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Natural Constraints, Scales of Analysis, and Information for the Perception of Growing Faces

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As psychologists studying human perception, we have frequently been asked why we are interested in the perception of growing faces. Each of us has been told many times during colloquia or informal presentations that although this growth research "sounds interesting, it isn't really psychology." Does research on the perception of craniofacial growth contribute to our understanding of fundamental problems in perception and cognition? After all, prior to the publication of Pittenger and Shaw's (1975a) study, there was no substantial literature or systematic psychological research on the subject. Moreover, the description of morphogenesis is usually viewed as the province of biology.

Many queries about our growth research reflect a second concern: one that pertains to some of the activities we have pursued during the course of our research. As part of our efforts to describe the perceptual information about growing faces and to validate a model of *craniofacial growth,* many activities have been performed that are not in the class of endeavors in which psychologists are typically engaged. These activities have included studying head-neck anatomy, clinical cephalometrics, radiology, and techniques for anthropometric measurement as well as learning orthodontic and surgical criteria for the evaluation of facial disorders, participating in a "growth seminar" in a School of Dentistry, and serving as members of a multidisciplinary clinical team concerned with the diagnosis, evaluation, treatment and management of craniofacial disorders. Our pursuit of these activities was driven primarily by an applied goal: developing a model of craniofacial growth that could enable surgeons and orthodontists to anticipate the effects of growth in their treatment of children with craniofacial disorders. Yet some of these endeavors eventually had a significant impact on the design of several perceptual studies that dealt primarily with fundamental issues in event perception (e.g., Mark, Shapiro, & Shaw, 1986; Mark & Todd, 1983, 1985; Mark, Todd, & Shaw, 1981).

Although the assigned mission of this chapter is to survey our 15 years of work on the perception of growing faces, we want to communicate more than what we did and learned about craniofacial growth. We also want to elucidate some of the reasons for our interest in this biological event—show how its study has contributed to our understanding of fundamental problems in perception and explore some of the tacit assumptions and applied concerns that have shaped the course our investigation.

To realize these objectives, we begin by examining two enterprises to which our project owes a substantial debt: James and Eleanor Gibson's ecological approach to perception (E.J. Gibson, 1969; J.J. Gibson, 1950, 1966, 1979) and D'Arcy Thompson's (1917/1942) approach to morphogenesis. The Gibsons have emphasized the importance of *natural constraints* on events as the basis of information for the perceiver about the world as well as about the perceiver's relationship to the world. D'Arcy Thompson's study of morphogenesis has demonstrated the importance of choosing the appropriate *scale of analysis* for examining the growth event. Moreover, his treatise helped us to identify the specific physical constraints that were responsible for the global remodeling of the craniofacial complex due to growth.

THE ECOLOGICAL APPROACH TO EVENT PERCEPTION

The study of human perception has a long history in philosophy and psychology. With Kepler's (1611) discovery of the optics of image formation, one of the fundamental problems of perception emerged: The image on the retina was found to be neither a copy of the world nor an accurate depiction of our perceptual experience. Rather, it stands in poor correspondence to both. For example, the image is inherently two dimensional, yet we experience the world as three dimensional. Furthermore, any retinal image can be produced by an infinite number of scenes. This mismatch between the world and the resultant sensory stimulation poses a fundamental challenge for understanding why perceptual experience is usually such a good representation of the world. In order to limit the possible environmental scenes to which a given retinal image might correspond, *constraints* had to be introduced. Since Kepler, students of perception have appealed to internal epistemic (i.e., cognitive) processes as the source of the requisite constraints. While the origin of these epistemic processes, either inborn (nativism) or through experience (empiricism), has long been debated, their existence, indeed their necessity, has not been questioned until recently.

Natural Constraints on What There Is To Be Perceived

In 1950 James Gibson introduced another source of constraints on the act of perception, namely the *terrestrial environment.* In doing so, he laid the foundation for an entirely different approach to perception.

Gibson observed that traditional perceptual theory has been directed toward understanding the perception of an object in otherwise *empty unstructured space*—he termed this view the *air theory.* What was perceived (i.e., the environment and the events taking place in the environment) was neglected entirely. In contrast, Gibson sought to determine the consequences of taking the nature of the terrestrial environment into account. Regularities in the structure of the environment impose *constraints* on the pattern of light to the observer. This "ground theory" supposed that what was perceived was not empty space, *per se*, but the layout of surfaces yoked to the ground plane by gravity. Gibson demonstrated that while the optical projection of points floating in empty unstructured space was indeterminate with respect to their distance from point of observation, relations in the retinal image did correspond to the relative distance of landmarks in the environment, *assuming that those landmarks reside on the ground plane* (Fig. 2.1). And, Gibson has shown that a natural perspective provides information about whether an object is yoked to the ground plane. Object position, relative to the ground plane, is specified by the shadows cast by objects onto the ground plane. This observation challenged the traditional starting point from which fundamental problems and theories of perception have emerged.

Gibson had been led to appreciate the importance of the terrestrial environment partly as a result of the research that he had undertaken during the Second World War on training pilots to land aircraft (J.J. Gibson, 1947). Prior to that time, traditional perceptual theory assumed that perceived object size (i.e., size constancy) was maintained only at relatively short distances from the point of observation. As the object receded from the observer, its perceived size was believed to diminish, though not at the same rate as its image on the retina. The proposal that size constancy breaks down at some distance from the observer was necessary to account for the fact that at some far distance, the object ceased to be visible.

The Gibsons examined this assumption on a flat, evenly textured field. A wooden rod was placed at a variable distance from an observer, who was asked to estimate its size relative to a set of standards placed near the observer. These judgments were repeated for rods of different sizes at distances up to 784 yards. In contrast to the prediction of traditional perceptual theory, size constancy did not break down over the range of distances used in the experiment: Estimations of object height remained constant, even at the farthest distance, and size judgments were highly accurate at all distances. These findings posed two serious challenges for traditional perceptual theory: *First,* why didn't size constancy break down at the farther distances as predicted? *Second,* how could the accuracy of observers' size estimations be explained in light of the supposed indeterminacy of the proximal stimulation?

The Gibsons' analysis of this situation revealed that the size and distance of the rods were *not* ambiguous if one took into account that the rods were planted on the ground. And, they argued, in the natural terrestrial environment, objects are yoked to the ground plane by gravity. Furthermore, that state of affairs is specified in the way shadows are attached to objects and cast onto the ground plane. (Objects are seen as floating "magically" in the air only under the most contrived circumstances. In such cases perceived size is more variable.) Given this "natural constraint" on the construction of the terrestrial environment, the Gibsons were able to identify a particular optical relationship between each rod and environment that was specific to the size of the rod and was preserved over distance. When a rod was seen to rise above the horizon, a ratio of the amounts of the rod extending above and below the horizon was maintained (invariant) over distance. This relationship was referred to as the *horizon-ratio invariant* (Fig 2.2). (A similar ratio was found to exist when the point of observation was such that the object did not extend above the horizon.) As a source of information about object size, the horizon-ratio invariant was based on two universal "facts of the aerial terrestrial environment": (a) objects rest on the ground plane, and (b) a horizon exists that relates an observer to the ground plane. From a generalization of this simple situation, James Gibson realized that the very nature of the terres-

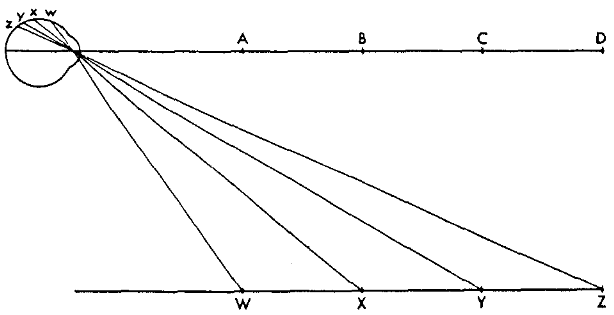

FIG. 2.1. Two formulations of the problem of distance perception. The "air theory of perception" (top) shows four points, A, B, C, D, in space that project to the same point on the retina. Since they have a common projection to the retina, there can be no information about distance given by any retinal projection. The "ground theory of perception" (bottom) shows four locations, W, X, Y, Z on a ground plane. These points are discriminable on the retina. The corresponding image represents a surface extending away from the observer. Note: From James J. Gibson: The Perception of the Visual World, p. 62. Copyright© 1959 by James J. Gibson, renewed 1977 by Houghton Mifflin Company. Used by permission.

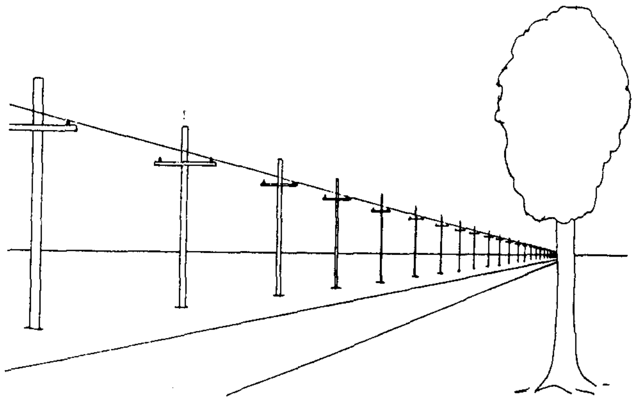

FIG. 2.2. The invariant horizon ratio for terrestrial objects. The telephone poles in this display are all cut by the horizon in the same ratio. The proportion differs for objects of different heights. The line where the horizon cuts the tree is just as high above the ground as the point of observation, that is, the height of the observer's eye. Hence, everyone can see his own eye-height on the standing objects of the terrain. Note: The Ecological Approach to Visual Perception (p. 165) by J.J. Gibson, 1979, p. 165. Houghton Mifflin Co. Reprinted by permission of the publisher.

trial environment could provide a source of constraints that might obviate the need for cognitive processes in perception.

As a psychologist in the functionalist tradition of American Pragmatism, Gibson was greatly concerned with the problem of *what* our perceptual systems have evolved to perceive. The evolutionary pressures on the human perceptual system must be rooted, at least in part, in the natural constraints (physical properties of surfaces and their layout) of the terrestrial environment. J.J. Gibson (1979, chapters 1-3) devoted considerable energy to identifying those events that are crucial to an animal's well-being. His survey of an animal's niche played an important role in delineating viable perceptual units of analysis. Gibson's pragmatic bent also led him to examine the utility of perception for providing information to control action. Perceiving and acting were seen as mutually supportive. Perception provides the animal with information about the environment for guiding action, which, in turn, provides the organism with new information about the environment.

