Converging operations revisited: Assessing what infants perceive using discrimination measures

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The study of visual perception in human infants is confronted by a number of special problems arising from the inaccessibility of verbal reports. In this paper, we discuss the experimental strategy of converging operations in the context of investigating the phenomenal experience of infants. The goal of this strategy is to logically and empirically delimit alternative explanations for a given behavior. Knowledge about the mature functioning of a perceptual competence, as well as knowledge about its developmental course, constrains the selection of viable explanations, but cannot produce a unique interpretation. This goal is pursued through the implementation of an iterative strategy in which competing interpretations are tested until only one plausible alternative remains. A series of experiments investigating infants' sensitivity to biomechanical motions are reviewed as a way of illustrating how this methodology is operationalized.

The perceptual world is formed by proximal stimulation and perceptual processes that are (1) shaped over the evolutionary course of our species or (2) acquired during the individual's developmental history. By definition, the human infant's perceptual world is primarily structured by innate perceptual processes, whereas the perceptual world of the adult benefits from extensive experience and knowledge about the environment. It thus follows that one of the most effective strategies for assessing *basic* competencies in perception is to study young infants.

What can we know of babies' perceptual experience? Skeptics argue that we can never know about the phenomenal experiences of infants because our assessments are restricted to nonverbal responses. By this reasoning, perceptual research with animals, as well as with human infants, yields results that will always fall short of those obtained with older children and adults who can provide verbal phenomenal reports. Contrary to this argument, the principle premise of this paper is that empirical evidence pertaining to babies' phenomenal experience is, indeed, attainable, even though the inaccessibility of verbal reports presents special problems in infant perception research.

Thirty-three years ago, Garner, Hake, and Eriksen (1956) discussed what perceptual research can tell us about

adults' phenomenal experiences. They challenged a prevailing view of the time (Allport, 1955) that asserted that verbal reports could only be defined operationally as discrimination measures, and thus, empirical investigations of phenomenal experience were impossible.

Garner et al. responded to this view with a methodological heuristic called *converging operations*, or *bootstrapping* (Garner, 1981). The use of converging operations involves an iterative problem solving strategy of generating a set of plausible alternative explanations for a particular experimental finding, eliminating all but one of these alternatives with appropriately designed studies, and generalizing from the particular case to a class of events. As will be discussed in the next section, defining the boundaries of plausibility when considering alternatives is the most ill-defined problem in this enterprise.

In this paper, we discuss the use of converging operations in research on infants' perception. In the first section, we address general issues in assessing infants' perceptions. Later, we illustrate this methodological approach by discussing how it has been applied in our investigations of infants' perception of structure from motion.

CONVERGING OPERATIONS AND GENERAL ISSUES IN INFANT PERCEPTION RESEARCH

In infant research, the converging-operations strategy leads us to entertain both *empirical* and *logical* questions. Questions of both sorts are involved not only in assessing infants' performance in particular experimental situations, but also when generalizing empirical findings to other settings.

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What Do Babies See in a Particular Event?

By and large, most assessments of infants' perceptual competencies depend upon some discriminative response. Consider, for example, the habituation paradigm (e.g., Bertenthal, Haith, & Campos, 1983; Bornstein, 1985), which is often used for assessing perceptual performance in infants. The logic of this paradigm is to repetitively present one stimulus display over a series of trials until the criterion response (typically visual attention) decreases to some preestablished level. At this point, one or more new displays are presented on subsequent trials. If the criterion response significantly increases on trials involving a new display, it is generally inferred that the two displays are discriminated. Although the putative goal for using this paradigm is to conclude something more than discrimination, the point to emphasize is that the infant's response provides direct evidence for nothing more than a discrimination. A number of other infant paradigms suffer from the same interpretive restrictions. These tasks include preferential looking (e.g., Fantz, 1964), operant conditioning (e.g., Bower, 1966; Rovee-Collier & Fagen, 1981), and spatial localization tasks (e.g., Acredolo, 1978; Bremner & Bryant, 1977), all of which rely upon a discriminative response by the infant.

The challenge for the researcher is to go beyond discriminative responses and infer the infant's perceptual experience. How is that inferential process to be operationalized?

Garner et al. (1956) proposed the method of converging operations as a solution to such questions. This methodological strategy was defined by them as follows: "Converging operations may be thought of as any set of two or more experimental operations which allow the selection or elimination of alternative hypotheses or concepts which could explain an experimental result" (p. 150).

By extension, in order to assess what babies see in a particular event, it is necessary to answer the logical question: *What could babies see in this event?* This is the problem of defining a set of alternative hypotheses. The method of converging operations allows one to support or eliminate alternatives once they are proposed. Regrettably, there is little in Garner et al.'s seminal paper instructing us on how to go about generating alternative hypotheses. This deficiency is easily understood.

