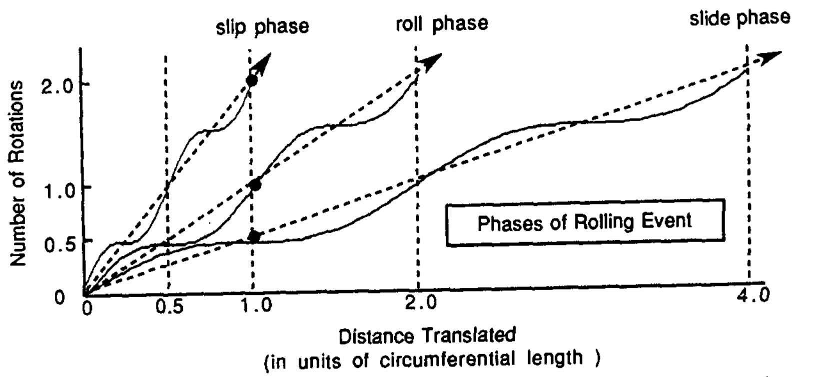

Figure 10.12. *Three phases of a rolling event arise from an object rotating with different degrees of frictional contact with a given surface. Slip phase: with some slipping the wheel rotates more than once for each circumferential length over which it translates. Roll phase: with perfect traction the wheel rotates exactly once for each circumferential length over which it translates. Slide phase: with the application of some outside pulling force the wheel rotates less than once for each circumferential length over which it translates*

these phases are *pure rotating* representing a wheel slipping without traction on a frictionless surface and *pure translating* representing a wheel sliding over a surface without any rotation whatsoever.

One might consider the existence of any object, in principle, to be mathematically describable in terms of its worldline over a variety of phases with different periods. If, as we have argued, event perception should be considered the scientific study of how people and animals detect and classify the successive symmetry of various styles of change, then a task for the field is to work toward empirical validation of a taxonomy of candidate transformational invariants.

In this regard, Figure 10.12 illustrates a key feature of phase diagrams for event information. Transformational invariants occupy temporal degrees of freedom while structural invariants occupy spatial degrees of freedom. If we assign a unit time to a rotation, then the ordinate of the graph plays the role of a temporal dimension, while the abscissa plays the role of a spatial dimension. The regularities in adjacent order that appear as constant intercept values along the spatial axes denote structurally invariant properties, while regularities in successive order that appear as constant intercept values along the temporal axis denote transformationally invariant properties.

For instance, in the roll phase the isometries comprising the SI along the abscissa are circumferential distance units that are in the ratio of 1:1 with the isometries comprising the TI time to rotate. The breaking of the symmetry relationship between the TI and SI in the slip phase, where the ratio is 1:2, or in the slide phase, where the ratio is 2:1, is responsible for the transition from one event phase to another. The breaking of symmetry between TIs and SIs, therefore, can be an important way both to classify events (i.e. by phases) and to characterize the parameter over which this higher-order generative information is defined.

In the next section, we show that taxonomies of event phases can be found not only in cases of real motion but also in cases of apparent motion.

3.2 Phases of Apparent Events

Perceptual phases are found to exist for apparent motion events as well as for real motion events. Perhaps the most famous and most studied apparent motion event was created by Wertheimer (1912). By changing the relative frequency of successive events, say a pair of small flashing lights, a range of apparent movement phenomena can be created. The interstimulus interval (ISI) is the temporal period separating the off-set of one event from the on-set of another such event. Such events may contain a pair of identical, similar or highly distinct objects. Some of the other most relevant variables are distance between the lights, time between flashes, and their intensity relative to each other and the background. Assuming we hold all the other parameters constant, then as the ISI is shortened the frequency of the successive flashing increases and a range of apparent motion effects is typically experienced by a person observing these events (Figures 10.13 and 10.14).

With a sufficiently long range of ISIs the flashes are seen as two separate, successive events But as the range of the ISI is decreased, a remarkable new event is seen – a 'pure' objectless motion passes between the two lights. This is Wertheimer's famous phi phenomenon and was taken by him to be evidence that motion as such is a fundamental dimension of experience independent of sensations of successive locations (i.e. positional information). This might be taken as arguing that information for transformational invariants may be available independent of information for structural invariance.

At still shorter ISIs one no longer sees two separate events but one event: a single object moving continuously from one place to the other. This is called *optimal motion*

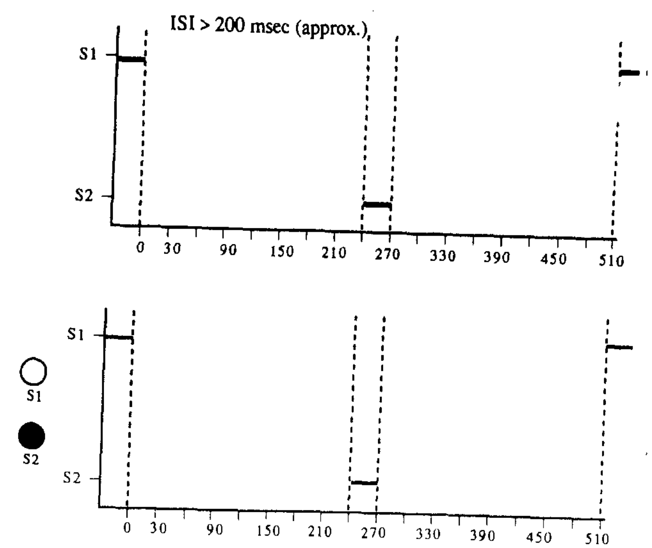

Figure 10.13. *Apparent motion (phase 1): at an ISI of approx. 200ms successive events are seen. The top diagram depicts the actual parameters of the display while the bottom one depicts what is seen. Here, there is no significant discrepancy between the two.*

