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# The Perception of Human Growth

*How does the human head change shape from infancy to adulthood? Tests of the way most people perceive the process show that growth can be represented by a particular type of geometric transformation*

by James T. Todd, Leonard S. Mark, Robert E. Shaw and John B. Pittenger

The human body, like any other growing organism, changes dramatically in form as it develops from infancy to adulthood. Everyone has an intuitive understanding of the morphological changes involved in human growth. It is easy to distinguish between normal maturation and other types of biological change such as a gain in weight or a disfiguring disease, yet the ability to perceive these changes as distinct events has never been explained adequately.

In order to comprehend better how people perceive the phenomenon of growth it is first necessary to describe the phenomenon in rigorous terms. One approach is to consider a growing object as a set of points. If the analysis is limited to two dimensions, the position of any point can be specified by the values of two coordinates, which are often designated by the variable names $x$ and $y$. The concept of a geometric transformation serves to describe how the coordinates of a set of points can be systematically altered by growth or some other process. A transformation is designated by introducing two new variables, $x'$ and $y'$, as functional relations of $x$ and $y$.

It is important to recognize that any system of equations relating $x$ and $y$ to $x'$ and $y'$ can be interpreted in two ways. In one sense such equations represent a change in the original coordinate system, as is commonly observed when data are transformed from rectangular coordinates to polar ones [*see top illustration on page 4*]. In another sense, however, the equations represent a change in an object within a fixed coordinate system. The latter interpretation is easily demonstrated by considering the different ways a square object can be transformed [*see bottom illustration on page 4*]. For example, one of the simplest ways of transforming a square is to rotate it. A rotational transformation changes the coordinates of every point on the object being rotated; although every point is displaced, however, there are more abstract properties of the object, such as its overall shape or the distance between each pair of vertexes, that are not affected by the rotation. In the language of mathematics these properties are said to remain invariant.

A geometric transformation can often be perceived as a distinct style of change independent of the particular objects to which it is applied. The abstract event of rotation can easily be recognized when it is applied to a triangle, a square or even an object one has never seen before. One possible basis for distinguishing different transformations is to compare the different properties they leave invariant. For example, it is easy to see that a rigid transformation such as rotation preserves the angles and the distances between the points of an object. By the same token, a conformal transformation preserves the angular coordinate of every point in a polar coordinate system, an affine transformation preserves parallel lines and a reflective transformation preserves bilateral symmetry about a specific axis.

One of the first people to recognize that the concept of a geometric transformation might be useful for describing morphological change was the Scottish naturalist D'Arcy Wentworth Thompson. In his classic work *On Growth and Form*, first published in 1917, he argued that the phylogenetic progression from one species to another and the ontogenetic progression from infant to adult are both processes involving the entire organism rather than a succession of minor alterations of individual body parts. His primary evidence for this assertion was his ability to represent apparently complex changes in morphology as the geometric distortion of a grid placed over an evolving or growing organism. Thompson also contended that these geometric distortions generally result from physical forces in an animal's environment, the effects of which can often be described by a single mathematical transformation.

Thompson's drawings are particularly instructive because they illustrate the fundamentally abstract nature of biological change and the ability of different observers to perceive change. His special insight was that the presumably complex processes of growth and evolution could be adequately represented with a simple object such as a square grid just as easily as with a complex object such as a human head. Thompson gave no physical or biological explanations for the phenomena he was modeling. In most cases he did not even attempt to describe the phenomena with mathematical equations. The power of his approach lay primarily in the domain of visual perception. Thompson's drawings made it possible to "see" how different transformations operate, even though he did not formally analyze their effects with any degree of precision.

Although Thompson's methods could be criticized for their inherent subjectivity, it is worth noting that a reliance on perception seems to be present in almost every attempt that has ever been made to study the morphology of either living or inert forms. In biology, for example, the taxonomic system of classification depends on the fact that human observers are able to agree on the various similarities and dissimilarities between the morphological characteristics of different biological organisms. Our own research on the growth of the human head is consistent with this tradition. The basic methodology is to select geometric transformations that could potentially describe the phenomenon of growth, and to evaluate each prospective transformation by how it is perceived.