There are an indefinite number of alternative explanations for any empirical finding, and, in the absence of an adequate theory, there is no formal way of deciding which of this number warrant empirical consideration. In the mature sciences, the number of plausible explanations for an empirical finding is constrained by the requirement that all competing hypotheses must be consistent with the natural laws of their discipline. With the possible exception of some specific theories in sensory processing, such as color theory, perceptual research is rarely well constrained by formal theoretical models. Gestalt psychology, information processing accounts, Gibson's (1979) ecological approach, and all other general approaches to perception lack either scope, precision, or both, and thus,

fail to define *boundaries of plausibility* for many of the hypotheses that perceptual psychologists entertain.

How are the set of plausible hypotheses for an experimental finding to be defined? Here, the burden is primarily carried by *argument* (Weimer, 1977) and *oversight*. Compelling arguments can typically be made for testing some alternatives as opposed to others. In the absence of theory, such arguments are grounded in empirical findings, metatheoretical thinking, and common sense. However, since the number of theoretically unconstrained alternatives is indefinite, the vast majority of candidates are never considered. In the absence of adequate theories, Occam's razor is guided largely by our lack of imagination.¹

These conditions of scientific practice encounter special problems in perceptual research involving infants. Arguments in perceptual research rely heavily upon the persuasive power of phenomenal demonstrations. Excellent examples are the demonstrations of the Gestalt psychologists and of Ames (Ittelson, 1952). Consider, as well, the perception of Julesz's (1971) random-dot stereograms. Support for the hypothesis that depth is perceived in these displays is provided by an extensive empirical literature; however, the strength of the empirically based argument pales in comparison to the robustness of the stereo depth phenomena when experienced first-hand. Among adults, phenomenal demonstrations provide a basis for common experiences that can be communicated through language. No such communication can occur between adults and infants.

In generating alternative hypotheses for research involving infants, we cannot help but be biased by our own acquaintance with the phenomenon under study. This bias is not necessarily bad, however. It provides a first approximation to what infants might perceive in the same displays. Converging operations can then be employed to assess the degree to which infant experiences conform with adult percepts. In this regard we offer the following caution: *Demonstrating a common sensitivity to stimulus information does not necessarily imply that adults and infants share meanings.* An example will serve to illustrate this point. There are few studies in the infant literature that are more familiar than Gibson and Walk's (1960) experiment with the visual cliff. Here, it was shown that infants of approximately 9 months of age are reluctant to crawl over the apparent edge of a cliff. This work provided compelling evidence that infants perceive a distinction between the two sides of the cliff's edge and apparently perceive the significance of falling off the edge on the deep side. In other words, the perceptions of these infants seem adult-like. Knowledge of this result evokes immediate interest in how younger infants would perform in this situation. Answering this question is problematic, however, because younger infants cannot crawl and, thus, cannot exhibit the dependent measure that was assessed in the Gibson and Walk study.

Schwartz, Campos, and Baisel (1973) circumvented the problems inherent in the behavioral limitations of young infants by employing a physiological dependent measure.

Infants were held above both sides of the visual cliff and lowered to the glass surface in a manner suggesting that they were about to be dropped. As indicated by changes in heart rate, both 5- and 9-month-old infants showed that they discriminated the difference between the deep and shallow sides of the visual cliff. Of equal interest, however, was the finding that young infants' cardiac responses were those associated with interest (their heart rates decelerated as they approached the abyss), whereas older infants of 9 months of age showed heart-rate acceleration, a response indicative of fear. (See Bertenthal, Campos, & Barrett, 1984, for a more complete discussion of this issue.)

These findings are instructive because both young and old infants showed discrimination between the deep and shallow sides of a visual cliff; however, the perceived significance of the apparent drop-off undergoes a qualitative change during early development (Bertenthal & Campos, in press). Thus, evidence of discrimination across ages does not ensure that the information is perceived in exactly the same way at each age.

This example cautions against equating infants' perceptual sensitivities with the meanings that these sensitivities confer to adults. This is not to say, however, that it is uninformative to relate findings from research with infants to known competencies of older children and adults.

The infant's perceptual system is following a developmental course. Alternative hypotheses about infants' competencies are justifiably evaluated in the light of knowledge concerning what the system is about to become. Recognizing that infants are not simply immature adults lacking in world experience should not cause us to lose sight of the fact that, given the benefits of maturation and experience, they will become adults. That is, what is known about the developmental course of a specific competence can be applied in interpreting the nature of that ability at a particular point in its development.

By way of summary, we reiterate that perceptual research with infants lacks the sharing of phenomenal experience that is possible in evaluating studies conducted with adults. On the other hand, research with human infants benefits from the knowledge that the system is a developing one, the final state of which is understood to a degree. It is important to emphasize, however, that many other aspects of a developing process remain open to multiple interpretations. We now turn to issues focusing on different ways to conceptualize the developmental process.