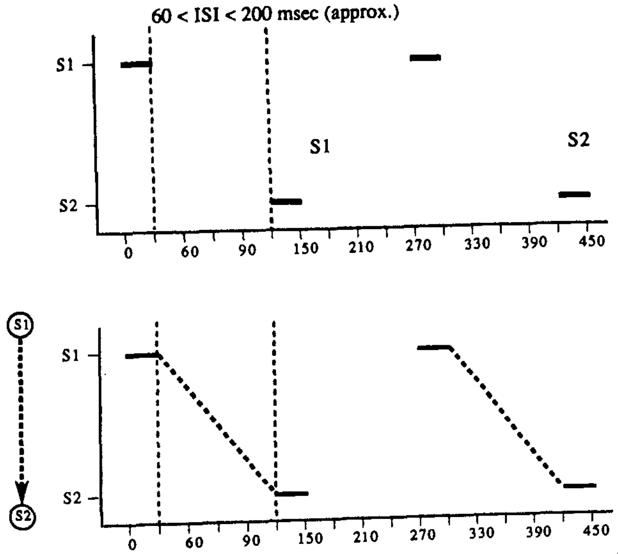

Figure 10.14. *Apparent motion (phase 2) at an ISI of approx. 60–200 ms phi (objectless) motion between the two stimuli is seen. Notice the discrepancy between what is actually presented (top diagram) and what is seen (bottom diagram). The pure objectless phi motion is shown as a dotted line.*

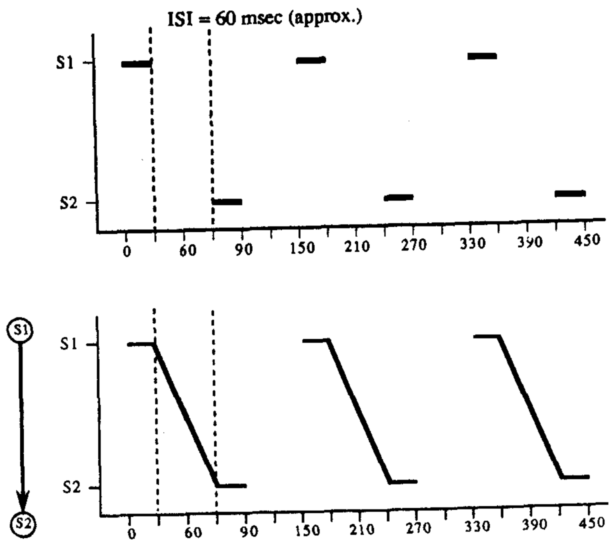

Figure 10.15. *Apparent motion (phase 3): at an ISI of approx. 60 ms optimum motion of one object is seen. The solid line connecting the events at positions S1 and S2 represent the optimal motion that is seen.*

(Figure 10.15). As the ISIs become even shorter, two partial movement events are seen (Figure 10.16). One object begins moving toward the other but then stops without making the full transit. Then the other light picks up the motion somewhat later and completes the transit to its own location. Finally, at the shortest ISI, two lights are seen in two locations at the same time (Figure 10.17).

Koffka's student Korte (1915) formulated principles that Koffka named Korte's 'laws', or as Anstis (1986) suggests are more aptly rules of thumb. These principles define the conditions for optimal apparent motion as involving three linear functions f, g and h of the variables T (ISI), S (spatial separation) and I (stimulus intensity),

(1) For $T =$ constant: $S = f(I)$ and $I = g(S)$, i.e. the spatial separation and the intensity are directly related.
(2) For $S =$ constant: $I = 1/h(T)$ and $T = 1/f(I)$ i.e. the intensity and the ISI are inversely related.
(3) For $I =$ constant: $T = g(S)$ and $S = h(T)$ i.e. the ISI and spatial separation are directly related.

These first two laws are tolerant over wide ranges of values. For instance, Korte (1915) recognized that displays with fine patterns and small distances separating them required shorter ISIs than displays with coarse patterns and longer distances (see Anstis, 1986, for a summary of the tolerance ranges for Korte's laws). The third law has been characterized as being more problematic than the first two – even being in error. Neuhaus (1930) maintained that the duration of exposure rather than intensity was a determinant of apparent motion. We will return to discuss these 'laws' later.

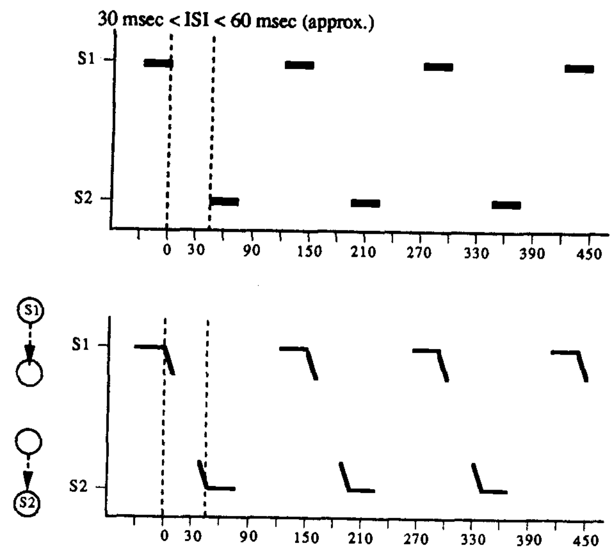

Figure 10.16. *Apparent motion (phase 4): at an ISI of approx. 30–60 ms partial motions are seen to take place near each terminus. These partial motions are shown as the short solid lines*

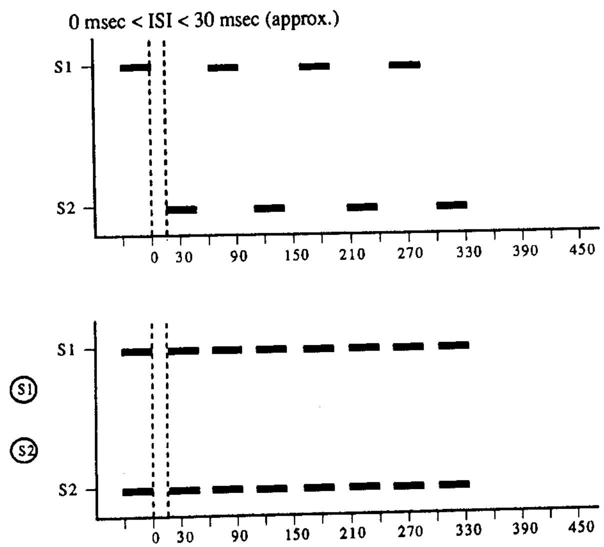

Figure 10.17. *Apparent motion (phase 5): at an ISI of less than approx. 30 ms two simultaneous events with no motion of any kind are seen.*

4 EVENT DIAGRAMS: THE RELATION OF APPARENT MOTION EVENTS TO REAL MOTION EVENTS

We now wish to examine the advantage of treating apparent and real motion phenomena as true spatiotemporal objects rather than as time-tagged, loosely ordered spatial objects. Many changes in spatial configurations look arbitrary and give rise to puzzling perceptual effects when treated as static frames edited into arbitrary temporal sequential order. By contrast, many aspects of event perception that are difficult to explain under sequencing of static samples are seen to arise as intrinsic properties of the appropriate space–time geometry. We consider next how spatial and temporal dimensions may depend on each other.