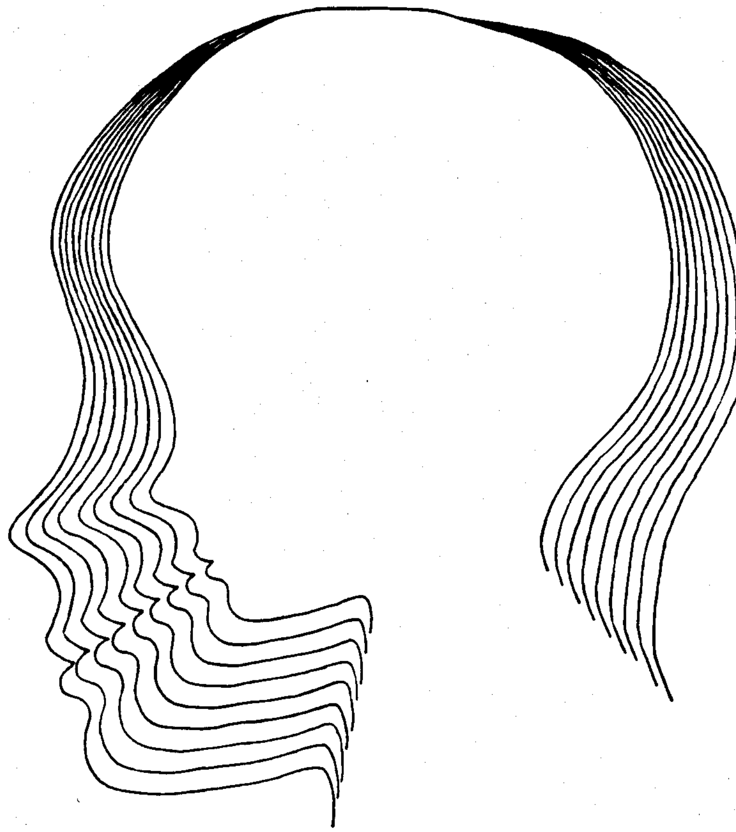
Our interest in the problem dates back to 1972 when two of us (Shaw and Pittenger), who were then working at the University of Minnesota, began to investigate the changes in craniofacial morphology that provide information for the perception of age level. Other investigators had previously noted that the head of a newborn infant has an exaggerated cranium and a diminutive face, but that during development the face grows more rapidly than the cranium, resulting in a change in facial angle. We wanted to show that similar effects could be produced by a single geometric transformation, and that such a transformation would be perceived as growth when it was applied to human craniofacial profiles in the absence of all other changes.

The initial series of experiments examined two transformations, cardioidal strain and affine shear, both of which are capable of producing the changes in facial angle that are normally characteristic of craniofacial growth. The cardioidal-strain transformation is so named because it transforms a circle into the heart-shaped form called a cardioid. The affine-shear transformation, in contrast, transforms a circle into a diagonally oriented ellipse; it is part of a more general class of affine transformations whose common invariant is that they preserve parallel lines.

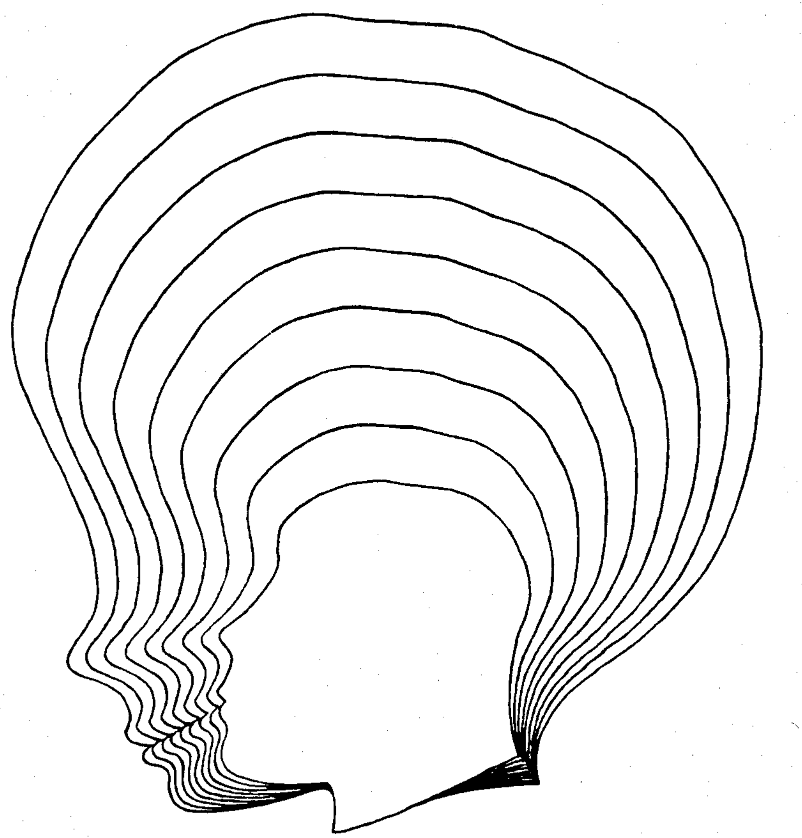
A "relative-age judgment" task was arranged to evaluate the effectiveness of these prospective growth transformations. Observers were presented with the profile of a human head and were asked to assign the profile an arbitrary number, say 100. They were then shown some additional profiles that had been systematically altered in various degrees by the cardioidal-strain and affine-shear transformations [*see illustration on page 6*]. The observers were told to rate the age of each profile with respect to the first. Thus if an observer assigned 100 to the first profile and a subsequent profile was perceived to be twice as old as the first one, the latter profile would be assigned the number 200.