Perceptual Processing During Infancy: What Develops?

A complete accounting of infants' perceptual mechanisms must include not only present competencies, but also the developmental course of these competencies. We are not simply interested in determining what infants can do at some particular age, we also want to relate current abilities with earlier and subsequent development. As is described below, this developmental perspective is facilitated by distinguishing between three levels of behavioral

assessment: performance, competence, and the developmental rules mediating change in perceptual processes.

Levels of Behavioral Assessment

1. *Performance.* Simply stated, behavioral assessments yield findings of the following form: Under some stimulus conditions, X and Y , the infant performs behavior a or b —these responses constitute the operational values for the behaviors that were selected for measurement. Prototypical of this level of assessment is the preferential looking paradigm. In this experimental situation, infants are presented with two different stimulus displays, and they typically spend much of their time fixating at one or the other of these stimuli. Differential amounts of looking at the two stimuli suggest that infants can discriminate between them. By itself, this assessment is of marginal value. There are no doubt an indefinite number of different stimulus displays that infants can discriminate. The issue is not whether infants can discriminate between stimuli, but rather, "Why do they discriminate between stimuli?" To answer this question, attention must be focused on the underlying competencies of the infant.

2. *Competence.* Perceptual competencies define the infant's abilities to transduce, organize, and interpret stimulus information. Competencies are inferred from performance data and are specific to the developmental period in which the assessment was made. Competencies predict what infants of a particular age will be able to do under the various situations that they encounter.

Accounts of infants' perceptual competencies provide state descriptions of developing systems. To understand more about the process by which they develop, current abilities must be related to prior and subsequent perceptual skills. Ultimately, the question of the source and development of perceptual competencies rests on the interaction of the innate human potential with the environmental information available to the senses.²

3. *Genesis.* Most of what we know about the perceptual competencies of very young infants is in the domain of sensory capacities. These infants, like adults, are sensitive to changes in luminance, wavelength, and movement in the stimulus array (Banks & Salapatek, 1983). Although threshold sensitivities for detecting this information are considerably higher in young infants than in adults, the point to emphasize is that many of the basic physical dimensions for perceiving the world are available to some degree from birth.

In addition to basic sensory abilities, there must surely exist deeper levels of perceptual organization, and, of course, there must be a learning mechanism. Perceptual research with infants has the potential to shed light on the form and extent of these primary inheritances.

One of the virtues of infant research is that the unfolding of specific competencies follows different time courses. To borrow an example discussed in detail by Yonas and Owsley (1987), it is known that depth information specified by stereopsis does not become functional until babies are 3 to 4 months of age (Fox, Aslin, Shea, & Dumais, 1980). On the other hand, sensitivity to depth specified

by motion information is evident at an earlier age (e.g., Yonas, Pettersen, & Lockman, 1979), and sensitivity to pictorial depth cues emerges later at between 5 and 7 months of age (Granrud, in press). The presence of developmental sequences, such as this, provides empirical substance upon which to evaluate claims that certain perceptual competencies are foundational to others.

Before proceeding to a specific account of our research program, we must discuss one final metatheoretical issue that haunts efforts to generalize from infant data. This is the tension that exists between structural and functional approaches to perception.

Contrasting Structural and Functional Approaches

The distinction between structural and functional perspectives on perception is essentially between inquiries into "how something is constructed" and "what it is for." In principle, these viewpoints ought to be complementary; in practice, they are often at odds. We address two points of contention.

1. *Structural versus utilitarian perspectives on perceptual processing.* A distinction can be drawn between two theoretical approaches in perceptual research. One approach views the perceptual system as structured by pervasive processing constraints. The goal is to explain how unique perceptual interpretations are derived from underdetermined retinal images. Numerous proposals have been made that refer to quite different sorts of constraints. Without intending to be exhaustive, these approaches include *dynamical* constraints (Köhler, 1969; Runeson & Frykholm, 1983), *geometrical* constraints (Shepard, 1984), *informational* constraints (Leeuwenberg, 1971), various *group theoretical* (symmetry) constraints (Cassier, 1944; Hoffman, 1966; Palmer, 1982; Piaget, 1970), and *probabilistic* constraints (Brunswick, 1956; Itelson, 1952).

In contrast, the utilitarian approach views the perceptual system as consisting of numerous functional components, each of which adheres to its own processing heuristics. One recent adherent of this view is Ramachandran (1985) who suggests that the perceptual system consists of a "bag of tricks." These "tricks" are adaptive heuristics that, much of the time, provide accurate information within the organism's ecological niche.