4.1 Space and Time Dependencies

There is considerable evidence that spatial and temporal dimensions of events are not processed equivalently by the visual system. In Korte's data for maintaining optimum apparent motion spatial separation, S, seems to relate to temporal separation by an approximate measure of 3:2 (i.e. $3S = 2T$) (Koffka, 1935). As Kolers (1972) observes, the ratios are more than 3:2 for Neuhaus' (1930) data. Judged spatial extent and measured physical distance are in close accord, while judged duration does not fit clocked duration very well at all.

In an experiment to determine the relationship of perceived spatial extent to duration, Mashhour (1964) had observers view and scale numerically a small object

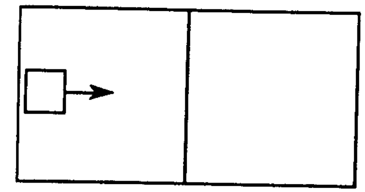

Figure 10.18. *Perceived velocity as a function of context. The perceived velocity of the small object moving in the frame is affected by the amount of background detail. The speed of the object appears faster near the end and middle lines of the frame than in between.*

moving at various speeds over various distances. The results were then plotted against the physically measured values to determine any discrepancies. He found that perceived velocity v^* related to physical velocity v by a power law estimate rather than 1:1, i.e. $v^* = kv^p$, $0.63 \leqslant p \leqslant 0.94$. This and the fact that there are many other determinants for perceived velocity makes the relating of perceived velocity to physically measured velocity a complicated affair. In many cases of velocity detection there are significant effects of the context in which the motion takes place (Brown, 1931). Figure 10.18 shows once again how context (SI) might have an effect on the TI – similar to Wallach's aperture window, only the effect is on velocity rather than the direction of motion. Thus, if Korte's laws apply at all, they must apply nonlinearly rather than linearly.

In keeping with the idea that velocity estimates may, more likely, reflect rates of processing event information than detection of velocity as such, Caelli, Hoffman and Lindman (1978) introduced a new metric consideration. Perhaps the data from apparent and real motion experiments should be analyzed in a space other than Euclidean space plus time – what physicists call the *Galilean view of space and time.* Numerous studies have shown that the perception of spatial and temporal factors are interrelated so that 'velocity seems to be a directly perceived attribute of moving stimulation' (Lappin *et al.*, 1975, p. 393) Furthermore, form (line of dots) detection seems also to depend on total space–time distance among component dots, independent of their distance apart or their temporal separation *per se* (Falzett and Lappin, 1983).

The perceived length of objects in real motion has been shown to be different from the perceived length of the same objects when viewed stationary (Ansbacher, 1944; Bhatia and Verghese, 1964; Brown, 1931). An inverse relationship has been shown to hold between separation of events in space–time and the so-called *threshold on motion detection* (Henderson, 1973). This threshold seems to be higher when the events are far apart than when they are closer together. After reviewing the available evidence and running three studies to verify the hypothesis, Caelli (1981) concluded that perceived time, length and velocity are all interdependent so that any attempt to base a theory of velocity detection on a fixed concept of distance and time treated as independent is bound to fail.

Hence, what is needed is a geometry of events that systematically and elegantly incorporates these interdependencies of time, length and velocity. Minkowskian geometry, used to express special relativity, as opposed to Galilean space and time geometry of classical mechanics, seems to offer the appropriate method of description. We turn next to this approach to event geometry.

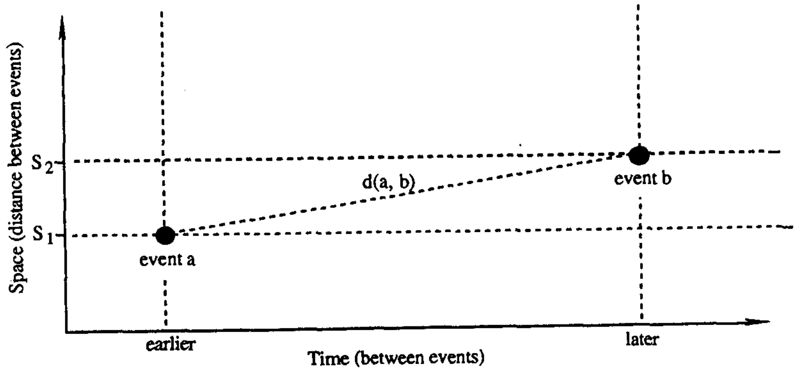

Figure 10.19. *Galilean event diagram.*

4.2 Event Descriptions

Events, by definition, have a four-dimensional spatiotemporal structure. They unfold simultaneously over space and time. Spatiotemporal structure need not, however, have a Euclidean distance metric. For instance, just as the two-dimensional Euclidean distance metric, $d = (x^2 + y^2)^{1/2}$, and the three-dimensional Euclidean distance metric, $d = (x^2 + y^2 + z^2)^{1/2}$, is a generalization of the Pythagorean theorem for two dimensions, $d^2 = x^2 + y^2$, and three dimensions, $d^2 = x^2 + y^2 + z^2$, respectively, so the four-dimensional Euclidean distance metric for space–time structures (i.e events) has the analogous form $d^2 = x^2 + y^2 + z^2 + t^2$. Or, as defined under Minkowski's hyperbolic geometry for space–time, we have the distance metric $d^2 = x^2 + y^2 + z^2 - t^2$. Let us begin with a simple Galilean event geometry as illustrated in Figure 10.19.