The results showed that the cardioidal-strain transformation produced large changes in the perceived age of the facial profiles and that the affine-shear transformation produced little change. The contrasting perceptual effects of these transformations suggest strongly that the necessary information for specifying growth is inherently abstract. Indeed, on examining the profiles it is difficult to isolate a specific dimension along which the two transformations differ. They both affect the facial angle and the overall shape of the head, but the changes produced by cardioidal strain resemble growth or evolution, whereas affine shear produces nothing more than an unidentifiable distortion. It should also be noted that the cardioidal-strain transformation is perceived as growth even though the stimulus profiles lacked all the internal detail normally associated with human faces. This observation provides some evidence that the perception of growth need not depend on any particular set of object properties.

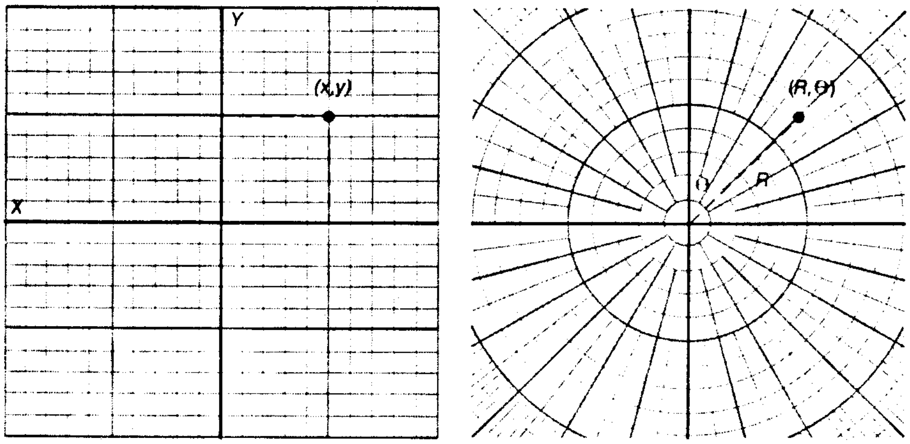
We have since performed a follow-up series of experiments that demonstrate this last point even more dramatically. We relied on the same procedure for making relative-age judgments as before, but this time we did not use hu-



**GROWTH OF A HUMAN HEAD is simulated in this sequence of computer-generated profiles obtained by the use of a geometric procedure called a revised cardioidal-strain transformation. Sequence proceeds from infancy (*innermost profile*) to adulthood (*outermost profile*).**



**EVOLUTION OF THE HUMAN HEAD is suggested by this somewhat different sequence of profiles generated by a variant of the revised cardioidal-strain transformation. Sequence proceeds from a "Neanderthal" man (*innermost profile*) to a futuristic being (*outermost profile*). Both sequences were drawn with the aid of a computer at the University of Connecticut.**




$x = R \sin \Theta$
$y = R \cos \Theta$

$R = (x^2 + y^2)^{1/2}$
$\Theta = \tan^{-1} y/x$

**GEOMETRIC TRANSFORMATIONS for converting data back and forth between a rectangular coordinate system (*left*) and a polar one (*right*) are given by pairs of equations at bottom.**

RIGID ROTATION
(POLAR COORDINATES)

$\Theta' = \Theta + k$
$R' = R$

CARDIOIDAL STRAIN
(POLAR COORDINATES)

$\Theta' = \Theta$
$R' = R(1 - k \cos \Theta)$

SPIRAL STRAIN
(POLAR COORDINATES)

$\Theta' = \Theta$
$R' = R(1 + k|\Theta|)$

REVISED CARDIOIDAL STRAIN
(POLAR COORDINATES)

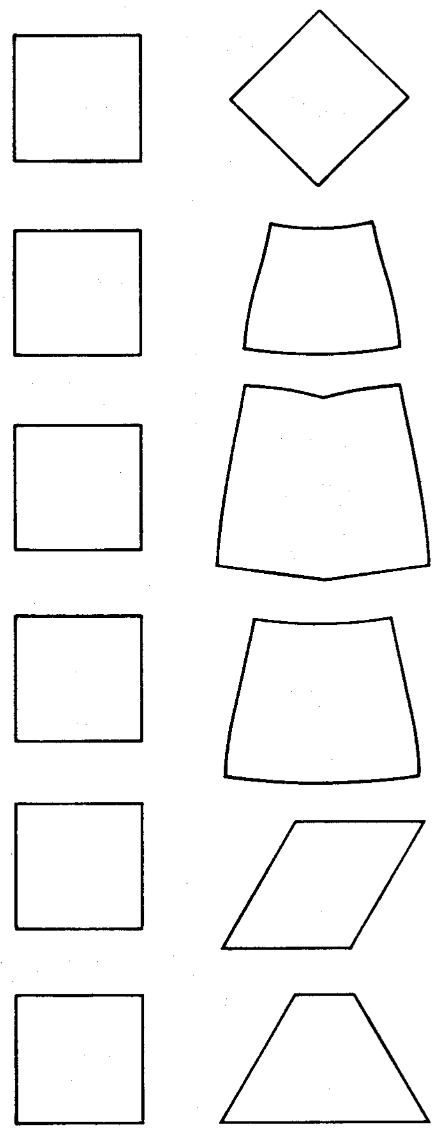
$\Theta' = \Theta$
$R' = R(1 + k(1 - \cos \Theta))$