From this ecological perspective, the study of perception began by delineating those natural constraints on the scene or event to be perceived as well as the importance of perception to the actor (J.J. Gibson, 1979). With those constraints in mind, the next task was to identify the relationships in the stimulus energy that are specific to properties of the layout and changes in layout of the environment. In short, Gibson began his study of perception by (to paraphrase Mace, 1977) asking what the head's inside of, rather than what goes on inside the head.

This strategy has important implications for dealing with a problem that is central to both studies of perception and social psychology: namely the basis for our belief in physical reality. In Asch's (1956) classic work on social conformity, virtually all of his subjects, regardless of whether they actually conformed to the judgments of the group, were extremely disturbed by the obvious discrepancy between their perception of the lengths of the lines and the group's. The situation proved so disturbing because it violated the basic assumption of each person that people share the same physical reality. What is the basis for this assumption?

Gibson's analysis of the optical information available, both at a glance and over time, as the observer moves around the world, demonstrates the basis for the consistency of the information provided by our senses. More importantly, the ecological survey of the natural constraints on the layout of the terrestrial/social environment establishes a lawful, physical basis for optical information that is specific to its source. It is precisely those lawful physical relations between observers and their environment that constitutes the basis of the shared "physical reality" that is crucial to our existence and well-being. The psychosocial consequences of perceived age level provide a useful illustration of these pragmatic concerns. In the next section, we briefly examine the psychosocial significance of the growth event.

The Importance of Craniofacial Growth: Social and Applied Concerns

Growth-related changes in craniofacial structure can have a significant effect on human action. Ethological studies suggest that perceived age is a significant factor in regulating the type and amount of behavior directed toward an individual. Age-variant characteristics like head shape have a vital bearing on various parental behaviors such as caregiving, warning, and protection (Alley, 1986). McCabe (chap. 5) examines some intriguing evidence that head shape may be a factor in at least some instances of child abuse. Age-related changes in the shape of the human head have other important consequences for human behavior (see Berry & Zebrowitz-McArthur, chap. 4).

Facial attractiveness (aesthetics) affects interpersonal relationships in numerous settings (Alley & Hildebrandt, chap. 6). Although the physiognomic enterprise ultimately failed to identify strong links between facial appearance and characteristics such as intelligence, personality, criminality, people do make such attributions about these characteristics of other people (see Alley, chap. 8). Changes in facial appearance, then, can be expected to have an important psychosocial impact on the individual. Since growth produces an extensive alteration of the entire head, it is likely to have some effect on facial aesthetics. In his review of the evidence to date, Alley (chap. 3) is skeptical that the nature of this impact is well understood. Nonetheless, he maintains that aging and perceived age level do affect facial attractiveness.

In light of the psychosocial importance of the human face, it is not surprising to discover that people attach great importance to their appearance. This is certainly evident in the ever increasing numbers of people who undergo various types of craniofacial treatment (e.g., plastic and maxillofacial surgery, orthodontics) primarily to improve their visage. These clinical enterprises make especially important contributions to the treatment of young children with serious craniofacial disorders. The technical capabilities of surgeons and orthodontists in treating even the most extensive disfigurements and deformities are truly remarkable. Yet until recently, there have been important limitations on the application of these treatment procedures to growing children. Unless practitioners are able to incorporate the effects of growth into their treatment plans, the immediate treatment outcome is likely to deteriorate as a result of normal, growth-related changes. Thus, "relapses" will necessitate further treatment and are often more difficult to treat than the original problem.

In the absence of a viable means for predicting the effect of growth on the immediate treatment outcome, many practitioners choose to begin treatment only after the child's growth is nearly complete. This decision has marked consequences for the psychological well-being of such children: They often have to go through childhood with a serious facial disfigurement. Too often, these children are subject to ridicule and experience difficulty in establishing strong interpersonal relations during childhood and adolescence (Shaw, chap. 9). Practitioners need a growth model that would allow them to anticipate the effects of growth in their treatment plan. Thus, another motivation for our study of craniofacial growth was to contribute to clinical efforts to develop a means for predicting the long-term effects of growth on treatment outcomes.

Events as the Primary Unit of Analysis

In the formative stage of his ecological approach to perception, J.J. Gibson (1950) adhered to the retinal image as a static projection of the world. Later on, he abandoned the retinal image in favor of the "ambient optic array" (J.J. Gibson, 1961, 1979), whereby properties of the environment were specified over time as the (observer's) point of observation moved through the environment.[1] Gibson observed that many classic demonstrations of inaccuracies of perception (e.g., those produced by the Ames Room) occurred only with a stationary, monocular vantage point. As soon as the observer moved, the ruse was revealed. Throughout the remainder of his career Gibson emphasized the importance of time and motion in the availability of information. He was able to show that many sources of information about the world and the observer's own movement through the environment were given, not in an instantaneous glance, but over time and multiple points of observation. To take but one example, consider the traditional pictorial depth cue of "interposition." This "cue" was widely acknowledged to be potentially misleading. However, when objects and/or the observer moved, the progressive hiding and/or revealing of one surface by another was specific to a particular configuration of surfaces (J.J. Gibson, Kaplan, Reynolds, & Wheeler, 1969; Kaplan, 1969).

Our investigation of craniofacial growth has attempted to develop Gibson's fundamental insights regarding the starting point for visual perception. Shaw (Pittenger & Shaw, 1975a; R.E. Shaw, McIntyre, & Mace, 1974; Shaw & Pittenger, 1977) viewed the *ambient optic array* as a reflection of the appropriate "unit of analysis" for describing the terrestrial environment. Gibson had demonstrated that many invariant relations between the environment and optical stimulation are revealed only over time. This encouraged Shaw to begin, not with static images, but with *events* involving a *structure undergoing a "style of change" over time.*[2]

To distinguish among the myriad of events typically encountered in natural environments, observers must detect both the *structure* (e.g., object) undergoing change and the particular *style of change* inherent in the event (e.g., rotating, bending, stretching, bouncing, running, walking, or growing). An object can undergo many different styles of change. A child, for example, can run, walk, bend, stretch, spin, smile, or grow. By the same token, many different objects can be seen to participate in a given event and, we postulate, undergo the same style of change: Records, tires, skaters, dancers, balls, pinwheels can all be seen as "spinning." With reference to "growth," a potentially infinite class of children can all be recognized as growing older. A basic problem in understanding the perception of an event is to determine how people are able to identify both the style of change and structure undergoing change.

Craniofacial Growth: A Slow Biological Event

Our investigation of craniofacial growth is fundamentally a study of event perception, which attempts to delineate the information for a complex biological change and for the structures that can be seen to undergo that style of change. As the human head grows from birth to early adulthood, it changes in both size and shape. An infant's head typically has a diminutive facial mask relative to its cranium. Within 2 years after birth, the facial mask starts to grow more rapidly than the cranium, thereby resulting in a marked change in facial proportions. The cranium typically approaches its adult size prior to the age of 10 years, whereas the face continues to grow well into early adulthood. Craniofacial growth, then, entails a salient style of change that can be recognized across a wide range of craniofacial structures.

An important objective in presenting this overview is to show how our work has contributed to a broader investigation of how human observers are

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[1] In talking about the "ambient optic array," J.J. Gibson (1961, 1979) observed that the world structures (reflects) light to every potential point of observation in the transparent medium (air). This pattern of light surrounding any potential point of observation is specific to the layout and properties of surfaces in the environment, and, as such, is potentially informative about the world. The act of perceiving begins when a potential point of observation is actually occupied by the eye of an observer. By looking in a particular direction from a particular location, the observer samples the rich structure in the "optic array." Gibson further identified additional information about the environment for observers as they move their point of observation through the optic array, that is, as they move. Thus, for Gibson, the ambient optic array constitutes an informational basis for perception, one in which the challenge facing the perceiver is to detect information about the world, rather than construct a representation of the world from impoverished snippets. (See J.J. Gibson, 1979, chap. 5 for a detailed examination of the ambient optic array.)

[2] In developing our conception of events as involving a structure undergoing a style of change, we acknowledge a significant debt to J.J. Gibson. Yet, at the same time, we note that Gibson did not use the phrase "style of change" to describe transformations in the world. In his writing he says only that:

> Continuous optical transformations can yield two kinds of perceptions at the same time, one of change and one of nonchange. The perspective transformation of a rectangle, for example was always perceived as something rotating and something rectangular. This suggests that the transformation, as such, is one of a kind of stimulus information for motion, and that the invariants under transformation are another type of stimulus information, for constant properties of the object. (J.J. Gibson, 1966b)

Although the framework for event analysis that was developed during the course of our growth research was inspired by Gibson's writings, it represents an elaboration and extension of his work.

able to recognize different styles of change. To date, there has been a considerable volume of research on the perception of *inanimate, nonbiological* events. Much of this work has focused on the analysis of *rigid* motions involving translations or rotations. However, many events involve *nonrigid, inanimate* motions, as bending and stretching. Other nonrigid events entail animate or biological styles of change, such as walking, running, and other forms of human movement, growth, facial expression and social interactions. (See Todd, 1982, for a list of relevant studies.)

Research on animate or biological events is of special significance to our concern with craniofacial growth. Inspired by the classic study of Michotte on causality, Heider and Simmel (1944) produced a now-classic 3-minute cartoon showing geometric figures (triangles and circles) acting out a complex social event involving such motives and emotions as aggression, courtship, fear, and frustration. A more recent impetus to studies of biological events derives from Johansson's (1973, 1975) patch+light demonstrations. These displays show spots of light in the dark attached to the joints of an otherwise invisible actor. In the absence of movement, these displays look like random dots: The human form to which they are attached is unrecognizable. However, when the actor starts to move, these point-light displays provide sufficient information for observers to distinguish not only the existence of a person, but the type of activity being performed (Johansson, 1973), the gender of the actor (Barclay, Cutting, & Kozlowski, 1978), the identity of the actor (Cutting & Kozlowski, 1977), the amount of force exerted by an actor in performing various activities such as lifting a box (Runeson & Frykholm, 1981), and even the intention of an actor to deceive the observer about the weight being lifted (Runeson & Frykholm, 1983).

In each of these studies of rigid or nonrigid styles of change, the event is specified by the relative motions of either one part of an object with respect to another or one object with respect to another. Growth, however, has a notable difference: It takes place over such long temporal periods that actual movement is too slow to be visible to the naked eye. The observer views only the *displacement* of craniofacial morphology, not the motion itself. This introduces a distinction between fast and slow events, a distinction that is orthogonal to the dichotomies of rigid and nonrigid or animate and inanimate events (R.E. Shaw & Pittenger, 1978). *Fast events* present observers with motion through which the style of change inherent to the event is defined. For *slow events,* like the displacement of the hour hand on a clock, blooming of flowers, and growth and evolution of biological forms, the motion is too slow to be noticed. The event, nonetheless, is perceived.