Newtonian physics assumes a Galilean event geometry embedded in Euclidean space with time as an added spatial dimension. Events, therefore, are objects in this space and time geometry that have both spatial and temporal coordinates. The interval separating two events, $d(a, b)$, has both a spatial separation and a temporal separation. The ratio of the spatial and temporal intervals separating the two events defines a rate or velocity. Instantaneous velocities are also possible in this coordinate system. A spatial dimension is needed to show the distances separating their sources (e.g. a pair of blinking lights) and another dimension to represent their timing (e.g. ISI).

A restriction must be imposed on Newtonian physics with its Galilean event geometry (Figure 10.19) to express our perceptual inability to discriminate very brief ISIs between two events. Even though an event is actually later in time, it can be seen as moving backwards in time to become simultaneous with an earlier event if the ISI between the two events is sufficiently brief (recall Figure 10.17). The limitation on the rate of causal action in physics is set by the extremely high but finite velocity of light. Since no physical process involving objects with a nonzero moving mass can exceed this rate, a null region in space–time exists in which such events are deemed to be effectively simultaneous–even though by an absolute Newtonian temporal measure they are not. Rather, they are simply separated by

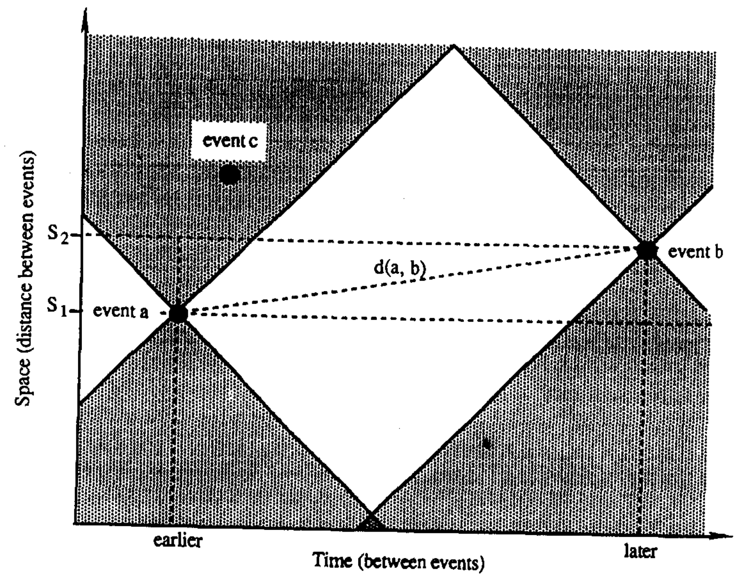

Figure 10.20. *Restricted Minkowski-like event diagrams. The intervals between events in this geometry are restricted. The slopes of the lines define forward (anticipatory) and backward (hereditary) cones within which events may causally interact (light color). The forward causal cone is shown here as defined from the perspective of event a with respect to event b. There are also null cones (dark color) representing regions in which no causal action can take place between events. For instance, since event c lies in the null cone of event a, they cannot causally interact. Rather, they are effectively simultaneous. Worldlines may not cross unless there is a merger of object identity. Objects with mass do not mechanically interact this way since one palpable volume must displace another and cannot occupy the same place at the same time.*

sufficient distance to prohibit causal interaction for the amount of time that separates them. Nothing can transpire between them without violating the limiting speed of light.

Analogously, there is an upward limit on the rate at which one event can be perceived as mechanically influencing another event. No person can perceive a causal interaction between two events faster than the CNS can respond to the information made available by such an interaction (e.g. the motion of an object moving from one place to another). Kolers (1972) has argued that motion perception is related to the CNS formation time for event information. Under this view diagrams for perceptual events, like those for physical events, must also have null cones surrounding any given event to represent the regions in space–time that lie beyond the limits of its ability to causally interact with other events. Figure 10.20 illustrates how such realistic restrictions might be built into an event space–time geometry.

To see how event diagrams might be used for perceptually restricted events, let us consider two examples: the Ternus and the Wertheimer apparent motion effects.

4.2.1 Case 1: Event Diagrams for the Ternus Effects

The Ternus effect is portrayed in Figure 10.21. Despite the fact that dots b and c remain in the same place over time while dots a and d are alternately on and off, the perceived motion is of a coherent three-dot pattern shifting up and down. The puzzle for the event diagramming technique is to explain why the invariant dots b and c do not retain their identity. If they did, then no apparent motion should be seen. Dots a and d lie in each other's null cones and therefore cannot causally interact; thus they should be seen as two successive events. Indeed this effect is reported for some values of on-time and off-time for the dots.

A second and more striking effect is portrayed in Figure 10.22. Here, the identity of invariant dots b and c persists. The timing between dots a and d has been changed so that dot d now lies in the causal cone of dot a. Hence, motion should be perceived between a and d. Indeed it is.

Finally, if the event diagramming technique is to be more than just descriptively adequate, then it should make predictions as well. By altering the timing between the first and second trio of dots so that dots a and d fall into each other's mutual null cones, one would predict that, unlike the second Ternus effect, no motion would be perceived between these end-points because they would be effectively simultaneous. This effect also holds (Figure 10.23).