We are much more inclined toward the former approach than toward the latter. Viewing the perceptual system as a complex of functional components loses sight of the fact that adaptive subsystems typically exploit pervasive structural constraints inherent to the organism. Gould and Lewontin (1979) discussed this issue within the context of evolutionary theory. They characterized the adaptationists' program in the following manner: "It is based on faith in the power of natural selection as an optimizing agent. It proceeds by breaking an organism into unitary 'traits' and proposing an adaptive story for each considered separately" (p. 581).³ Such a program fails to account for the pervasive influence of natural constraints. Consider one of the many examples that could

have been taken from their article: The shells of mollusks possess ribs, the form of which has been attributed by adaptationists to their function as scoops, anchors, or sieves. Gould and Lewontin, however, cite the work of Seilacher (1970, 1972) as showing that the form of mollusk shells reflects constraints on the architecture of shell development. These natural constraints are exploited for adaptive purposes by only a small minority of mollusks. Thus, the form of mollusk shells cannot be deduced from their adaptive significance in a few species, rather they are an emergent property governed by the structural constraints that accompany the growth of the shell.

Our perceptual system serves many adaptive purposes; however, its structure was not shaped solely by expediency. Viewing the perceptual system as a "bag of tricks" is akin to attributing the falling of apples to the adaptive role falling plays in getting apple seeds in contact with the ground. Natural laws, such as gravitation, are not to be understood in terms of their adaptive significance, yet they influence the architecture of all living and nonliving things. Again, to quote Gould and Lewontin (1979), "If blushing turns out to be an adaptation affected by sexual selection in humans, it will not help us to understand why blood is red. The immediate utility of an organic structure often says nothing at all about the reason for its being" (p. 593). For similar reasons, we are predisposed toward the view that the pursuit of general constraints in perception is more likely to yield success than is the adaptationists' strategy of viewing the perceptual system as a "bag of tricks."

2. *Structural versus affordance accounts of meaning.* Structural descriptions of meaning typically appeal to the geometrical attributes of objects and events, whereas affordance descriptions relate these attributes to the organism's behavioral repertoire. The affordances of an object correspond to the functional significance that it has for the perceiver (Gibson, 1979). For example, for an organism possessed of hands and the wherewithal to use them skillfully, an object may be "graspable," "pickup-able," "throwable," and so forth.

Perceiving affordances is undoubtedly a goal of perception, and the noticing of affordances is dependent upon the appreciation of the object structure upon which the affordances depend. In our view, the perception of affordances and structure are complementary achievements.

Be that as it may, there are reasons to believe that the infant's perception of structure is prior to the appreciation of affordances. We are persuaded that this conclusion is correct given the degree to which motor development lags behind perceptual development in the young infant. In general, the behavioral repertoire of young infants is exceedingly limited relative to what is known about their perceptual competencies.

Accordingly, most early visual experiences are restricted to visual exploration, per se, and there is little opportunity to perceive self-produced transformations, such as those that occur through locomotion or haptic exploration. As the infant's motoric skills develop, the op-

portunity for self-produced transformations increase, and so does the infant's appreciation or understanding of the affordances of the visual environment. For example, recall how the infant's appreciation of an apparent drop-off on the visual cliff changes from interest to fear and avoidance as a function of early locomotor experience (Bertenthal, Campos, & Barrett, 1984). By analogy with other visual events, we expect that this developmental shift from interest to perception of affordances is the rule rather than the exception. As such, we acknowledge that certain sights are inherently interesting to infants and may have utility for later developments; however, the meaning of current percepts cannot be the affordances that they offer a more mature individual.

We will return to more specific issues dealing with affordances after discussing some of our own research on infants' perception of structure from motion. As will become apparent, we find that infants demonstrate a developing facility to extract structure from motion displays, even though these displays offer little opportunity for behavioral interaction.

Converging Operations in a Specific Context: Infant Perception of Structure from Motion

Recent work shows that young infants are sensitive to a variety of motion displays that evoke definite meanings in adults. To cite just a few examples, Kaufmann-Hayoz, Kaufmann, and Stucki (1986) report that 3-month-old in-

fants are sensitive to dynamic occlusion displays that afford the perception of surface segregation in depth for adults; other investigators (Arterberry & Yonas, 1988; Kellman, 1984) find that 4-month-old infants show sensitivity to kinetic depth displays; and Bertenthal, Proffitt, Kramer, and Spetner (1987) report evidence that 3-month-old infants are sensitive to point-light walker displays.

What meanings do these displays evoke in infants? Here, it is necessary to employ converging operations to address this question. To illustrate this approach, we focus on our own work with point-light walker displays, a depiction of which is shown in Figure 1A.

In 200 msec or less, adults can identify the human form when viewing a natural point-light walker display (Johansson, 1973). Naturally based displays, in contrast to computer-generated ones, are produced by attaching point-light sources to people and filming them in the dark. Computer-generated displays mimic many, but not all, of the kinematic properties present in natural displays and, when viewed by adults, appear to be somewhat less suggestive of the human form (Proffitt, Bertenthal, & Roberts, 1984).