The distinction between slow and fast events raises an important question. Can the perceptual information for both types of events be described using the same principles or will additional cognitive processes (e.g., memory) be required to explain the apprehension of slow events? R.E. Shaw and Pittenger (1978) and Warren and Shaw (1985) presented a detailed discussion of how slow and fast events can be understood within the same perceptual framework.

We now turn to our study of craniofacial growth. First, we explore the problems entailed in describing a complex biological event like craniofacial growth, and how the work of D'Arcy Thompson guided our efforts to identify both the natural constraints on the growth event and a geometric transformation that describes the global remodeling of the head due to growth. With that preparation we survey the contributions of perceptual research on craniofacial growth to our understanding of the fundamental problems in event perception identified previously.

THE DESCRIPTION OF CRANIOFACIAL GROWTH

From the ecological perspective, the study of any event—rigid or nonrigid, animate or inanimate, slow or fast—begins with a description of the event for the purpose of delineating the perceptual information specific to that class of events. The initial task in our investigation of craniofacial growth was, therefore, to develop a description of the global remodeling of the craniofacial complex entailed in this complex biological event. The requisite description had to capture those changes that were common to the myriad of structures that could be recognized as growing. Prior to confronting this challenge, we had to find an appropriate tool for describing craniofacial growth.

The Concept of a Geometric Transformation

The description of rigid styles of change is relatively straightforward, because formal descriptions of translations and rotations are well known and readily accessible. These formal descriptions are written in the language of *mathematical transformations.*[3] In mathematics these are functions that map the elements of a given nonempty set (domain) into or onto the elements of a second

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[3] Although J.J. Gibson did discuss transformations extensively, he never gave an unqualified endorsement to our use of these mathematical entities to express the structural effects of change. He said they are not adequate to describe the information for event perception because only special cases of change are truly structure preserving. He did say, however, that it may be helpful, though insufficient, to examine mathematical transformations of the optic array. It is important to realize that our use of mathematical transformations is not to describe perturbations in the optic array. Rather, we are attempting to describe the pattern of craniofacial change associated with the growth event in the world. This invariant pattern of change is a product of the natural constraints on the growth event. To date, we have yet to examine the information about growth in the optic array.

nonempty set (range). To understand the notion of a transformation, imagine a two-dimensional object represented as a set of points—for example, a halftone photograph of the sort printed in the newspaper. The position of each point can be described using two coordinates. In some cases it is advantageous to use the standard Cartesian system, where X and Y represent distances from some reference point (the origin) on two perpendicular axes. In other cases, a polar coordinate system is more convenient. Again, two coordinates are also used: The distance of the point from the origin is denoted by R, while the angle or direction of the point from the origin is denoted by θ (Fig. 2.3). A geometric transformation provides a function for systematically altering the original coordinates of the object, thereby producing a new pair of coordinates for each point, (x', y') or (r', θ'), which are functionally related to the original coordinates $[x' = f(x),\ y' = f(y);\ \theta' = f(\theta),\ r' = f(r)]$.

Any system of equations relating the original and transformed coordinates can be interpreted in two ways. In one sense, these equations represent a change in the original coordinate system, such as when data are transformed from rectangular coordinates to polar coordinates (Fig. 2.3). Alternately, these equations represent a change in an object within a fixed coordinate system. The latter interpretation is easily demonstrated by considering the different ways in which a square object can be transformed (Fig. 2.4).

It is important to recognize two facts about spatial coordinate transformations: First, each transformation changes certain properties of the object to which it is applied, but leaves others unchanged; second, transformations differ with respect to those properties that they leave unchanged. To illustrate, consider a square that is rotated about a point within its perimeter. *Rotation* changes the location of every point on the square except the center of rotation. However, the square's metric shape (that is, the set of distances between pairs of corresponding or homologous points on the object) is unchanged. Rotation will produce just these effects on any planar figure. In the language of mathematics, the properties which do not change under a transformation are said to be "invariant" under it. Another transformation that preserves the square's metric shape is *translation*. Unlike rotation, however, translation changes the coordinates of every point on the object.

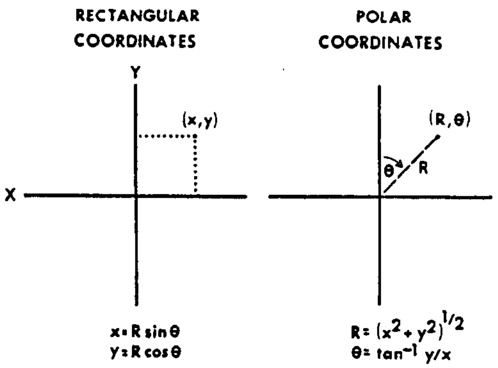

FIG. 2.3. An illustration of rectangular and polar coordinate systems along with equations for transforming coordinates between the two systems.

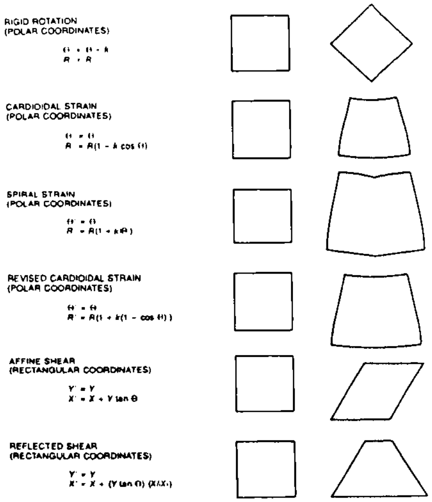

FIG. 2.4. The shape of an object can be altered within a fixed coordinate system by applying a variety of geometric transformations, six of which are listed by name and also represented in the form of the equations at the left. (The fixed coordinate system is given in parentheses.) The effects of the different transformations on a square are shown at right.

Now consider a similarity transformation, which results in a uniform expansion or contraction of an object. A similarity transformation changes the position of all points, with the exception of the center of expansion or contraction, as well as the distances between every pair of points. However, it preserves the proportions of the figure. Thus, if a square doubled in size, it is bigger, but the lengths of the sides of the new square remain equal to each other and the diagonal is still the length of one side times the square root of two. Unlike translation and rotation, a similarity transformation is said to be a nonrigid transformation, since the distances between all pairs of points are changed. The properties maintained under a similarity transformation are different from those left invariant under rotation or translation.

Each geometric transformation produces a mathematically distinct style of change that is independent of the particular object to which it is applied. Rotation, for example, entails the same style of change whether it is applied to a square, a triangle, or an ellipse; at the same time, rotation produces a distinct style of change. This property makes transformations especially useful tools for describing a salient style of change that can be perceived over a variety of objects. The abstract event of rotation can easily be recognized when it is applied to various objects including objects the observer has never seen before. In the next section of this chapter, we examine how these properties of mathematical transformations might enable psychologists to distinguish the information about perceptually salient styles of change, notably craniofacial growth.

Transformations and the Description of Growth

D'Arcy Thompson pioneered the use of geometric transformations in the study of morphogenesis. In his classic work, *On Growth and Form* (1917/1942), Thompson presented graphic representations of coordinate systems in which he had embedded a biological form. By transforming the coordinate system (carrying along the biological form with it), he was able to produce ontogenetic or phylogenetic relatives of the original object (Fig 2.5). These transformed coordinate systems provided a graphic depiction of the transformation associated with each morphogenetic event. Thompson's special insight and contribution lay in his *graphic* representation of a seemingly complex transformation of a biological form with a seemingly simpler object, such as a Cartesian grid. His drawings made it possible to "see" the abstract nature of the change, independently of the particular form undergoing change, thereby leading to an "intuitive" appreciation of invariant aspects of change in the growth or evolution of the species.

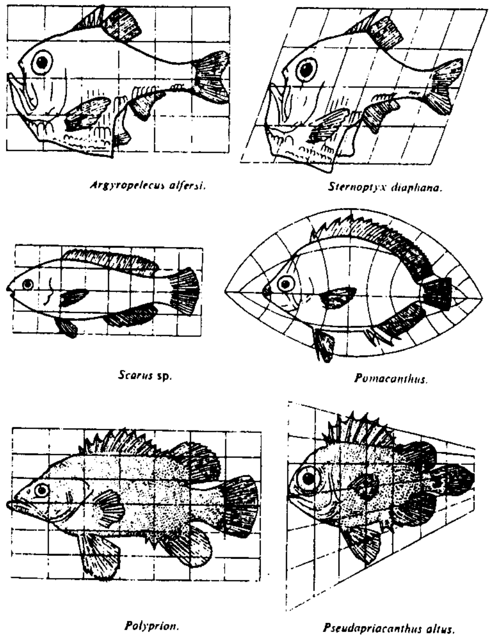

FIG. 2.5. Coordinate transformations from D'Arcy Thompson (D'Arcy Wenthworth Thompson: On Growth and Form, p. 299. Copyright (c) 1944 by Cambridge University Press. Used by permission).

For our goal of describing the growth event, we were obliged to offer a formal description of the deformed grids. The development of viable mathematical transformations constitutes a formidable challenge in describing growth. From where do such candid descriptions derive? Again, D'Arcy Thompson's study of morphogensis provided valuable suggestions.

Transformations as Descriptions of the Effects of Physical Forces. Thompson contended that the geometric distortions associated with morphogenetic change are the result of physical forces in an animal's environment. According to a well-known principle, commonly referred to as Wolff's Law, *stress is a direct stimulus to growth.* A biological structure will remodel in accordance with the *amount* and *direction* of forces acting on that structure. For example, the weight-bearing bone of the lower leg, the tibia, grows so as to increase its cross-section in response to the weight that it must support. The fibula, in contrast, is a narrower bone, reflecting the lesser loads normally placed on it.

Thompson's method of coordinate transformations was developed to do more than describe changes in morphology through global geometric transformations. The resultant grids were intended to help identify the origin of biological forms in forces imposed by dynamic potentials, such as gravity and biomechanical stress. Thompson, in 1917, maintained that such forces act directly on organisms, shaping their changes to optimize resistance to stress. Although we now recognize that Thompson's proposed mechanism is in error, we should not reject completely the role of physical forces in shaping morphology (Gould, 1971; R.E. Shaw, Mark, Jenkins, & Mingolla, 1983). Rather, physical forces operate through natural selection; the genetically determined plan produces shape changes that are optimal with respect to the existing pattern of forces.