It is worth noting that the metric for the space–time involved in these diagrams is treated as being essentially flat rather than curved. A variety of additional effects however, can be predicted if one imposes a hyperbolic metric on space–time

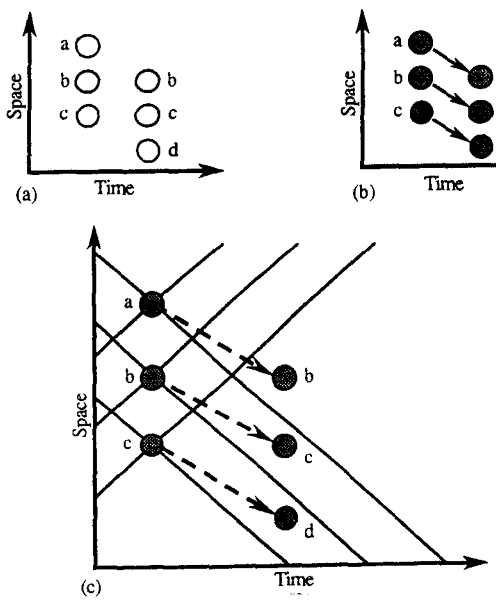

Figure 10.21. *The Ternus effect I. Three dots are seen to shift together from one place to another although the two middle dots are not actually displaced between frames.*

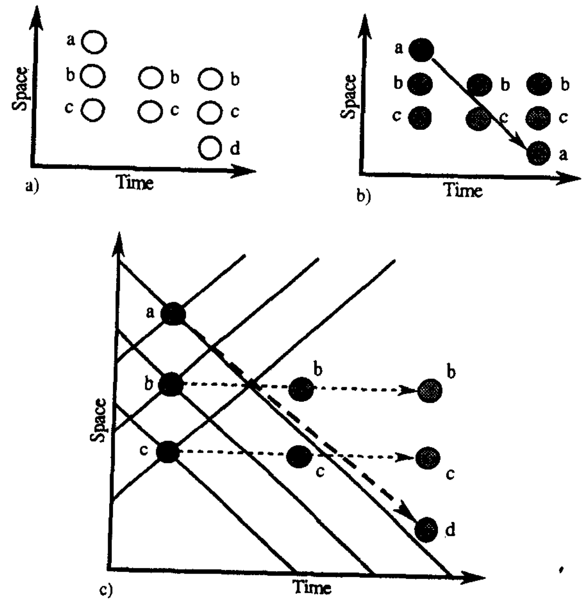

Figure 10.22. *The Ternus effect II. The timing has been changed so that an apparent motion is seen between the dots on the ends even though the two middle dots are not seen to move.*

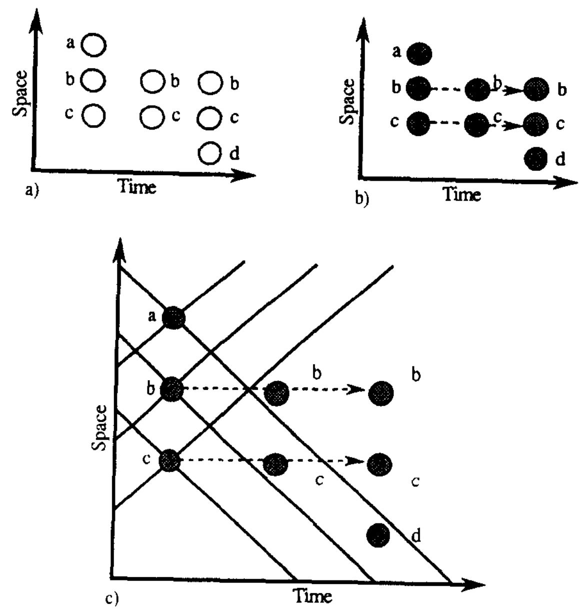

Figure 10.23. *The Ternus Effect III. The timing has been changed so that no apparent motion is seen between the dots on the ends. This effect is achieved by moving these dots into each other's null cones thereby rendering them effectively simultaneous.*

instead (Caelli, 1981). Nevertheless, the diagrams as presented are sufficient for expressing the ordering relationships among apparent and real motion phases (i.e. the order parameter) as the function of a control parameter (e.g. ISI)

4.2.2 Case 2: Diagramming the Phases of Apparent Motion Events

A worldline connects two events that comprise the fore and aft termini of Wertheimer's apparent motion events. The phases of interaction between these events, as expressed by monotonic variation in the ISI, are depicted in Figure 10.24. Compare the parallel between the earlier space and time depictions of Wertheimer's apparent motion effects (Figures 10.13–10.17) and this new event diagram. Phases 1–5 in Figure 10.24 correspond to Figures 10.13–10.17, respectively.

Recall that Korte's 'laws' define the conditions for optimal apparent motion as a linear function of ISI (*T*), spatial separation (*S*) and stimulus intensity (*I*). If we allow the intensity variable to be interpreted as but one example of a more general stimulus salience dimension, then stimulus on-time (e.g. flash duration) may be considered another example as others have argued (Bartley, 1941; Boring, 1942; Neuhaus, 1930). Figure 10.25 provides a graphic interpretation of Korte's laws by event diagrams that have been augmented with tolerance ranges around the velocity angles. A word of caution: the graph of these conditions is presented as being strictly linear. That is, as expressing each phase as exhibiting a *velocity invariance*. This means that the phase in question always lies within the tolerance range around a fixed angle (e.g. optimal motion falls close to the angle whose tangent is approximately 1/2). This is a gross oversimplification for two reasons.

First, in other types of displays, velocity invariance as predicted by Korte's laws has been brought into serious question. Using more complicated (multiple event) lattice displays, Burt and Sperling (1981) have shown that visual angle (i.e. distance between events) seems to have little to do with the apparent motion paths seen in

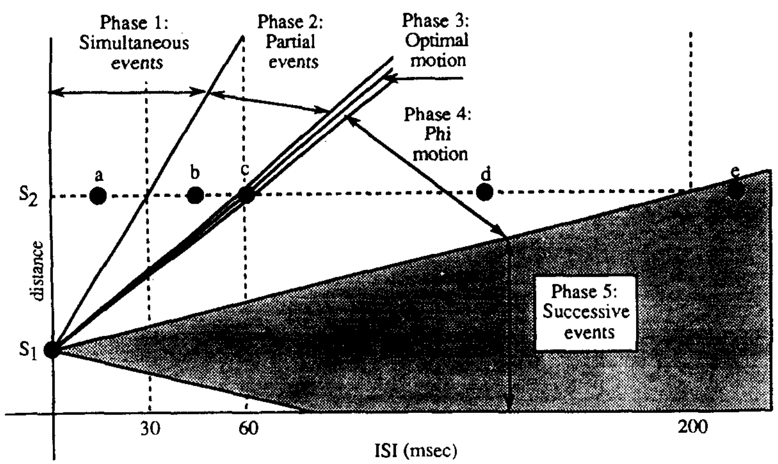

Figure 10.24. *Diagram of the five phases of Wertheimer's (1912) apparent motion event. The phases are defined by the rates at which the transitions take place between stimulus 1 and stimulus 2.*