In an earlier paper, we suggested that moving displays, such as the point-light walker, could be perceptually organized or meaningfully interpreted at five different levels (Bertenthal, Proffitt, & Cutting, 1984). Subsequent studies were designed to delimit this set of possibilities. The following levels of interpretation are presented in order of

Figure 1. Panel A: Array of 11 point lights corresponding to the head, shoulder, hip, elbows, wrists, knees, and ankles of a person walking. The motion vectors drawn through each point light represent the perceived relative motions within the figure, and the motion vector drawn above the walker depicts its perceived observer-relative displacement. Panel B: Inverted, mirror image version of the walker depicted in Panel A. Panel C: Scrambled display, identical to Panel A, except that the relative locations of the point lights are scrambled. Correspondingly numbered point lights have the same absolute motions.

their degree of organization and memorial influence. They comprise our response to the following logical question:

What Could Babies Perceive in Moving Point-Light Displays?

1. *Individual motion patterns.* Given that the point lights have been detected as moving, the minimal perceptual organization of a moving point-light array would consist of an appreciation of the motion path(s) of one or more of the display's elements. Such an interpretation would represent absolute trajectories, in either environmental or retinal coordinates, without regard for relative motions among subsets of points. Relative motions define perceptual groupings of two or more trajectories and signify configural relations.

A series of converging experiments were designed to eliminate this alternative from consideration with infants as young as 3 months of age. In one experiment, it was shown that infants discriminate a point-light walker display from its inverted image (Bertenthal, Proffitt, & Cutting, 1984; Fox & McDaniel, 1982), and also from a scrambled version (see Figure 1) that displayed the same element motions but in different locations (Bertenthal, Proffitt, & Cutting, 1984; Bertenthal, Proffitt, Kramer, & Spetner, 1987). In another study, we presented the displays depicted in Figure 2. As is shown for just the right arm, these arrays differ in regard to the phase relations among the presented points; the absolute motions of individual points are identical across these displays. It was found that 3-month-old infants are sensitive to the differences in these two point-light walker displays even though they present identical element motions in the same locations (Bertenthal, Proffitt, & Kramer, 1987).

These studies demonstrate that infants are not responding to the absolute motions of the point lights, but rather

are responding to some degree of organization among the elements. Such organization could be either local or global.

2. *Local groupings.* Minimal perceptual groupings could be formed between pairs or subsets of points. Infant performance in the above studies could have been based solely upon their noticing the relative motions among such local groupings.

To test this possibility, we created two stimuli that were identical in all respects except for the phase relations among the point lights (Bertenthal & Davis, 1988). The difference between the two stimuli is illustrated in Figure 3. One of the displays corresponded to a stick-figure representation of a person walking, in which all joints reversed direction at the same time (bottom panel, right side). The phase relations of the other display were perturbed such that all joints no longer reversed direction at the same time (top panel, right side). (In Figure 3, the distance between connected point lights remained fixed, whereas the point lights in Figure 2 were not rigidly connected.) These stimuli were presented in the normal upright and inverted orientations. For each infant, orientation was held constant and phase was contrasted.

Three-month-old infants discriminated the two displays when they were presented in either orientation. In contrast, 5-month-old infants discriminated these two displays only when they were presented upright.

The results for the younger infants can be accounted for by assuming that they were sensitive only to local groupings; however, those for the older infants cannot. The extraction of local groupings should be independent of orientation. Thus, the older infants must have achieved a more global organization for the arrays, an organization that was influenced by orientation. This increased sensitivity to orientation by older infants is a general finding to which we will return.

Figure 2. Relative positions of the shoulder, elbow, and wrist lights at three phases of the gait cycle. The darkened circles correspond to positions in the phase-shifted display; the open triangles correspond to positions in the canonical display. Note that all corresponding point lights follow the same trajectories, but that the instantaneous directionality and location of the phase-shifted point lights are not equivalent to the corresponding canonical point lights.

3. *Global figural coherence.* A global organization of the point-light walker display corresponds to a pattern in which all of the points are organized together as a stick figure of the human form. We sought evidence for infants' perception of this structure by creating a set of stimuli that manipulated the point-light occlusion that occurs in natural displays whenever a joint on the far side of the walker's body passes behind the body. Three stimuli were computer-generated; these are depicted in Figures 1A and 4. One display (Figure 1A) mimicked the motions of a walker's head and all of the major joints; however, all points remained visible throughout the gait cycle. A second display (Figure 4A) was identical except that the appropriate point lights turned on and off as if the simulated walker's body was occluding them. The last stimulus (Figure 4B) was the same as the second except that occlusion occurred in locations inconsistent with the human form. An additional set of three stimuli were created to control for any nonspecific effects of the occlusion information. These displays corresponded in structure to the scrambled display depicted in Figure 1C, but the period of visibility of the point lights was matched to equivalent point lights in the corresponding canonical displays. Thus, the control display for the point-light walker with no occlusion was programmed to continuously display point lights, whereas the point lights in the other two scrambled displays appeared and disappeared at different phases of the cycle, corresponding to those programmed for the walker displays with occlusion.