AFFINE SHEAR
(RECTANGULAR COORDINATES)

$Y' = Y$
$X' = X + Y \tan \Theta$

REFLECTED SHEAR
(RECTANGULAR COORDINATES)

$Y' = Y$
$X' = X + (Y \tan \Theta)\ (X/|X|)$



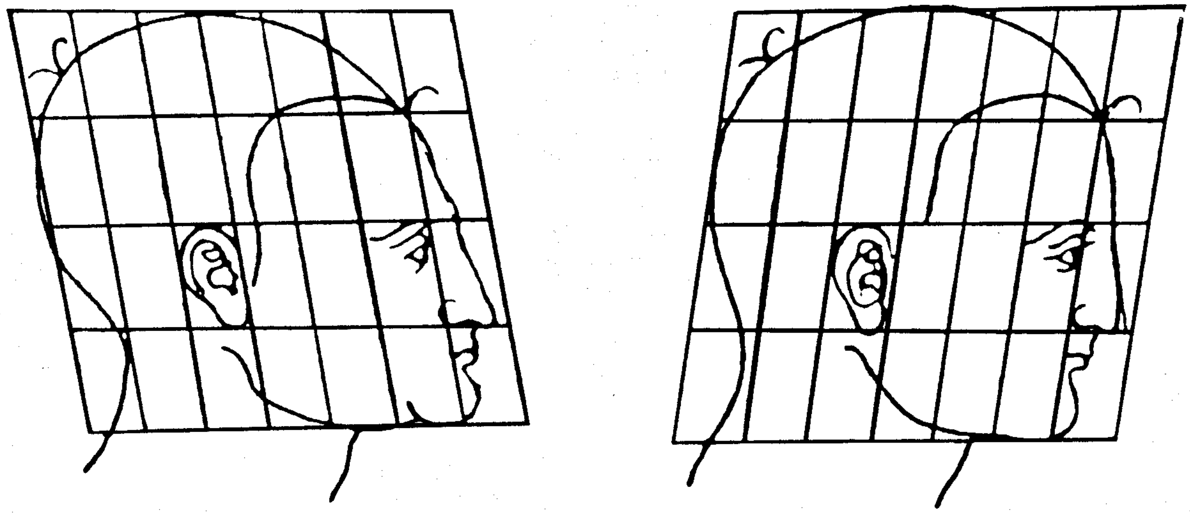
**SHAPE OF AN OBJECT can be altered within a fixed coordinate system by applying a variety of geometric transformations, six of which are listed by name and also represented in the form of equations at the left. (The fixed coordinate system in each case is given in parentheses.) The effects of the different transformations on a square object are shown at right. A conformal transformation such as spiral strain or the two kinds of cardioidal strain depicted has the special property of preserving the angular coordinate of every point in a polar coordinate system.**

man facial profiles as stimuli. In one experiment observers were presented with profile drawings of birds, dogs and monkeys that had been systematically transformed with various amounts of cardioidal strain and affine shear. As in the earlier experiment with human facial profiles, the results showed clearly that the cardioidal-strain transformation was perceived as growth, whereas the affine-shear transformation again had little effect on perceived age.

The results of a second experiment were even more revealing. Observers were presented with transformed drawings of front and side views of Volkswagen "beetles," both with and without facial features drawn in to make them look more facelike. The cardioidal-strain transformation produced large changes in the perceived age of all these stimuli in spite of the fact that Volkswagens do not grow. The affine-shear transformation produced almost no changes. These results suggest that observers were responding to growth as an abstract type of change, much like rotation, which is easily recognized regardless of the objects to which it is applied.

In a more recent series of experiments done at the University of Connecticut we have attempted to determine whether the effects of cardioidal strain are perceptually equivalent to the morphological changes normally produced by the actual growth of a human head, and whether other transformations not previously examined might be perceived similarly. Our stimuli consisted of many different sequences of five facial profiles, each arranged from left to right on a single page [*see illustration on page 7*]. Observers were instructed to rate each sequence from 0 to 4 on the basis of its resemblance to actual growth and to indicate the direction in which growth appeared to be occurring. The sequences were designed so that the perceived age of the different profiles would increase sequentially from left to right. For those sequences that generally produced low ratings, however, there were a few instances where subjects reported that the direction of growth seemed to be in the opposite direction. Whenever this occurred, the rating was interpreted as a negative number.