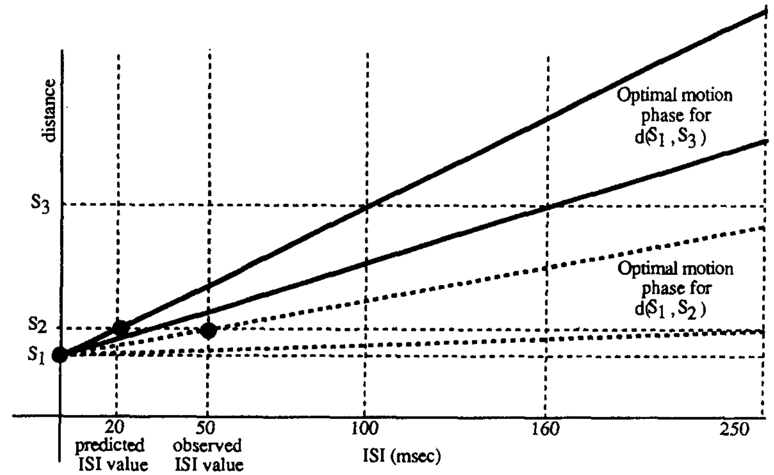

Figure 10.25. *The violation of Korte's (1915) velocity invariance law as a function of change in distance. The predicted upper limit on the optimal motion phase for the distance separating S_1 and S_2 should occur at an ISI of approx. 20 ms. Instead, the observed value of the ISI is approx. 50 ms.*

their displays. Because of this result, they argue that timing parameters are independent of the distance parameter so that *scale invariance* rather than velocity invariance holds. By ignoring the angles in Figure 10.25, we can easily represent the scale invariance hypothesis. Scale invariance would predict that the apparent motion phases should lie between the vertical lines in Figure 10.25 defined at the various values of ISI.

Second, for Wertheimer two-event displays scale invariance does not hold. But, unfortunately, neither does strict velocity invariance. Neuhaus (1930) found the optimal motion phase to lie within ISI values of 50–250 ms for a viewing angle of 0.5°, while at 4° the ISI had to be 100–160 ms. These ranges are plotted in Figure 10.26. (see Section 4.3). To complicate matters even further, we see that not only do the velocity angles vary nonlinearly with a change in distance (visual angle) between the events but so also does the spread of the tolerance regions around these angles. If Korte's laws were velocity invariant over change in distance between events, then one should be able to predict the expected range of ISI values for displays where the events (flashing lights) are moved closer or farther apart. This is clearly not the case for these data. Others have also found optimal motion to hold over a wide range of distances. Zeeman and Roelofs (1953) found the optimal motion phase to hold over 2–18° of visual angle, and Smith (1948) over angles reaching 100°.

What can we conclude from these discrepant results? In general, qualifications must be applied to Korte's 'laws'. These principles are not absolute but require tolerance ranges. Nor do they apply linearly. Still a general trend is predicted by them. Displays with fine patterns and small distances separating them generally require shorter ISIs than displays with coarse patterns and longer distances (Anstis, 1986).

A major difficulty encountered by attempts to diagram apparent motion events is the existence of nonlinear regions where phase transitions occur. The difficulty is compounded by the fact that the boundaries of these phases may themselves be dynamically altered by a change in value of some parameters associated with the displays. These issues are addressed in the next section.

4.3 Graded Determinism, Order Parameters and Distribution Functions

Recall the discussion of slipping-rolling-sliding event phases (Figure 10.12) gone through when an order parameter (R/T) is manipulated via a change in either R or T treated as a free control parameter. Analogously, from our discussion of the two-event apparent motion case, it became clear that the ISI variable can likewise be interpreted as a control parameter for some order parameter yet to be determined. Recall that an order parameter is a measure and a determiner of the phases of orderliness that a dynamical system moves through when a control parameter is manipulated. It provides a quantitative measure of the difference between the phases coalescing at the critical point in the transition from one phase to another (Bruce and Wallace, 1989; Haken, 1977; Landau and Lifschitz, 1985). We would like to generalize the notion of control and order parameters to psychological phenomena in the following way: an independent variable of a dynamical (perceptual) system qualifies as a control parameter if, under extensive variation, the range of values of the dependent variable includes well-demarcated (nonlinear) intensive effects. Such nonlinearly demarcated, intensive effects comprise the *phases* of orderliness. These intensive effects (order parameter), if obtained as nonlinear outcomes from the manipulation of an extensive (control) parameter could be either perceptually or behaviorally demarcated categories (Shaw and Cutting, 1980).

In classic psychophysics the boundaries demarcating perceptual phases were called *thresholds*. Consider the successive phases of object visibility under *change-in-viewing-distance* – the control parameter – as implicating some order parameter. Phase 1: not seeing the object at all because it is too distant; phase 2: the object coming into view but remaining too indistinct to be recognized; and phase 3: the object finally becoming recognizable. Likewise, a change in order parameter can demarcate action phases. For instance, a four-footed animal will go through a well-delineated sequence of successively ordered locomotive phases, called *gaits* (e.g. walk, trot, gallop) as the control parameter of locomotive velocity is monotonically increased. Mathematically speaking: what concepts are needed to express the relationship between control and order parameters?

Control parameters are attached to functionals – order parameters – that govern *distributions* of functions where ordinary parameters attach to single functions that govern data sets. Thus, a control parameter can be construed as a free parameter on an order parameter treated as a generalized function, or what has been called a *distribution function* (Schwartz, 1966). Distributions are continuous linear functionals on a vector space of continuous functions which have continuous derivatives of all orders and vanish appropriately at infinity. They generalize the notion of a radon measure (i.e. a regular Borel measure) and are intimately related to the theory of Lebesgue integrals – the most general integral known. The importance of these two concepts for order parameter theory is: (1) The sets in a distribution may be more complicated than what we typically encounter; they may be functions with many points of discontinuity (e.g. phase transition points). (2) The typical integral usually encountered (the Riemannian integral) is not, in general, defined for distributions. Instead, we must select another integral (the Lebesgue integral that generalizes the Riemannian integral) over discontinuous functions (e.g. distributions).