These stimuli were shown to 5-, 7-, and 8-month-old infants, and it was found that infants did not discriminate between the canonical occlusion display and the display without occlusion until 8 months of age (Bertenthal, Proffitt, Spetner, & Thomas, 1985). In addition, these older infants were found to discriminate between the appropriate and inappropriate occlusion displays, but only when they were presented in the normal upright orientation.

Figure 3. The left side depicts 13 point lights moving as if attached to the major joints and head of a person walking on a treadmill. The two right panels depict the relations of the right shoulder, elbow, and wrist lights, enclosed by the dashed lines in the left panel, during three successive phases of the gait cycle. Upper panel (out of phase): The point lights remain at fixed distances, but differ as to when they reverse direction. Lower panel (canonical): The point lights remain at fixed distances and all reverse direction simultaneously.

Figure 4. Both panels represent apparent occlusion versions of the point-light walker depicted in Figure 1A. The point lights shown are the elbow, wrist, knee, and ankle on the walker's far side. In the occlusion displays, point lights disappeared and appeared at the locations denoted by the cylinders. Panel A shows the display in which occlusion occurred at canonical locations; Panel B depicts anomalous occlusion locations.

None of the scrambled displays were discriminated at any age.

Taken together, these findings constitute relatively firm evidence that 8-month-old infants appreciate the global organization of the point-light walker display. Recall that the point-light trajectories in all three displays were identical, only the occlusion information varied. If infants had responded only to local differences in the occlusion, discrimination of the scrambled displays should have occurred as well. Instead, 8-month-old infants discriminated only the canonical displays that, aside from occlusion, differed in regard to their global 3-D structure.

It was interesting to find that this global sensitivity is evident only when the display is in its "natural" orientation. How might this orientation effect be interpreted?

Infants could acquire a perceptual appreciation for natural orientations through either of two developmental courses (cf. Bertenthal, Proffitt, & Kramer, 1987). First, through experience or maturation they could come to an appreciation for *natural dynamics*. By this account, the upright point-light walker can be assimilated into a dynamically appropriate representation of a possible biomechanical motion occurring in an orientation-specific gravitational field, whereas the inverted one cannot. Thus, dynamical constraints could account for the orientation specificity found for older infants. The second developmental course is that formed through *experience*. By this account, the upright, but not the inverted, point-light walker can be assimilated into a memorial representation and, thereby, be identified as a *familiar* event. The increased sensitivity observed among older infants could reflect the influence of experience on perceiving familiarity and, in turn, the effect of familiarity on discrimination.

Disentangling the constraining influences of natural dynamics versus familiarity is terribly difficult since they

are confounded in experience: Natural laws structure the events that are experienced. The psychological question is whether the perceptual processes of infants, or of adults for that matter, utilize internalized general dynamical constraints or, alternatively, utilize motion processing constraints that interact with memorial representations of the physical world. That is, do dynamical influences have an independent status as opposed to one that is derivative to the events that are familiar?

This issue is elaborated in the next section. Although the relative roles of dynamical versus familial constraints are far from resolved, we believe that current empirical evidence offers little support for the contention that general dynamical constraints are pervasive influences inherent in perceptual processing.

4. *Dynamically constrained representations.* The motion patterns presented in any transforming projection of a rigid or jointed object are inherently ambiguous without processing constraints. Constraints with sufficient power to allow for the extraction of 3-D structure from such displays can be based purely on regularities in manifest motion patterns, such as *kinematics* (see, e.g., Ullman, 1979; Webb & Aggarwal, 1982). That is, geometrical constraints on the manifest motion patterns can, in principle, form the basis for structure from motion algorithms. In essence, the first three interpretations could be derived entirely from different geometrical constraints.

There exists, however, a higher order level of constraints for natural motions, which is articulated in the laws of classical mechanics. These laws place pervasive restrictions on the manner in which objects can move through the enforcement of dynamical conservation laws.

Runeson (1977; Runeson & Frykholm, 1983) argues that the perceptual system has internalized analog processes that embody laws of natural dynamics. His theory, called *kinematic specification of dynamics* (KSD), asserts that people are directly sensitive to dynamical relations because there are regularities in proximal stimulation that manifest these higher order variables, and our perceptual system is attuned so as to be able to automatically extract them.

Let us consider an example discussed at length by Runeson (1977). When two objects collide, say two billiard balls of unequal mass, the resulting motions are defined by the laws of energy and momentum conservation. There is nothing in a kinematic representation of this event that restricts the resultant motions of a collision, and, thus, a kinematic prescription provides a less restrictive representation of the event than does a dynamical one. Within a dynamical representation, not only are the resultant motions defined by the precollision variables, but also knowing pre- and postcollision motion patterns allows for the recovery of the objects' mass ratio. Thus, relative to kinematic or geometrical constraints, dynamical representations place additional restrictions on object motions and allow for the recovery of dynamical variables.