What D'Arcy Thompson appreciated was that any description of morphological change ought not to be a purely mathematical exercise, for geometric and kinematic descriptions of change cannot be evaluated without considering the forces responsible for the change. Specification of event dynamics is necessary in order to delimit the event in question and constrain the search for a kinematic description. To clarify this point, consider our interest in describing craniofacial growth. Our goal is to describe what is common to all growing individuals. The longitudinal data banks from which such descriptions are usually derived present students of growth with a serious problem that purely kinematic approaches cannot address. Changes reflected in longitudinal records for a given indivdual are the product of "more than just growth"; that is, the change in facial morphology is a product of both a style of change (growth) common to all individuals *and* various habits specific to an individual (e.g., changes produced by nonoptimal biomechanical forces such as thumb-sucking, nail-biting, and mouth-breathing, as well as diet, facial expressions, and other oral habits). Growth researchers who attempt to derive their descriptions from longitudinal records are confronted with the task of delimiting "pure" growth-related changes that are *invariant over all individuals* from those changes that are *specific to an individual.* All too often investigators fail to acknowledge this difficulty, let alone address the problem.

Thompson's work, then, has important implications for our efforts to describe craniofacial growth: The growth event must be delimited by identifying the *dynamic (physical) constraints common to all growing faces.* Curiously, this is the same point that we discussed in surveying the ecological approach to perception. James and Eleanor Gibson attached tremendous importance to the natural constraints on events and the layout of the terrestrial environment. The similarity between the Gibsons' and Thompson's respective enterprises does not end here. Both also recognized the importance of choosing a scale of analysis commensurate with their interests and goals.

Scales of Analysis

The description of events, like craniofacial growth, is an endeavor shared by many fields of scientific inquiry. It is rarely the case that descriptions developed by other disciplines can be transported directly to psychology. Events and the physical constraints on events can be studied at different *scales of analysis*, ranging from the quantum level through scales of far greater expanse than that of our terrestrial environment, such as employed in astrophysics. To be sure, there is no right or wrong scale for studying any event. Rather, the chosen spatial-temporal scale must be *appropriate to* or *commensurate with* the aims and concerns of the investigation, a point made by both the Gibsons and Thompson.

In his survey of the terrestrial environment and in his analysis of the physics required to describe how the material properties of surfaces structure light, J.J. Gibson (1961) contended that physics had to be *ecologized.* That is, specification of the information for an event utilized by a perceiver would entail delineating the material properties of the structure and the dynamic aspects of the change as they might relate to the ambient optic array. The problem was to discover how light is structured in a manner specific to the material properties of substances and the layout of surfaces, and in a manner useful to specific types of animals.

Similarly, much of D'Arcy Thompson's (1917/1942) treatise was predicated on the choice of a scale commensurate with the global morphological changes resulting from growth or evolution. In his analysis of the physical constraints on morphogenesis, Thompson was sensitive to the hazards of choosing a scale that was too molecular to account for the morphological change. He realized that analysis of forces affecting molecules or cells would be unable to illuminate the global morphologic transformation. Although Thompson did not discuss hereditary influences, we suspect he would have been skeptical that they could provide a wholly adequate explanation. Today, we know that the informational content of DNA is woefully inadequate to account for every detail in facial microstructure (Enlow, 1968; Moore & Lavelle, 1974). To summarize the essential point, both D'Arcy Thompson and J.J. Gibson were concerned with physical constraints that were both *global* and *universal.*

With respect to craniofacial growth, the head has to be viewed, not as a collection of chemicals, cells, or tissues, but as a complex, contoured, three-dimensional structure. Our objective was to identify those forces that affected the entire craniofacial structure and were applicable to all (normal) instances of this growth event. Modern biology usually works at the more "micro" scales of molecules, genes, cells, and tissues. (Unfortunately, the study of morphology, which proceeds at a "macro" scale akin to the requirements of Thompson's interest in morphogenesis and Gibson's ecological psychology, has been on the wane for several decades.) The challenge for the ecological psychologist was to develop a description of craniofacial growth at a scale appropriate to the human perceiver.

In this section, we have examined how mathematical transformations might enable us to describe various styles of change, including the global remodeling of the craniofacial complex due to growth. Consideration of scales of analysis at which the growth event is to be viewed and natural (physical) constraints common to all instances of growth have established limits on the search for a transformational description of craniofacial growth. The natural constraints on growth must be both *universal* and *global.* They must be universal, since they must be applicable to all heads that can be seen to grow. And they must be global, since they must apply to the remodeling of the entire craniofacial complex. It is this scale that seems commensurate with human perception. *What forces in the natural terrestrial environment satisfy these two conditions of acting on the head globally and universally?* There are few, if any, candidates other than gravity.

Finding a Growth Transformation

Earlier, we noted that Wolff's Law proposed that stress is a direct stimulus to growth. This means that a growing structure remodels in accordance with the amount and direction of stress acting on it. This principle was the basis for a hydrostatic analysis of the effects of gravity on a growing head. To simplify the analysis, Todd, Mark, Shaw, and Pittenger (1980) treated the human head as an idealized system: a fluid-filled, spherical water tank. What can be said about the distribution of pressure on the walls of the container? Four characteristics can be identified (Fig. 2.6): (a) the distribution of pressure is continuous throughout the container; (b) the direction of pressure is orthogonal to the wall of the container, radiating from the center of the sphere; (c) the pressure distribution is bilaterally symmetrical around the central vertical axis; and (d) the amount of pressure at any point is a function of the amount of fluid above it (i.e., the pressure increases from top to bottom).

Following Wolff's Law, what would happen if the tank were allowed to remodel (grow) in accordance with the direction and amount of pressure exerted by the fluid? (Assume for the purpose of this idealized analysis that additional fluid was being pumped into the tank to keep it filled.) This analysis produced the cardioidal strain transformation, which can be written in polar coordinates as: $\theta' = \theta$, $R' = R(1 + k(1 - \cos\theta))$, where k is a free parameter that increases over time. (See Fig. 2.7 for a depiction of the effects of this global geometric transformation when applied to a human head.)

Although the hydrostatic model is highly simplified and idealized, it has been extremely useful in helping us to appreciate the effects of a global and universal dynamic constraint, *gravity*, on the course of craniofacial growth. Todd and Mark (1981) have further shown that the resultant transformation makes highly accurate predictions of facial appearance when applied to hard tissue (bone) profiles (Fig. 2.8).

This hydrostatic model can be viewed as but one of a class of related growth models. Several years earlier, Robert Shaw had developed a similar "growth" transformation independently of this analysis of dynamic constraints on growth (Shaw et al., 1974). (We have come to refer to the transformation derived from the hydrostatic model as the "revised" cardioidal strain transformation.) Shaw's "growth" transformation (the cardioidal strain transformation depicted in Fig. 2.4) was intended to capture the effects of certain strain and radial patterns of change that D'Arcy Thompson had associated with growth. Although the effects of Shaw's original transformation were different from the transformation derived from the hydrostatic model in at least one aspect—Shaw's model did not produce an increase in head size—his nodal point-based

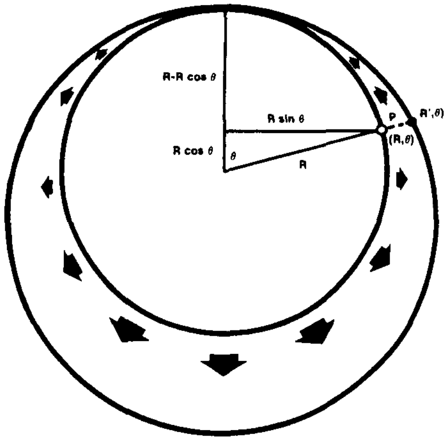

FIG. 2.6. The pressure distribution inside a fluid-filled sphere due to gravity. The inner circle represents a spherical tank filled with fluid. The pressure (P) at any point on the surface of the tank is always normal to the surface of the tank. From elementary hydrostatics, pressure can be expressed by the relation $P = k(R - R\cos\theta)$, where R is the radius of the sphere and k is a product of the density of the fluid and gravitational pressure. The distance (P) between any point on the surface of the tank (R,θ) and a point on the outer curve (R',θ), found by extending the radius through point (R,θ) to the outer curve, represents the pressure at point (R,θ). Thus, as angle θ increases, the pressure at point (R,θ) increases as the distance between (R,θ) and (R',θ) increases. If new material were laid down in accordance with this pressure gradient, the revised cardioidal strain transformation [$\theta' = \theta$, $R' = R(1 + k\{1 - \cos\theta\})$], would be observed.

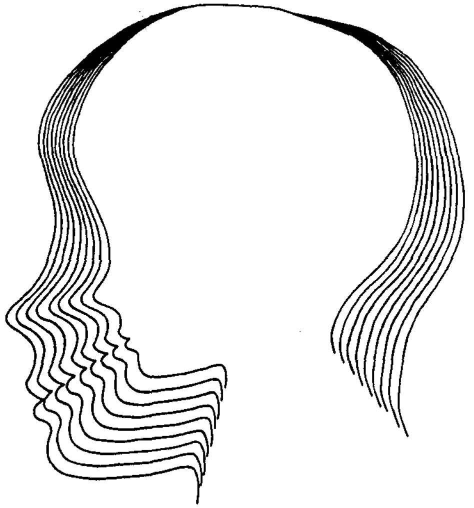

FIG. 2.7. Increasing amounts of the revised cardioidal strain transformation have been applied to the profile of a young child (innermost profile). Successive profiles appear older.

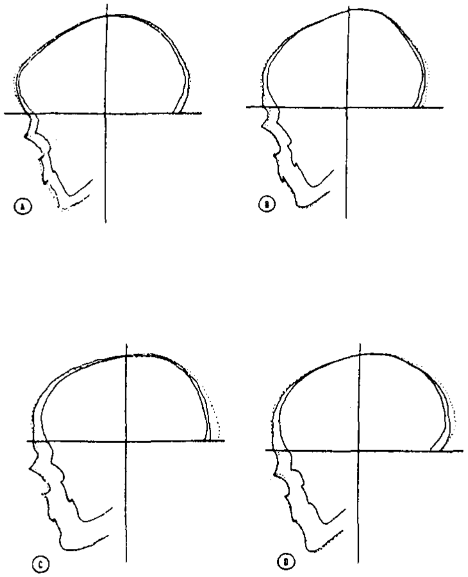

FIG. 2.8. Samples of growth predictions of 10 males and 10 females. The solid profile outlines show the younger (inner) and older (outer) profiles traced from lateral head films of a person's actual growth records. The dotted profile shows the growth prediction made by transforming the younger profile with the revised cardioidal strain transformation. A, Male, ages 5.9 and 13.9, 68.9%. B, Male, ages 6.3 and 19.0, 80.3%. C, Male, ages 4.3 and 18.6, 76.1%. D, Male, ages 5.1 and 17.0, 81.1%. Note: From "Issues Related to the Prediction of Craniofacial Growth" by J.T. Todd and L.S. Mark, 1981, *American Journal of Orthodontics, 242*, p. 74. Reprinted by permission.

cardioidal strain transformation shared the other essential geometric properties associated with the gravity-derived hydrostatic model.