Laws of nature expressed by distribution functions exhibit a *graded determinism* rather than an absolute determinism (Shaw and Kinsella-Shaw, 1988). This is typical of principles that have the thrust of laws for biological and social sciences. Therefore, we should not expect the same precision that is possible with the laws of physics. Graded deterministic laws are especially sensitive to changes in boundary conditions. For instance, water normally boils at 100°C and freezes at 0°C at one atmosphere of pressure; but under variable atmospheric pressure it will boil and freeze at considerably higher or lower temperatures. Hence, there exists a wide range of values at which the transition from liquid phase to gaseous phase, or from liquid phase to solid phase will be observed.

Just because, in our ignorance, we observe these phase transitions in nature at different altitudes, it does not mean that temperature is disqualified as a legitimate control parameter for the order parameter that determines the observed phase transitions. Rather, we must recognize that when boundary conditions are not or cannot be ideally controlled, then a tolerance range must be placed around the control parameter, thereby making it a distribution function. Our inability to control the boundary conditions of a statistically complex phenomenon does not invalidate the search for order parameters, it merely makes the search more difficult.

Let us apply this concept of control and order parameters to Korte's laws presented earlier. Since the variables S, T and I interact, it is not possible to give definite boundaries to the control parameter ranges that separate one phase of apparent motion from another. These are nonlinear boundaries for which no mathematical expression currently exists. The best we can do is to define the invariant order of phases that a change in one of these variables effects when that variable is used as a control parameter. The order of apparent motion phases has been found to be invariant even if the metric is yet undisclosed (Kolers, 1972; Korte, 1915; Neuhaus, 1930). Nevertheless, for the sake of illustrating how such graded deterministic laws might be expressed, consider the ranges illustrated in Figure 10.25.

Recall that for an appropriate selection of values for stimulus intensity (I) and stimulus separation (S), as illustrated in Figures 10.13–10.17, the interstimulus interval (ISI) acted as a control parameter producing the following order of intensive effects:

Phase 1: above approx. 200 ms → successive events;
Phase 2: approx. 60–200 ms → phi (objectless) motion between the two stimuli;
Phase 3: approx. 60 ms → optimum motion of one object;
Phase 4: approx. 30–60 msec → two partial motions near termini;
Phase 5: less than 30 ms → two simultaneous events with no motion.

The order of phase transitions implicates an order parameter that is quite general, holding equally well for displays with a different selection of distances between events and event salience. The generality of Korte's laws suggests that whatever the order parameter involved, it must be at least as general. This generality extends to apparent motion events that are found to occur for sensory modalities other than vision.

For instance, the cutaneous apparent motion phenomenon is very much like its visual counterpart. It also follows Korte's law. The phase of two vibrators, for example, can be alternated-say, one on the arm and the other on the wrist 15–20 cm apart. If single pulses with an ISI of approximately 100 ms are applied, an apparent tactile motion between sites is experienced (Sherrick, 1968). If we plot the curves of the ISI against the stimulus duration for both tactile and visual optimal motion conditions, the two curves lie nearly on top of each other (Sherrick and Rogers, 1966). 'The conditions that maximize the visual and tactile apparent movement are similar enough to suggest that they are not specific to a modality, but result from the operation of a common set of neurological principles' (Kenshalo, 1972, p. 140).

Related apparent motion phenomena are sensory saltation effects. These involve the impletion of apparent vibratory stimuli between end-point vibrator stimuli. Three identical square wave pulsed tappers are placed approximately 10 cm apart along the forearm. These three tappers are then activated in cyclic successive order for a few milliseconds with a near-zero ISI. The person then experiences a saltation effect: namely, a slow sweeping sequence of taps are felt that successively fill-in between the three actual taps. Analogous saltation effects have been achieved for auditory and visual cases as well (Geldard, 1975).

Thus, we have evidence for various cases of analogous impletion effects across sensory modalities. In all cases the origin of the impletion is assumed to be central and cognitively constructed. But an equally likely hypothesis is that they depend on vibratory information samples that support generative specification.

As pointed out, Korte's laws have been impugned because the values that give rise to the various phases of apparent motion lack specificity (Anstis, 1986; Hochberg, 1986). These criticisms are fair only if you expect the laws of psychology to express an absolute determinism. On the other hand, if you expect laws to express only a graded determinism, then the criticism is unfair. Rather, the ranges of values exist that suggest the need to develop laws governing control variables with tolerance ranges. These laws may be more difficult to formulate but they are no less laws because of this fact. Consider the following example.

Korte's laws entail order parameters that are distribution functions, then, by fixing two of three control parameters, it should be possible to discover the envelope of the distribution function whose tolerance limits the order parameter satisfies. A beautiful example of a distribution function for apparent movement can be found in Kolers (1964; reproduced in Kolers, 1972, p. 29). Kolers conducted an experiment replicating Neuhaus (1930) that indicates an arrangement of event processing curves. Two flashes of light were exposed for different durations and different ISIs. The observer's task was to report whether a smooth continuous motion event was seen. The duration of the flashes varied over the range of 24 to 215 ms. The probability of observers reporting that a motion event had occurred at shorter ISIs was found to increase as the flash durations increased. Notice how the curves are arranged as shown in Figure 10.26. But also notice that the distribution has no clear-cut shape.