Are infants sensitive to any of the dynamical constraints in a biomechanical event? Although there is no data

directly relevant to this question, a number of recent findings in the infant literature are interpreted as suggesting that infants are sensitive to the natural dynamics in other events (Baillargeon, Spelke, & Wasserman, 1985; Keil, 1979; Leslie, 1982, 1984). For example, Leslie (1982, 1984) showed that infants discriminate events in which the launching of one object by another occurs (1) with or without contact or (2) immediately upon collision or after a delay. It is important to emphasize, however, that evidence showing infants to be sensitive to dynamically relevant spatiotemporal parameters tells us little, if anything, about what dynamical properties may have been extracted. This issue is best evaluated in light of what is known about adults' dynamical appreciation of events, such as collisions. As discussed below, we find little reason to attribute general dynamical sensitivities to adults, let alone to infants.

Gilden and Proffitt (1989) examined the ability possessed by adults to make mass ratio judgments while watching collision events. Contrary to the predictions of KSD, they found that people do not have a general ability to make these judgments. Depending on the collision parameters that are presented, people will perform at a near-perfect, chance, or below-chance level on this task. The making of mass ratio judgments was found not to be based on dynamical principles, but rather upon two heuristics that were related to salient kinematic variables. The essence of these heuristics are: (1) Following a collision, the faster moving object is lighter, and (2) an object that bounces back after striking another is the lighter of the two objects. Application of these heuristics leads to accurate performance in some situations but not others.

Proffitt and Gilden (1989) proposed an account of human dynamical understanding that asserts that people possess accurate dynamical intuitions for only the most simple of object motions. They reviewed studies on a wide variety of situations and concluded that, in general, people are unable to perceptually penetrate the inherent dynamics of any but the simplest of events.

We therefore conclude that, if adults do possess internalized dynamical processing constraints, they are certainly not general, are highly simplistic, and are not applicable to events as complex as collision or point-light walker displays.⁴ What does this imply for assessments of infants' perceptual experience?

It seems to us highly implausible that infants come into this world possessing perceptual processes that embody general dynamical constraints, and then lose these abilities with experience and maturation. Rather, we think it more likely that, throughout the lifespan, motions are perceptually represented in terms of kinematic parameters, and dynamical intuitions are largely formed from these parameters as they are structured by experience-based heuristics. As such, we think it more appropriate to view dynamical constraints as just one of a host of experience-based influences on perceptual functioning.

5. *Experience-based representations.* The final level of processing that we consider is that which occurs when

percepts are related to memorial representations. With respect to the point-light walker display, this level would include identifying the 3-D structure of the human form; however, recognition of less specific structures is also possible. For example, any property common to the human form, such as the normal range of joint angles, or any structure with a hierarchical nesting of pendular motions might correspond to the information about the human form that is stored in memory.

There is some preliminary evidence to suggest that this level of processing is also available to infants. By 5 months of age, infants show greater responsiveness to changes in point-light walker displays when presented in their natural upright, as opposed to inverted, orientation (Bertenthal, 1988). More specifically, virtually every pair of displays shown to 5-month-old infants elicits significant response recovery *only* when shown in an upright orientation. In contrast, 3-month-old infants show response recovery to changes in these displays regardless of orientation.

One interpretation for this finding is that familiarity emerges as a significant variable by 5 months of age. An upright point-light walker display is perceived in some way as familiar, whereas a perturbed display is perceived as unfamiliar. In contrast, neither canonical nor perturbed displays are perceived as familiar when presented upside down. Interestingly, adults also do not recognize inverted point-light walker displays as depicting the human form (Sumi, 1984). It is our contention that this difference in familiarity is responsible for the differential pattern of responding to the upright and inverted displays. The finding that 3-month-old infants do not show this differential pattern of responding suggests that they are responding to more specific structural differences in the display, and these differences are not affected by orientation.

By way of analogy, we can say that 3-month-old infants perceive the displays in a manner not unlike the way that novice chess players encode the pattern of chess pieces positioned on a playing board. Both groups are capable of perceiving configural relations, but one pattern is no more meaningful than another. In contrast, 5-month-old infants perceive the point-light displays in a manner resembling the way that expert chess players encode a chessboard. Specific patterns are recognized as familiar and are responded to very differently than are arbitrary patterns.