While the similarity between the original cardioidal strain transformation and the later hydrostatic model might, at first, appear coincidental, this is not the case. Shaw's efforts to develop the cardioidal strain transformation were guided by the same constraints that eventually led to the development of the hydrostatic model and the revised cardioidal strain transformation. In fact, the similarity between the two transformations convinced us that what we were attempting to find was not a single "best" transformation, but a "class" of transformations that preserved certain geometric properties. Throughout the course of this project, assumptions entailed in the application of the relevant dynamic constraints on the growth event have led us to three such models of craniofacial growth: Shaw's original nodal point model (Pittenger & Shaw, 1975a; R.E. Shaw et al., 1974); a hydrostatic model (Todd et al., 1980; Todd & Mark, 1981); and finally a hydrodynamic model (R.E. Shaw et al., 1983). We now survey our investigation of the perceptual consequences of this class of transformations.

THE PERCEPTION OF CRANIOFACIAL GROWTH

Defining the Class of Transformations Perceived as Growth

Initial Studies. In their first investigation of craniofacial growth, Pittenger and Shaw (1975a) examined the relative importance of three characteristic patterns of growth—*strain, shear,* and *radial* growth (Thompson, 1917/1942)—which seemed applicable to the global remodeling of the human skull (R.E. Shaw et al., 1974). From Thompson's study of morphogenesis, Shaw devised two transformations depicting the strain and shear components: cardioidal strain and affine shear, respectively (see Fig. 2.4). (The radial component, by itself, could not be an appropriate model of growth, since it did not produce a remodeling of facial proportions. Cardioidal strain, however, incorporates a radial component, which D'Arcy Thompson, 1917/1942, had previously shown to be an aspect of growth.)

Various amounts of each transformation were applied to the profile of an 8-year-old child (Fig. 2.9, Profile 0/0). In all, 5 levels of shear were combined with 7 levels of strain, thereby producing the 35 profiles shown in Fig. 2.9. Three converging perceptual measures were employed. The first was designed to measure the effect of each transformation on perceived age by recording judgments of relative age. Observers were asked to make magnitude estimations of the age-level of each profile relative to the numerical rating that they had assigned a standard. Though both transformations affected the magnitude estimates of perceived age, cardioidal strain had a far more powerful and consistent effect than affine shear.

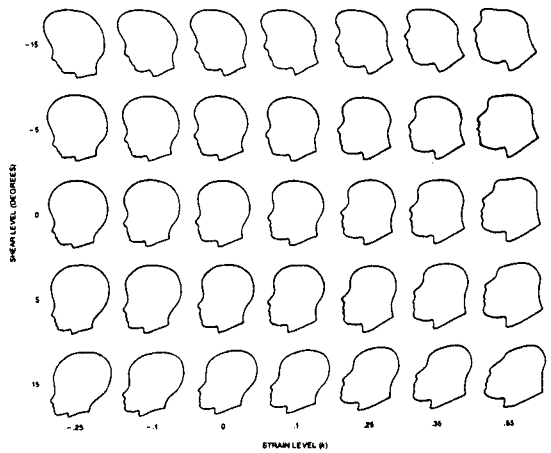

FIG. 2.9. Transformations of a facial profile by shear and cardioidal strain (untransformed profile is at shear = o, strain = 0). Note: From "Aging Faces as Viscal=Elastic Events" by J.B. Pittenger and R.E. Shaw, 1975, *Journal of Experimental Psychology: Human Perception and Performance, 5,* Expt. 1. Resprinted by permission.

In their second experiment, Pittenger and Shaw used a paired comparison task to examine observers' sensitivity to small changes in the facial profile produced by cardioidal strain transformation. Observers were presented with pairs of profiles produced by differing amounts of the free parameter and asked to identify the "older" profile of each pair. The accuracy and reliability with which observers were able to perform this task was impressive, given the side-by-side arrangement of the profile pairs, and the extremely subtle differences between some of the profile pairs. R.E. Shaw and Pittenger (1977) later observed that, in light of the size of the projected images used in this experiment, observers were able to discriminate shape differences between adjacent profiles that were only a few times greater than the absolute limit determined for visual acuity in resolving spatially adjacent lines (Schlaer, 1937). Although this initial study did not examine observers' sensitivity with respect to age-related changes produced by the affine shear transformation, a later investigation found that observers were considerably more sensitive to small differences produced by cardioidal strain transformation than to comparable differences produced by affine shear (Mark & Todd, 1985).

These initial experiments provided valuable demonstrations of the relative importance to perception of the strain component over the shear component. This finding establishes an important constraint on the types of transformations that may prove to be viable descriptions of the growth event. In addition, observers were found to be extremely sensitive to the effects of the cardioidal strain transformation, both in terms of their ability to recognize differences in age level and to recognize individual identity in transformed profiles. At the very least, Pittenger and Shaw (1975a) had identified a psychologically interesting transformation, one worthy of additional study.

Shortcomings of the Initial Studies. With the benefit of hindsight, we can identify some methodological shortcomings of Pittenger and Shaw's original test of the cardioidal strain growth model as well as other problems that they were unable to address. Perhaps, the most significant problem was the lack of a baseline for comparing the perceived effects of this model to actual growth. Unfortunately, they did not have access to a longitudinal data bank required to construct such a standard. (Several years later, when Shaw came to the University of Connecticut, we discovered that records of one longitudinal study involving approximately 100 individuals were available at the University Health Center.) Such longitudinal records would have permitted them to equate the ranges of the free parameter used in producing the transformed profiles to the effects of actual growth.

Lacking these guidelines, extreme values of cardioidal strain changed the profile appearance well beyond the range associated with normal growth (see Fig. 2.9). Some of the younger profiles (i.e., high negative values of strain) were reminiscent of the "super-intelligent humanoids" depicted in science fiction movies, while many of the older profiles (i.e., high positive values of strain) appeared "Neanderthal-like." Thus, in addition to obtaining a longitudinal baseline against which to evaluate the perceptual consequences of the growth model, follow-up studies also had to restrict the range of the transformation to that produced by normal growth, thereby eliminating the nonhumanlike extremes.

Pittenger and Shaw might have also included a measure of the natural "salience" of the growth transformations, such as might be obtained from a free response task, in which observers viewed sequences of faces and were asked to label the event responsible for producing the observed change. This method would have permitted them to assess whether the age-related changes produced by the strain transformation could be detected spontaneously or whether they were noticed only when experimental instructions prompted the observers to attend to age. In the latter case, it would have been unlikely that the particular strain transformation used in the study would ultimately prove to be an adequate model of information about the growth event.

A frequently offered criticism of Pittenger and Shaw's initial study of the growth event is that they examined only two transformations: "How do you know there is not another transformation that would provide a better model of growth than cardioidal strain?" "There are an infinite number of mathematical transformations. How are you going to test them all?" With a little thought, it is not difficult to see that these criticisms are misguided. They are also unfair, for they establish a criterion that is never applied elsewhere: namely, to test *all possible* models. Because these criticisms are raised frequently, it behooves us to examine them.

To the critic who objects, "But how do you know that some other transformation wouldn't provide a better model of growth than cardioidal strain?", there is a relatively simple response: We do not know if the current model is the best possible model. In light of the vast number of untested candidates, we would not be surprised if a "better" model is found. The question, however, misses the essential thrust of this enterprise. Could this "better" model be *entirely* different from the one examined by Pittenger and Shaw? Given the observers' strong tendency to *perceive* the effects of cardioidal strain as growth, it is unlikely that a viable alternative could be identified that is entirely different from that original transformation. There are certain characteristics of the growth event that any viable candidate model of growth must depict. (As we demonstrate shortly, the hydrostatic model [Fig. 2.6] has permitted us to identify at least some of those characteristics that are shared among a class of transformations that are perceived as growth.)

What is perceived as growth should be related (i.e., similar) in some important way to the actual event. It stretches our commitment to realism to suggest that two transformations perceived as growth (and thus related to actual growth) are entirely unrelated to one another. What is really important about alternative growth models are not the differences among them, but the properties that are *shared* by such candidate transformations. We believe that other viable growth transformations can be found, but that they will share certain properties with the cardioidal strain transformation. These properties that are common to each member of the class of growth transformations constitute the perceptual information about this salient style of change. This observation points toward a potentially important contribution of research on growth to our understanding of a fundamental problem in event perception: How are observers able to distinguish different styles of change from one another?

Studies on How Growth can be Distinguished from Other Styles of Change

Until recently, there had been relatively little research on the specific properties of visual displays that make one style of change distinct from another. Because observers can recognize many styles of change in a variety of contexts, it is unlikely that the visual system handles each distinction as a separate problem. Event perception research needs to establish a unified framework for classifying the information by which perceivers are able to distinguish different styles of change from one another. An extension of Pittenger and Shaw's original study examined a geometric framework for distinguishing styles of change (Mark et al. 1981).

To this point, we have characterized transformations in terms of the pattern of change that they produce. For example, a translation moves every point the same distance in the same direction. A similarity transformation, which produces a uniform expansion or contraction of a form, moves each point out along a radial line from the origin.

Every transformation also preserves (leaves invariant) a unique set of properties in the transformed object. Translation, for example, leaves angles and lengths of lines unchanged; similarity also leaves angles invariant, but it changes the length of all lines, though it does maintain the proportions among them. The set of properties left invariant by a transformation thus serves as a second way to characterize the transformation. Of course, sets of transformations will share certain invariants. In the case of translation and similarity, both maintain angles and the proportions of lines.

These observations suggest an approach toward evaluating candidate growth transformations. It is most unlikely that our perceptual system has evolved so as to discriminate among all possible pairs of transformations or that all transformations have unique, perceptually salient (meaningful) consequences. It seems more reasonable to suppose that there will be classes of transformations defined by common invariants. Members of each class, while mathematically similar in some respects and different in others, will have "perceptually equivalent" effects; that is, they will produce the same style of change. In this view the style of change is established by the invariant characteristics of a class of transformations, rather than by a single, "best" transformation.

Delineation of the invariants associated with transformations provides a tool for selecting transformations for study in perceptual tests, and for specifying both the similarities among those transformations that are seen as growth and the differences between growth and nongrowth transformations. For a given event, a set of properties must be preserved for a particular style of change to be seen. If this framework provides a viable means for distinguishing the perceptual information specific to various styles of change, then it should be the case that: (a) transformations that maintain the same class of invariants should be seen as producing the same style of change; and (b) transformations that do not maintain the same class of invariants should not be seen as producing the same style of change. Mark et al.'s (1981) study of growth examined these predications.