The stimulus sequences were prepared from a selection of long-term growth records originally collected by the Child Research Council of Denver, Colo., as part of a study lasting from 1925 to 1970. One group of stimuli, the actual growth sequences, provided a convenient base-line measure for evaluating different transformations. Each actual growth sequence consisted of facial profiles of a single individual at five different ages. These profiles were traced directly from X-ray plates made with small amounts of radiation so that the outline of the skin was clearly visi-

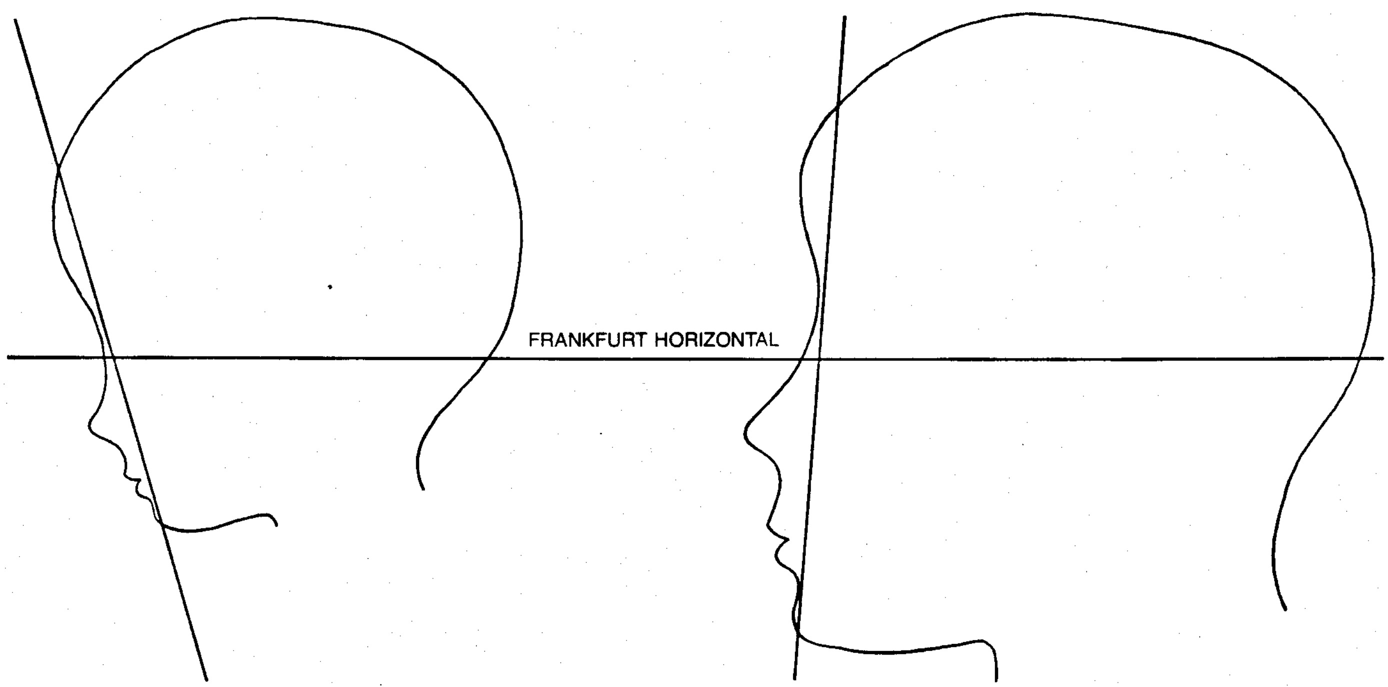


**PIONEERING ATTEMPT** to apply the concept of a geometric transformation to the description of morphological change was made by the Scottish naturalist D'Arcy Wentworth Thompson, who succeeded in representing all kinds of apparently complex changes in morphology in terms of the geometric distortion of a grid placed over an evolving or growing organism. In this illustration of the basic technique, taken from his 1917 book *On Growth and Form*, Thompson superposed a pair of square grids, distorted by different degrees of affine shear, over two line drawings of human heads that he copied from the 1613 edition of Albrecht Dürer's *Treatise on Proportion*.

ble. The overall change in facial angle between the youngest profile and the oldest one was used as an index of the amount of deformation that had resulted from actual growth. A second group of stimuli, called transformation sequences, were mathematically computed on a digital computer by systematically transforming the youngest profile of each actual growth sequence. Specific values of cardioidal strain, spiral strain, affine shear, reflected shear and rotation were selected for each individual so that the overall change in facial angle would be identical with the change that had occurred in the individual as a result of normal growth processes. There was also a group of control sequences in which all five profiles were identical. These provided an additional base-line measure for evaluating transformations that did not resemble growth.