Kolers argues that the visual system requires a certain amount of time to process the events (e.g. light flashes) that give rise to apparent motion phases. Consequently, the perception of the imputed velocity of the moving apparent object is

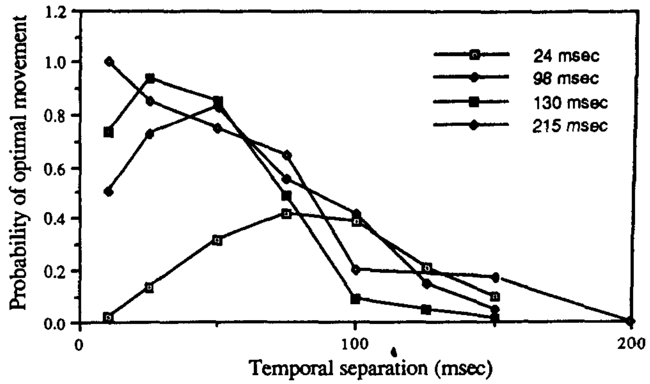

Figure 10.26. *Figure formation functions. The likelihood of seeing optimal motion between two flashes as a function of variation in flash duration and ISI. Note the duration tag on each curve (in 7.ms). The abscissa shows the ISI (offset of first stimulus to onset of second stimulus (in ms). Each curve shows the hypothetical 'figure formation' function for the given stimulus duration and ISI. Assuming that a process is initiated by stimulus onset, then we see that its rise and decay are a direct function of stimulus duration. [From Kolers, 1972, p. 27. © 1972 by the late author.]*

merely a reflection of the perceptual work done during the interval. For example, a 24 ms flash initiates the process (rise of curve) but it fails rapidly (the decay of curve). Compare this with the faster rise and slower decay of the likelihood of detection curve for the process initiated by the 130 ms duration flash. Under these working assumptions the data curves need to be replotted in terms of stimulus onset asychrony (SOA) so that the abscissa includes the onset-to-onset interval.

Upon replotting these same curves a higher-order arrangement clearly emerges. Figure 10.27 shows the shaded envelope around the hypothetical functions that Kolers called 'figure formation' functions-taken collectively they seem to provide a beautiful example of a distribution function determined by an order parameter. This distribution function expresses the tolerance ranges surrounding the phases revealed by variations in a control parameter.

To have a strong case for this envelope actually being a distribution function, certain formal criteria must be met (Schwartz, 1966). One important criterion is to discover the mathematical form of the transformation that maps one curve into the other. Such a transformation would have to apply invariantly to each sampled curve in the distribution. Such a distribution function is a function of functions – a functional.

In other words, a transformational invariant (TI) must exist that expresses explicitly the invariant action that the order parameter has on each of the sampled functions. If so, then the overall shape of the distribution can be geometrically plotted as an envelope over the extreme values of the family of curves. Kolers (1972) came very close to anticipating the generative specification hypothesis for event perception when he called this TI a hypothetical *generator function* for apparent motion.

In principle, the curves can be individuated by experimentally discovering the appropriate weights to be placed on the parameters of the distribution function. Of

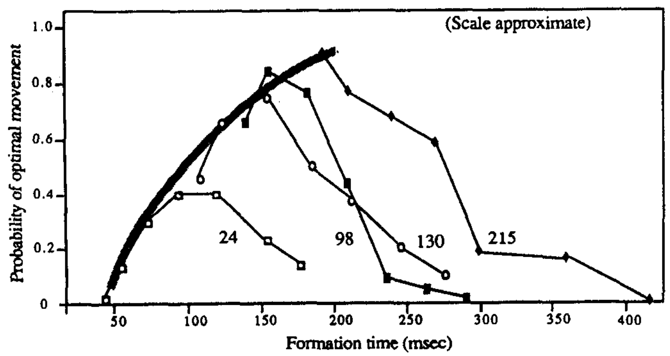

Figure 10.27. *Generator (distribution) function. Curves plotted with stimulus onset asynchrony (SOA) rather than ISI on abscissa. The shaded area shows the envelope of the hypothetical distribution function whose transformational invariant would relate all of the sampled functions in the distribution. The rise and decay of the individual functions seem to be a function of the duration of the stimulus. Presumably the apparent velocity of object motion reflects the processing time of the event information. [From Kolers, 1972, p. 29. © 1972 by the late author.]*

course such work remains to be done before the worth of these conjectures can be ascertained. However, we seem to have little choice but to broaden our tools for formal descriptions if we expect to resolve these long-standing perceptual issues.

5 CONCLUSIONS

In this chapter we have considered the case for a space–time geometry that provides a possible foundation for event information. The hypothesis put forward seeks to expand the dimensions of event perception beyond merely treating events as constructs from static glimpses of local features. Instead, it proposes that events are objects of perception *per se* with their own information transformational and structural invariants. Certain samples of this event information generatively specify a virtual space–time window that the event fills. Under this view, event perception is the filling of this window retrospectively, perspectively and prospectively. This is achieved by detection of a sample that acts as a generator to specify undetected portions bounded retrospectively and prospectively (i.e. filling the virtual window in space–time). How strange an assumption is this? A special emphasis has been given to clarifying the usefulness of the concept of transformational invariant as a fundamentally natural way to define event categories and thereby delimit the subject matter of this new field of scientific endeavor. To express the TIs for different events, the techniques of event diagramming were introduced. In the light of this brief survey, let us summarize the motivation and promise of this graphical technique.

Classic event space spatializes time by allowing motion over any distance, no matter how far, to take place instantaneously. The arguments offered in our attempts to describe the Ternus effects suggest a need to restrict classic space and time diagrams. Hence, we chose a Minkowski-like event space–time which disallows such impossibly fast events by adding a space–time restriction, namely, the

maximum rate of causal action. This limit can be used to express more realistically the rate at which the CNS can handle event information.

In addition, the exercise of attempting to capture Korte's laws indicated that both the precision and the linearity of these laws are suspect. To have explicit principles of this sort will require that they explain the occurrence of the nonlinear phenomena such as phase transitions. By augmenting the Minkowski-like space–time with tolerance ranges, thereby creating a space–time tolerance geometry, the descriptive adequacy of the event diagramming technique is vastly improved. In this way, there is hope that phases may be incorporated into event space–time. The notion was also put forward that tolerance geometries are the natural breeding place not only for phases but for distribution functions as well. Together these two properties provide a means for bringing CNS constraints to bear on event space–time so that the resulting geometry reflects both the environment's and the perceiver's contribution to event perception.

Perhaps the strongest motivation for using event diagrams, however, is to provide researchers who are working on event perception problems with a common means of expressing their findings in some commensurate way. There is little doubt that research and theory in this field would be aided immeasurably if researchers shared a common scientific vocabulary and convenient graphical techniques for portraying event information. Perhaps the suggestions made here may provide a direction for such developments.

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