Using Pittenger and Shaw's (1975a) initial findings and the global and universal constraints on the growth event that were established by the hydrostatic analysis of an idealized growing system (Fig. 2.6) which followed (Todd & Mark, 1981; Todd et al., 1980), Mark et al. (1981) distinguished three invariants that the cardioidal strain transformation preserved: (a) the angular coordinate of each point on the head, $(\theta'=\theta)$; (b) bilateral symmetry across the vertical axis; and (c) the continuity of all contours and their directions of curvature. Each of these geometric invariants corresponds to one of the *dynamic* constraints on the remodeling of the idealized hydrostatic system analogous to a growing human head as discussed earlier. In contrast, affine shear, the transformation that, in earlier studies, had little effect on perceived age, preserved only one of these properties: continuity of the profile contour (cf. Fig. 2.4 and 2.6).

Mark et al.'s (1981) proposal for distinguishing styles of change leads to the following prediction: Only transformations that maintain all three of the invariants associated with the hydrostatic model and the resultant cardioidal strain transformation should be perceived as growth. To examine this proposal, two new transformations, illustrated in Fig. 2.4, were devised. The first, *spiral strain* preserved all three invariants and, thus, should be seen as growth about as often as cardioidal strain. The second, *reflected shear,* preserved only two of the three invariants and therefore, like affine shear, should not be seen as growth.

These predictions were tested using two experimental tasks. For each transformation a sequence of five facial profiles was produced by applying increasing amounts of the transformation to the profile of a 5-year-old male (Fig. 2.10). In the first task, observers labelled the event depicted in the sequence of facial profiles. In this "free response" task, observers were not instructed to look for growth in the series of faces. Thus, the frequency of spontaneous references to growth served as a measure of the perceptual salience of each transformation as a model of growth. The second task required observers to rate each sequence as to how much like growth it appeared; this provided a converging measure of each sequence's depiction of growth.

Mark et al. (1981) were also able to incorporate two baseline series. The first was a sequence of actual profiles taken from longitudinal records. This actual growth series (see Fig. 2.10) permitted us to compare observers' judg-

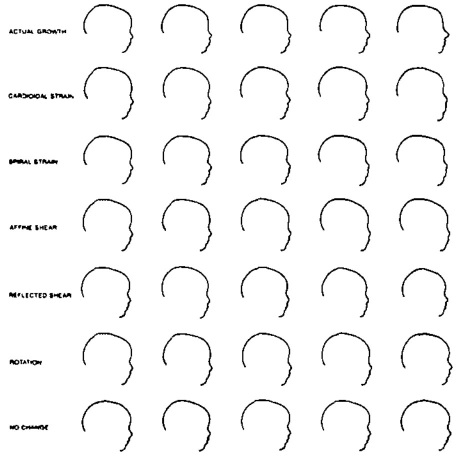

FIG. 2.10. Examples of profile sequences resulting from the four prospective growth transformations, actual growth and rotation. Note: From "Perception of Growth: A Geometric Analysis of How Different Styles of Change are Distinguished" by L.S. Mark, J.T. Todd, and R.E. Shaw, 1981, *Journal of Experimental Psychology: Human Perception and Performance, 7,* p. 859. Reprinted by permission.

ments of simulated growth to their judgments of the actual event. Although one transformation might be seen as more like growth than another, the better model might still not be judged as comparable to actual growth. The actual growth baseline established an upper limit on expectations for observers' performance on the experimental tasks. This baseline also equated the ranges of the various transformations to one another by finding the value of the free parameter that produced an equivalent amount of change in facial angle to that observed in the comparable profile in the actual growth sequence.

The second baseline series was used to determine the lower limit of expected performance. For this purpose, observers judged faces produced by a transformation that was not a reasonable candidate. Thus, a series of faces differing only in their degree of rotation from the upright position was used to establish this second baseline. As a rigid transformation, rotation cannot capture the nonrigid remodeling of facial proportions that characterizes growth.

The geometric framework for distinguishing different styles of change predicted that cardioidal strain and spiral strain would be seen as more like actual growth than affine shear, reflected shear, or rotation, because the latter do not preserve one or more of the three invariants. The results of both the free response and the growth rating tasks were consistent with these predictions (see Fig. 2.11). The categorical distinction between these two classes of transformations was further demonstrated by the finding that reflected shear, the transformation that preserved two invariants, was not seen as more like actual growth than affine shear, which preserved only one invariant.

In summary, Mark et al.'s (1981) study demonstrated that this class of transformations provides a naturally salient depiction of growth, when applied to the profile of a human head.

Before dismissing transformations that do not preserve all three "growth" invariants, it should be determined whether those transformations can produce changes that are perceived as growth under conditions where observers are strongly urged to see the transformed profiles as being at different ages. The free response and rating tasks did *not* press observers to try to see each sequence as growth. Perhaps, the effects of the two shear transformations would be seen as growth if the response required participants to look more carefully for age-related differences. To test this possibility, a paired comparison task was used. In contrast to a free response procedure, observers are forced to choose which face of each pair looks older in the paired comparison task. Hence, this task more strongly encourages observers to attend to age-level differences.

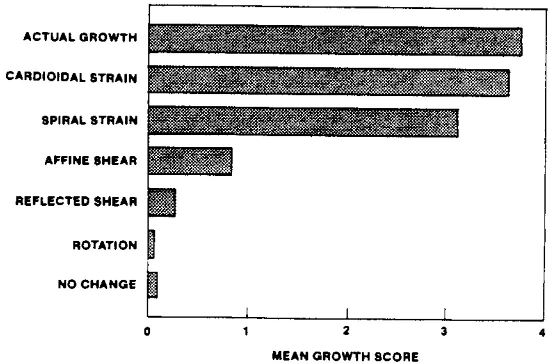

FIG. 2.11. Results of Mark et al.'s (1981) growth rating task. The mean growth scores for the cardioidal strain and spiral strain transformations were closest to that of the actual growth sequences. None of the other geometric transformations yielded a significantly greater score than that of the control sequence, "no change."

Mark and Todd (1985) conducted such a paired comparison task using the profiles from Mark et al.'s (1981) study. For each pair of profiles, the "older" profile was taken as the one which had been produced by the larger value of the free parameter of the transformation. (The effects of each transformation had been equated to one another and actual growth by determining their effects on facial dimensions that are observed to change during growth.) The basic pattern of results conformed to the predictions: Ordinal age was judged more "accurately" for pairs of profiles produced by transformations that preserved the three growth invariants than the other transformations. In addition, performance on profiles produced by the cardioidal strain and spiral strain transformations was virtually indistinguishable from judgments made on the actual growth profiles. In contrast, pairs of profiles produced by the transformations that did not preserve the three growth invariants were not judged reliably above chance. Mark and Todd also demonstrated that the physical differences produced by the two classes of transformations were equally discriminable. Thus, differences in perceived age judgments could not be attributed to differences in discriminability.

The results of these experiments support the proposal that the styles of change produced by the two classes of transformations are perceived categorically. A question still remains, however, about the perceptual equivalence of the growth transformations and actual growth. Looking more closely at Mark et al.'s (1981, Exper. 1 and 3 findings), some of the sequences produced by the "growth" transformations were not judged as comparable to the actual growth sequences on which they were based. The informational basis for the lack of complete comparability lies in certain craniofacial changes that are not captured by the growth transformations.

When observers did not have a prior expectation that any of the sequences depicted growth, they were more likely either to label as growth or assign a high growth rating to at least two of the actual growth sequences than for sequences produced by the growth transformations. On debriefing, participants indicated that those two actual growth sequences depicted age-related characteristics that were not modeled by the "growth" transformations. These changes included the development of the frontal sinus (a bump just above the bridge of the nose that enlarges noticeably after puberty) and changes in the size and shape of the nose. Under these "unconstrained" viewing conditions, the additional cues apparently increased the likelihood that growth would be noticed on the, admittedly, impoverished profile silhouettes employed (Mark et al., 1981, Exper. 1). The findings of another experiment supported this interpretation: Under less demanding conditions, where observers were told beforehand of the experimenter's interest in the perception of growth, the growth ratings and number of free response "growth" labels for the growth transformations were comparable to those of the actual growth sequences (Exper. 2 and 3). In addition, the paired comparison experiment also failed to differentiate between the transformations and actual growth. This suggested that while profiles in the actual growth sequences were "contaminated" by the effects of certain idiosyncratic forces, perceptual judgments of actual growth sequences were based largely on the effects of the universal gravitational constraint modeled by the class of cardioidal growth transformations. These extraneous features in the actual growth sequences effectively made this study a more conservative test of the model, since the sequences produced by actual growth should have been more salient than the sequences produced by the growth transformations.

Applying Cardioidal Strain to More Realistic Representations

One reason why the facial characteristics that were present only in the actual growth sequences proved to be so important to observers' judgments was that the facial representations used in these experiments were highly impoverished profile silhouettes lacking internal detail. Two demonstrations showed that the cardioidal growth model can produce the appearance of growth when applied to more detailed representations of the human face (Mark & Todd, 1983). In the first, the cardioidal strain transformation was generalized to a three-dimensional data base. A 13-year-old girl was photographed using a special camera for gathering a three-dimensional data base. From that data base, a computer was able to carve a bust of the child. The original data base was then transformed using the three-dimensional cardioidal strain transformation and a new bust was generated from the transformed coordinates. We predicted that this bust would depict the child as she appeared at an *earlier* age (Fig. 2.12). Those people who knew the girl at roughly the time she first entered school agreed that the growth transformation had produced an excellent likeness of her, with the possible exception of some missing "baby fat." When asked to judge the relative age of the two busts, naive observers overwhelmingly (356 out of 360) saw the bust produced by the cardioidal strain transformation as younger than the original. Unfortunately, this demonstration proved to be a one time opportunity in light of the prohibitive cost of producing additional busts.

In the second demonstration, Mark and Todd (1983) employed a technique whereby a "photographic-quality" representation could be digitized on a computer and transformed to produce a comparable portrait of the individual as he or she might appear at a later or earlier time. Figure 2.13 shows an example of the results of this procedure.

FIG. 2.12. The two, 3-dimensional busts used by Mark and Todd (1985). Right, the original bust of a girl, age 15 years, 1 month; left, the bust resulting from transformation of the original data structure by applying 3-dimensional cardioidal strain to make the head appear younger. Note: Figs. 2.12 and 2.13 [from Describing Geometric Information About Human Growth in Terms of Geometric Invariants" by L.S. Mark and J.T. Todd, 1985, *Perception and Psychophysics, 37,* p. 194. Reprinted by permission.

These demonstrations indicated that the growth transformations were applicable to more natural and realistic representations of faces.

To summarize, a series of studies have furnished evidence that information about craniofacial growth is specified by a class of transformations that preserve certain geometric characteristics of the head over the course of growth. From this work a geometric framework has emerged for describing the information about growth and, perhaps, other styles of change (cf. Todd, 1982). In each of the studies considered previously, the effects of a single transformation were perceived as growth over a number of different human heads. This finding shows that the perceptual information about the growth event must, indeed, be highly abstract; that is, it must be largely independent of the specific object undergoing change. In the next section, we consider just how abstract this information must be.