The experiment was carried out with 40 subjects. As might be expected, the highest mean ratings were produced by the actual growth sequences. The ratings were slightly lower for cardioidal strain and lower still for spiral strain. None of the other transformations produced significantly greater ratings than the control sequences did.

This basic pattern of results has since been replicated with a variety of other procedures. For example, a free-response task was administered in which subjects were not told of our specific interest in growth. They viewed the same profile sequences the subjects in the earlier experiment had and were asked to describe, if possible, how each pattern of change might have come about in a natural environment. As we expected,

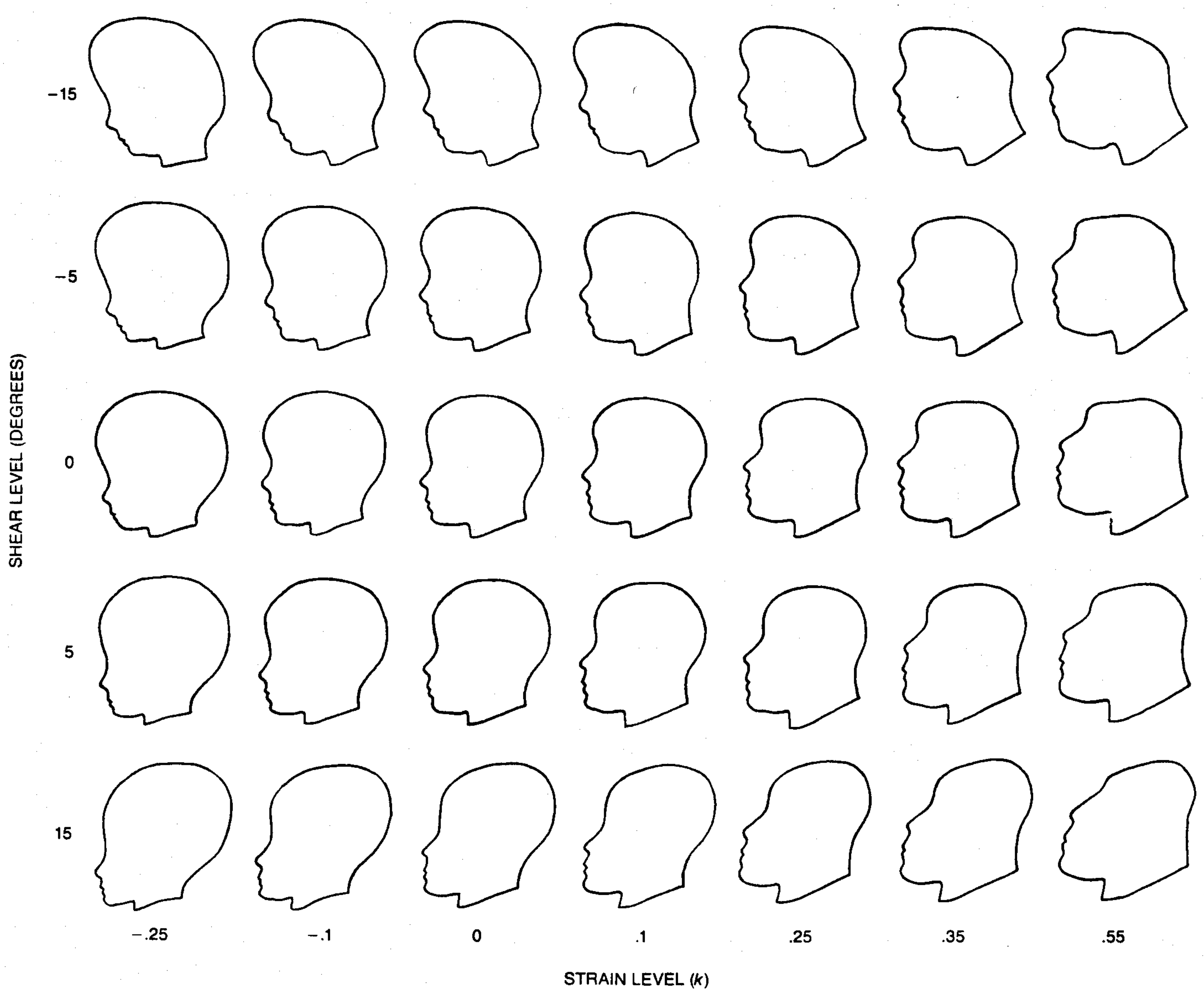



**FACIAL ANGLE** changes during growth. In the authors' work the facial angle is defined by the intersection of two lines. One line, the Frankfurt horizontal, passes through the top of the earhole and the bottom of the eye socket. The other connects the most prominent part of the chin with the deepest part of the depression just above the nose. The profile at the left is of an infant; the one at the right is of an adult.

there was a high incidence of growth-related responses for the cardioidal-strain, spiral-strain and actual-growth sequences, and there were almost no growth-related responses for the affine-shear, reflected-shear, rotation and no-change sequences. These findings appear to be general. The same basic pattern of results has been observed for more than 85 percent of the subjects who have participated in these experiments or related ones.