Although this familiarity interpretation remains somewhat speculative, it receives additional support from other recent experiments involving infants' perception of biomechanical motions. Fox and McDaniel (1982) report that 4-month-old infants do not show differential attention to a point-light display of a hand versus a perturbed version (i.e., off-joint display), whereas 6-month-old infants do show a preference. This finding is consistent with the previous interpretation, because infants do not begin to observe their hands until the onset of visually guided reaching, which occurs around 5 months of age (Gesell, 1928). Thus, the perception of a structure corresponding to the hand would not be detected as familiar until after 5 months of age, which explains why 4-month-old infants

did not show differential attention to the displays. (Although the younger infants might have shown differential attention to any of the specific structural differences between the two displays, they did not, suggesting that 4-month-old infants are already responding primarily to the "meaningful" changes between displays.)

An additional source of support derives from a study by Stucki and Kaufmann-Hayoz (1984) examining 3-month-old infants' sensitivity to a point-light display of the human face. Interestingly, infants discriminated a canonical from a perturbed display when the stimuli were presented in an upright orientation, but not when presented in an inverted orientation. It is known that recognition of the human face is orientation specific (Diamond & Carey, 1987). Thus, one interpretation for the preceding findings is that infants recognized some property of the upright canonical display as familiar, but recognized nothing as familiar in the inverted displays. Although we previously suggested that familiarity is not a relevant dimension until 4 to 5 months of age, faces may constitute an exception because of their extraordinary importance to the world of the young infant.

Collectively, these findings suggest that infants respond differentially to displays that could be perceived as familiar by 5 months of age. Yet, even if this interpretation is correct, it only serves to beg the question as to what property is detected as familiar. To address this question, we are currently engaged in a new series of experiments that are designed to more explicitly probe the content of the infant's representation of the human form. One paradigm uses an analogue of semantic priming (Meyer & Schvaneveldt, 1971) to explore which properties of the human form are detected as familiar. Another paradigm is designed to evaluate the categorical boundaries of the familiarity response. For example, point-light displays of animals or more artificial structures are shown to infants to assess their sensitivity to the properties depicted in these displays. As always, the success of this research is intimately linked to the validity of the developmental hypotheses guiding the choice of experiments.

What Could Babies Perceive in Moving Point-Light Displays That We Have Not Considered?

As our discussion in the first part of this paper suggests, the number of unconsidered alternatives is indefinite. Working in a pretheoretical period of our science, we must suffice with plausibility criteria for the hypotheses that we elect to test. In this regard, we have attempted to delimit a set of plausible alternatives that vary in their degree of organization and memorial influence.

There is at least one obvious omission to our account of meaning. We have said nothing about affordances. As was discussed earlier, affordances are the functional significances of perceived objects (Gibson, 1979). For infants, real people afford being picked up, cuddled, fed, and so forth. However, our displays afford none of these things. No adult has ever confused one of our point-light

walker displays with a real person; instead, these displays are seen as obviously consisting of animated computer graphics. In this sense, animated displays evoke in adults the same dual awareness that Gibson discussed in reference to picture perception (Proffitt & Kaiser, 1986). Observers are aware that they are looking at a display, and they are also aware of what real-world event the display was programmed to represent. If affordances are perceived in point-light displays, they are derivative to the identification that occurs in this second awareness.

CONCLUSION

The perceptual world of infants can be assessed using nonverbal responses and converging operations. Although this conviction is based more on principle than on exemplars, we conclude that there is nothing in the inaccessibility of verbal reports that precludes inquiry into the meaning of infants' phenomenal experience.

Perceptual research involving infants advances through two activities: (1) formulating plausible hypotheses and (2) empirical investigations designed to eliminate all but one of the proposed alternatives. The most problematic of these activities is typically the former. Without theoretical guidance, the boundaries of plausibility are ill-defined. The latter enterprise consists of the application of converging operations and is limited only by our methodological ingenuity.

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NOTES

1. Substitute, if you wish, "imaginal constraints" for "lack of imagination."
2. Our distinction between perceptual competence and genesis is analogous to that made by Chomsky (1965) between descriptive and explanatory grammars for language.
3. Gould and Lewontin refer to the adaptationists' strategy as the *Panglossian* paradigm due to the logic it shares with Voltaire's Dr. Pangloss: "Things cannot be other than they are. . . . Everything is made for the best purpose. Our noses were made to carry spectacles, so we have spectacles. Legs were clearly intended for breeches, and we wear them" (Gould & Lewontin, 1979, p. 583).
4. Runeson and Frykholm (1981) and Bingham (1987) seem to have counter evidence in that they have shown that people can make mass judgments for weights lifted by an actor displayed only in point-light form. These studies are similar to the earlier collision experiments that seemed to support KSD theory (Kaiser & Proffitt, 1984, 1987). The initial collision studies sampled a restricted set of events in which performance happened to be quite good. This competence, however, turned out not to be a general ability (Gilden & Proffitt, 1989). Not only are the lifted-weight studies difficult to evaluate because of the restricted set of events investigated, but more problematic is the fact that no model has ever been forwarded that defined the manner in which manifest motions are given dynamical representation. Without a precise definition of KSD rules, their psychological reality cannot be empirically evaluated.