Abstractness of Information About Growth

As a mathematical formalism, a transformation can be applied to any structure. Thus, cardioidal strain could be applied to a drawing of any object, be it

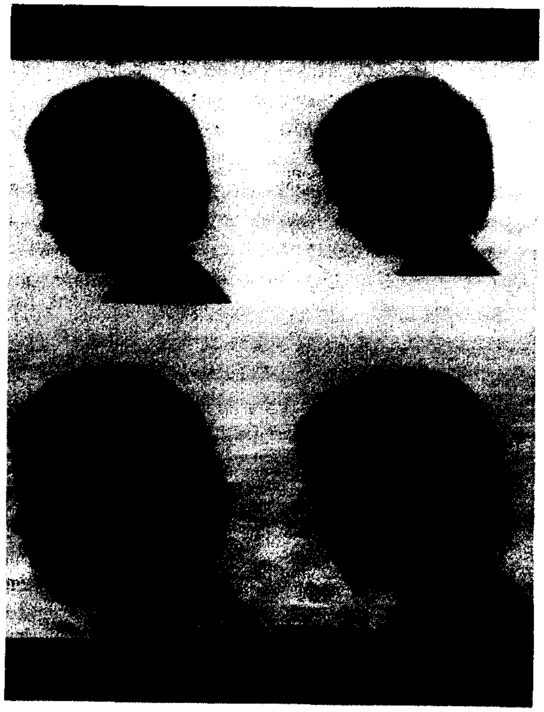

FIG. 2.13. A series of transformed photographs produced by applying cardioidal strain transformation to the actual photograph of a 12-year-old boy (lower right). The transformation producing the photographs on the upper row was intended to make the boy appear increasingly younger (left to right); the transformation producing the photograph at the lower left was intended to make the boy appear older. Note: From p.195.

a human face, an animal face, a flower, a rock, or even an abstract geometric form. However, we are concerned, not simply with transformations as mathematical formalisms *per se*, but with their use in characterizing the pattern of actual physical growth and in specifying the perceptual information for growth. We must then consider the problem of delineating the set of structures to which the growth transformation is physically and perceptually appropriate—at least as a growth transformation. From the standpoint of the physical event, all objects do not grow; and objects that do grow do not all do so in the same way. It seems likely that not every object transformed by cardioidal strain will be seen to grow.

The problem of specifying the range over which a transformation can be seen to produce a style of change, such as growth, is complex. First, it involves establishing the set of real objects for which the growth transformation is a physically accurate description of growth. Our hypothesis is that this set includes all normally growing heads. In light of the hydrostatic analysis (Fig. 2.6), heads of other mammals might well be expected to be members of the set. With respect to perception, we would predict that all objects for which the transformation is physically appropriate would be seen to grow. However, this set might be quite large. Cartoonists, for example, can make inanimate objects or imaginary animate objects take on the appearance of various ages. Thus, the information about a style of change like growth must be quite *abstract*, because a single globally applied transformation is applicable to a range of objects.

In this section we examine several studies that explore the domain of structures that can be seen to grow under our class of growth transformations. The outcome of the first set of studies emphasizes the diverse collection of objects that can be seen as growing under cardioidal strain. A second group of experiments begins to delimit the properties of objects that grow under these growth transformations.

An early study by Pittenger and Shaw (1975b) revealed that information about the age level of faces must be highly abstract. This work had been undertaken to assess observers' ability to judge age from facial photographs. The underlying rationale assumed that the transformation of facial structure produced by growth constitutes the primary information for age, and that information about age level exists throughout the craniofacial complex because of the global remodeling produced by growth. From yearbook photographs they constructed 15 longitudinal series with each set consisting of six photographs of a single person taken at roughly 1-year intervals between the ages of 12 and 19 (Grades 7 through 12). Cross-sectional series were also constructed from the longitudinal series; those sets consisted of photographs of six different individuals, one in each of the six grades. Observers were asked to make either ordinal or absolute age judgments for both the longitudinal and cross-sectional series.

Age judgments were quite accurate on both series. This result was consistent with the idea that age-level information was largely independent of the structural properties by which individuals were distinguished from one another. This does not mean that constancy of the underlying structure had no effect on age judgments. In fact, age estimates were slightly more accurate in the longitudinal condition than in the cross-sectional condition. However, a fixed identity was not required in order to make accurate ordinal age judgments.

By taking the longitudinal and cross-sectional series of photographs and masking out various parts of the photographs, Pittenger and Shaw were further able to demonstrate that age information is carried throughout the craniofacial complex. One mask blocked out all hair as well as the person's shoulders and neck, leaving the jaw untouched. This condition assessed the effects of hair and hair length on age judgments. A second mask blocked out all parts of the photograph except the eyes, eyebrows, nose, and mouth, thereby allowing them to assess information provided by the internal structure of the face independent of the outline of the craniofacial complex. The pattern of age judgments under the masked and unmasked conditions indicated that the presence or absence of either mask had surprisingly little effect on the overall ordinal relationships for either the absolute or ordinal age judgments. Observers, then, were able to utilize a variety of different facial areas for age information. The masks' effects were most noticeable on the absolute age judgments; people tended to overestimate the age of the masked photographs, with the degree of overestimation increasing with the amount of facial structure occluded by the mask.

In view of Pittenger and Shaw's (1975b) findings, it would be unreasonable as well as unparsimonious to suppose that growth information is specific to particular shapes of isolated features of an individual face at a given moment in time. Moreover, the information must be sufficiently general so as to apply across the facial features of all individuals during the period in which growth occurs. That is, it must be invariant across the range of faces that can be seen as growing. Two follow-up studies demonstrate the generality of the information specified by the growth transformations.

In an unpublished series of experiments, Mark replicated the paired comparison, free response, and growth-rating tasks discussed earlier using profiles of both sexes (the original study used only males) and different races (Black and Caucasian). The results of this replication showed that only the cardioidal strain and spiral strain transformations were perceived as growth over profiles of each race and sex. This evidence for a single pattern of morphological change across people of both sexes and different races is an important indication of the generality of the relationships captured by the class of growth transformations. To appreciate the significance of this result, one needs to understand that an important presupposition of traditional "normative" descriptions of craniofacial growth, derived from longitudinal data banks, is that any resulting description cannot be generalized from the population on which it was developed to other groups (e.g., from Caucasians to Blacks, males to females, etc.). Descriptions of growth, according to tradition, are highly limited in their generality, even to the point where one might hesitate to transfer a normative scheme developed in one geographic region to another region.

A second study (Pittenger, Shaw, & Mark, 1979) provides further insight concerning the generality and abstractness of the information specified by this class of growth transformations. Cardioidal strain and affine shear were applied to cartoon-like drawings of animal heads: the monkey, bird, dog shown in Fig. 2.14. Observers saw only the cardioidal strain transformation as having a significant monotonic effect on age, as indicated by their relative age judgments of the transformed animals.

Two possible explanations for this finding were considered. First, people may try to explain the visual analogy between growth and cardioidal strain in terms of some "unconscious inference" derived from people's knowledge of animals and the styles of change to which they are normally subject. This "cognitive mediation" account assumed that any change is perceived with reference to the types of changes normally undergone by that object. An alternative interpretation attributed the effects of the cardioidal strain transformation to specific changes produced by the growth process itself. That is to say, the information specified by cardioidal strain was *invariant* in spite of the marked changes produced by growth, and was independent of all but a modicum of properties of the structure to which it was applied. This "invariance hypothesis" did not appeal to cognitive mediation in order to explain the generality of the transformations across various animals.

To examine these contrasting proposals, the growth transformation was applied to an inanimate object, a Volkswagen "Beetle," which does not actually grow and for which no prior experience could have prepared observers to see the object as growing. The cognitive mediation account would require precisely such previous experience in order to recognize the object as growing under any transformation or set of conditions. Thus, evidence that observers can see a car as growing under cardioidal strain would damage the cognitive mediation account. The "invariance hypothesis" predicted that cardioidal strain would result in changes in age-level of the VW, assuming, of course that the VW satisfied the modicum of properties required to support the growth event.

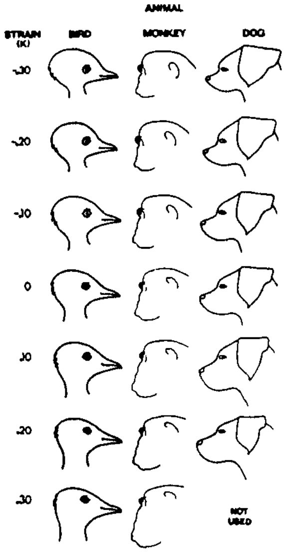

FIG. 2.14. Examples of the cartoon animals produced by applying cardioidal strain to the profiles shown at strain (k) equal to zero. Note: Figs. 2.14 and 2.15 from "Perceptual Information for The Age Level of Faces as a Higher Order Invariant of growth" by J.B. Pittenger, R.E. Shaw, and L.S. Mark, 1979, *Journal of Experimental Psychology: Human Perception and Performance, 5,* p. 482. Reprinted by permission.

Cardiodial strain and affine shear were applied to four different representations of the VW: front and side views, each view with and without cartooned in faces (Fig. 2.15). On a relative age judgment task, only the cardioidal strain transformation was perceived to have a consistent effect on the age of the VWs. The outcome, then, was inconsistent with the prediction of the cognitive mediation account. In accordance with the invariance hypothesis, observers seemed to be detecting highly abstract, "higher order" relationships independently of either the structure undergoing change or their experience in having seen that object grow previously.

But just how abstract was the information about growth? Can any structure be seen to undergo any style of change, or will only certain structures support a particular style of change?

Delimiting the Structures to Which Cardioidal Strain Produces Growth

Not all physical structures have the properties required to support every style of change. For instance, water and juice can flow, but paper and clothes will not. Paper and clothes, on the other hand, can be burned or cut, styles of change that are not supported by fluids, like water and juice. Similar restrictions are found with respect to the applicability of mathematical transformations that can be used for describing physical events. Recall that a *transformation* is a function that maps the elements of one nonempty set, called the "domain," into or onto the elements of another nonempty set, the "range." Just as physical events are defined only over a limited equivalence class, so mathematical transformations are defined over a restricted *domain*. (For example, the square root function is defined only over the domain of positive real numbers, unless one admits the use of imaginary numbers.)