It is possible to conclude from these results that the perception of growth is surprisingly selective. Of the five transformations examined, only cardioidal strain and spiral strain are consistently responded to as growth. These transformations have much in common mathematically. They both preserve the angular coordinate of every point in a polar coordinate system, and they both produce a cusp, or indentation, at the top of the object being transformed. The consistency of subjects' responses in these experiments and the fact that cardioidal strain is perceived as growth almost as readily as growth itself provide strong evidence that this particular type of change is a close approximation to the overall effects of maturation in a variety of naturally occurring situations. After all, it would be difficult to imagine that observers would selectively respond to a particular transformation as growth if that transformation had no relation to the actual event seen in their everyday experience. Our results suggest, therefore, that human heads are somehow constrained to grow cardioidally.

Why do heads grow in such a regular manner? Thompson addressed the issue by suggesting that the biological processes of growth and evolution are somehow integrated with the physical forces in an animal's environment. He noted that the application of pressure or stress on living tissue seems to have a direct influence on the control of growth. There are many examples of this phenomenon. The soles of one's feet grow thicker the more one walks on them. Bone becomes thick where stress is high and thin where stress is low. Even the internal structure of a bone reflects the environmental forces to which it has been subjected. When one examines the interior of any weight-carrying bone, there is a clearly defined lattice structure that bears a striking resemblance to the lines of stress produced by the bone's natural load. The biological mechanism by which growing cells are aligned is not entirely understood. One promising hypothesis is that stress generates an electric field within the growing material and that electrically charged molecules and ions align themselves in exactly the same way that iron filings become aligned in a magnetic field. This is an important area of research, but it is nec-