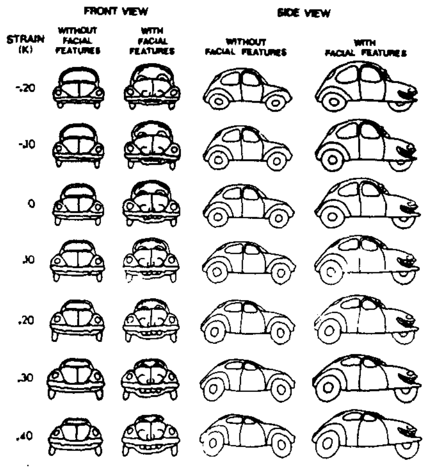

FIG. 2.15. Examples of the cartoon Volkswagens produced by applying cardioidal strain to the drawings at strain (k) equal to zero. p. 486.

These observations have important implications for efforts to describe perceptual information about events: Mathematical transformations should be seen as producing a particular style of change only over a restricted *domain* of objects. Although a transformation alters certain object properties, it must also preserve properties common to those structures that can support the style of change associated with that transformation. Just as physical events are limited in terms of the amount of change that naturally occurs (e.g., objects cannot stretch or bend indefinitely), so too a transformation may be seen as producing a style of change only within a limited range of change. Exceeding that range will produce the perception of a different style of change. For this reason, a complete description of a given style of change must delineate both the *range* of objects that are naturally produced by a given style of change and the *domain* of structures that can be subject to a particular transformation.

Although the findings of Pittenger et al. (1979) and Mark et al. (1981) have demonstrated the generality and abstractness of the information about growth provided by the cardioidal strain transformation, unpublished work by Pittenger and Shaw has shown that armchairs were not seen as growing older under cardioidal strain. Follow-up work by R.E. Shaw and Carello (1979) qualified this finding: Certain styles of armchairs and shoes could be seen as growing more consistently than other styles. This evidence provides an important challenge for research on event perception, namely, to delineate structural properties required to support the perception of a particular style of change.

Toward this goal, Mark et al. (1986) have begun to delineate the necessary structural properties of objects perceived to grow under the class of "growth" transformations. At the outset of their investigation, two object properties were of particular interest: the curvature of the object form and the deviation of the form from rectilinearity. These components contributed to what they intuitively thought of as the "biomorphicity" of an object. *Biomorphicity* literally means living shape or form, produced by processes such as growth or erosion. To that point, all objects seen as growing under the cardioidal strain transformation, including human and nonhuman heads, VWs, shoes, and armchairs, possessed a curved form, notable for the absence of straight lines and right angles. Naturally occurring biological forms are curved; the form of these curves has long fascinated biologists (Cook, 1911; Thompson, 1917/1942), architects (Stevens, 1974) and artists (Hogarth, 1965). Interestingly, when cartoonists attempt to animate objects, such as cars, tugboats or trains, they tend to curve straight lines and soften right angles. These observations are consistent with the proposal that biomorphicity is a necessary property in order for an object to be seen as growing under the class of growth transformations identified in previous work (Mark et al., 1981; Mark & Todd, 1985).

To evaluate the role of "biomorphicity," Mark et al. (1986) took a clearly nonbiomorphic face and transformed it in successive steps to make it look biomorphic. This was done by having an artist draw an inanimate, robot-like form (Fig. 2.16a) and progressively soften (curve) or "biomorphize" the form (Fig. 2.16b,c) into one that should be seen as growing (Fig. 2.16d). Although for these experiments the objects used were seen as "faces," "faceness" by itself is not a necessary structural property in order for an object to be seen as growing under cardioidal strain (R.E. Shaw & Carello, 1979). Faceness, however, is related to the applicability of cardioidal strain, because VWs with faces, when transformed with cardioidal strain, produce a stronger impression of growth than VWs without faces (Pittenger et al., 1979).

Three converging methods were used to examine the effects of growth (cardioidal strain) and nongrowth (affine shear and rotation) transformations on the continuum of profiles depicted in Fig. 2.16. Each procedure utilized series of five profiles (Fig. 2.17) produced by applying increasing amounts of each transformation to the four profiles comprising the biomorphic continuum.

A paired comparison procedure (Exper. 1) showed that observers' ability to discriminate the relative age levels of two profiles within a transformation series was a function of both the transformation used and the structure to which the transformation was applied (Fig. 2.18). That is, judgments of the "nonbiomorphic" robot profiles were equivalent for the growth and nongrowth transformations. However, as the profile became more biomorphic, the ordinal age judgments became more accurate for the pairs of profiles produced by the cardioidal strain (growth) transformation; in contrast, no such increase was observed for the nongrowth transformations. This interaction between transformation and structure was also found on a relative age judgment task (Exper. 2) and on an unpublished identity task, modeled after Pittenger and Shaw's (1975a) first and third experiments, respectively. An additional experiment demonstrated that the four profile series were comparable in their discriminability.

These data document an interaction between transformation and structure. As such, they constitute evidence for the importance of defining the domain over which a particular style of change is defined. In addition, the characteristics of a structural continuum, which interacts with a class of transformations in producing a given style of change, are indicative of at least some of the defining structural properties required to support that style of change.

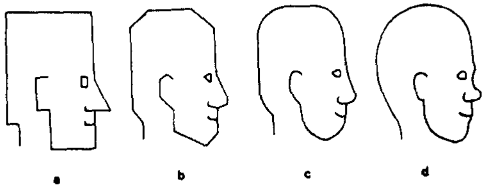

FIG. 2.16. The standard series of profiles employed by Mark et al. (1986). Profiles b, c, and d were created by applying successive amounts of a softening transformation to the robot profile, a . Note: Figs. 2.16, 2.17, and 2.18 from "Structural Support for the Perception of growth", by L.S. Mark, B.A. Shapiro, and R.E. Shaw, 1986, *Journal of Experimental Psychology: Human Perception and Performance, 12,* p. 152. Reprinted by permission.

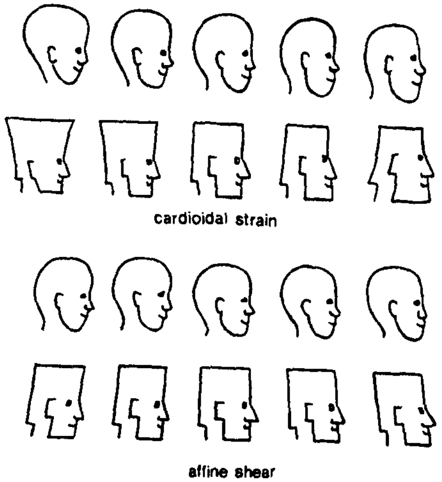

FIG. 2.17. An example of the stimulus sequences created by Mark et al. (1986, Exper.1). (Positive and negative values [+ or −10 degrees] of the cardioidal strain and affine shear transformations were applied to the robot and human profiles, Fig. 16, panels a and d.) p.153.

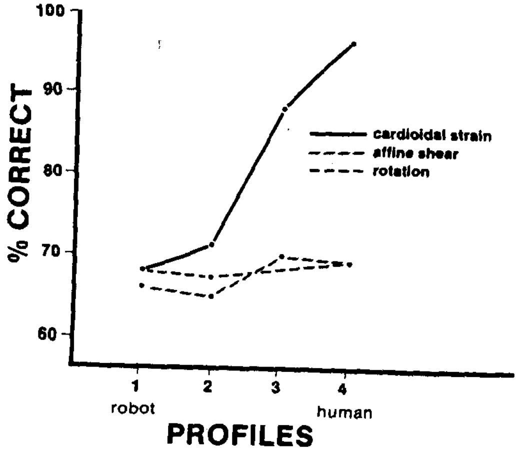

FIG. 2.18. The mean percentage of correct responses given by subjects is shown for the cardioidal strain, affine shear, and rotation transformations when applied to the continuum of heads depicted in Fig. 2.16. (From Mark et al., 1986, Experiment 1).

SOCIAL IMPLICATIONS OF THE ECOLOGICAL APPROACH TO PERCEPTION

This chapter has examined some influences on our investigation of the perception of craniofacial growth. Our plan of study was grounded on the Gibsons' ecological approach to perception: We began by examining the event itself in order to identify the natural constraints governing the global remodeling of the craniofacial complex. It was at this stage of our project that D'Arcy Thompson's treatise on morphogenesis provided numerous insights, which ultimately made it possible for us to develop a formal description of the perceptual information for craniofacial growth. The resultant perceptual research has demonstrated that the effects of a specific class of transformations were consistently perceived as growth over a broad range of craniofacial structures. It is important to emphasize that the properties of this class of growth transformations were specific to the natural, biomechanical constraints governing the growth event.

Looking at the outcome of this investigation as a whole, it becomes apparent that the ecological approach toward understanding perception addresses a seminal problem in the field of social psychology: An essential part of people's existence and well-being is the belief that they share the same physical reality. As Asch's (1956) work on social conformity has shown, it can be deeply disturbing to an individual when that belief is shaken. His experimental situation was so disturbing because it violated a basic premise of the subject's existence, namely, that people share the same physical reality.

The Gibsons' ecological approach to perception has shown that his belief in a shared reality rests, in part, on the *consistency* and *regularities* in sensory stimulation. Their ecological analysis of the available optical information, both at a glance and over time as the observer moves around the world, shows that the consistency of information provided by our senses rests on a solid foundation. For example, locomotion results in a pattern of optical flow specific to the direction of movement; parts of our visual field go out of view progressively in a manner specific to the environmental layout and the path of locomotion. In addition, the Gibsons have also observed that changes in observers' point and direction of observation—such as those that might result from movement of their eyes, head, or bodies—produce a change in the pattern of optical stimulation that is specific to their movement and the environmental layout.

Moreover, the ecological survey of the natural constraints on the layout of the terrestrial/social environment establishes a lawful, physical basis for optical information that is *specific to* its source. It is precisely this lawful, physical relationship between observers and their environment that lies at the heart of our collective belief in a shared "physical reality,“ a belief crucial to our existence and well-being. An ecological survey, then, addresses this fundamental social psychological problem, and the ecological approach to perception is, at heart, a social perspective on perception. It is directed toward identifying a lawful basis for the consistency of perceptual experience between and within individuals.

The investigation of craniofacial growth underscores the inherently social basis of the ecological approach to perception: Our objective was to identify the common basis on which observers perceive the same style of change across a myriad of different structures. The ecological approach further encouraged us to consider the adaptive significance of this growth event and its implications for various actions. (The remainder of this volume examines many of these implications.) Thus, several researchers have examined the adaptive significance of the perception of age level (see Berry & Zebrowitz-McArthur, chap. 4; and McCabe, chap. 5) for discussions of this and related issues. The psychosocial implications of those changes also motivated our concern with the application of this work to clinical treatment of children with craniofacial disorders. Our investigation of craniofacial growth, then, has turned out to be more than a study of perception. It has provided an example of how the specification of information about an event establishes a framework in which certain social psychological problems can be examined.

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