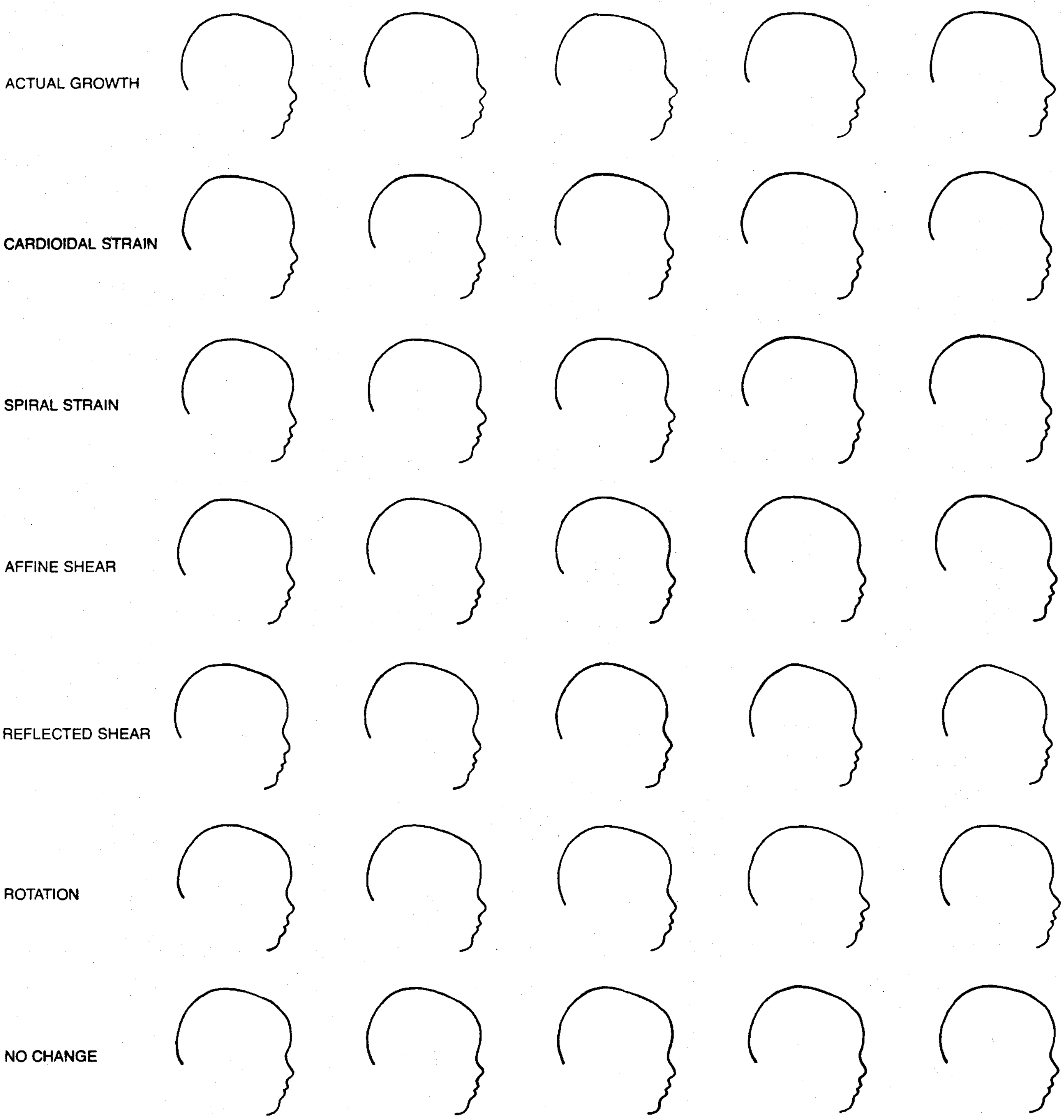



**ASSORTED PROFILES of a human head were produced by applying various combinations of affine shear and cardioidal strain to the profile of a 10-year-old boy. In an early experiment conducted by two of the authors (Shaw and Pittenger) at the University of Minnesota observers were asked to judge the relative age of each of the transformed profiles with respect to the untransformed original (which appears here at the position where both the shear and the strain are equal to zero). The results demonstrated that the cardioidal-strain transformation accounted for much greater changes in the perceived age of the craniofacial profiles than the affine-shear transformation.**

essary to recognize that such research can never explain why growth is cardioidal. Even if one understood in complete detail how cells respond to stress, one could not predict changes in morphology unless one also understood the patterns of stress to which the growing material is subjected.

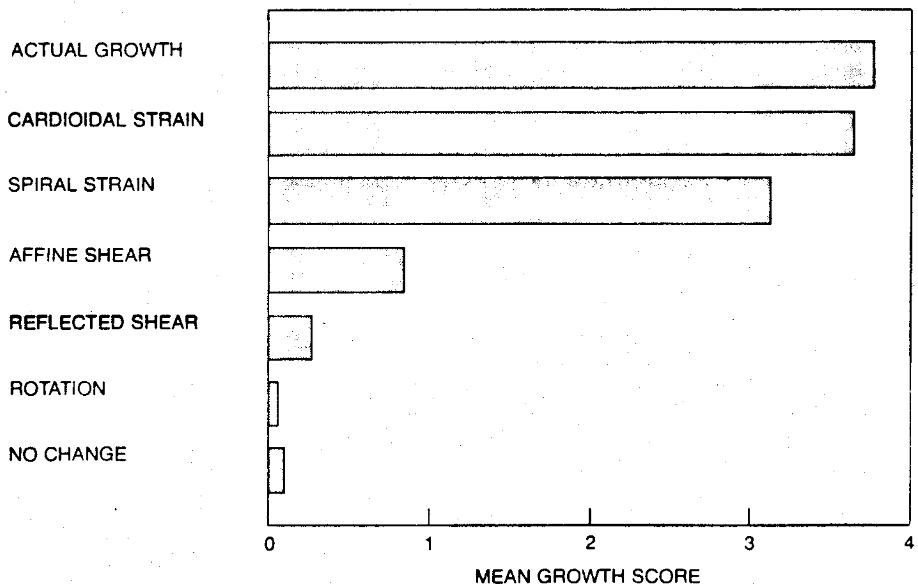
Following this line of argument, it seems reasonable to speculate that if heads grow cardioidally, then the patterns of stress to which heads are subjected must also be cardioidal. In order to test this hypothesis we considered the craniofacial complex as a spherical tank filled with fluid. From elementary hydrostatics we knew that the amount of pressure at any point on the surface of the tank is directly determined by the amount of fluid above it. This pressure can easily be expressed as a function of position by an equation that relates the pressure to the radius of a sphere multiplied by a constant representing the product of the force of gravity and the density of the fluid. If the structure of the head is remodeled in accordance with this pressure gradient, a new transformation is obtained.

As it happens, the new transformation




**RECENT SERIES OF TESTS was designed to compare various prospective growth-simulating transformations, including cardioidal strain, with actual growth. For this purpose the authors used as stimuli a number of different sequences of facial profiles, each sequence arranged from left to right on a single page. Forty observers were asked to rate each sequence from 0 to 4 on the basis of its resemblance to actual growth and to indicate the direction in which growth seemed to be occurring. The sequences were prepared from long-term growth records collected by Child Research Council of Denver, Colo., from 1925 to 1970. Unchanging sequence (*bottom*) served as a control.**

is strikingly similar to the cardioidal-strain transformation originally devised by two of us (Shaw and Pittenger). For this reason it is referred to as a revised cardioidal strain. Both styles of change preserve the angular coordinate of every point in a polar coordinate system, and both will transform a circle into a cardioid. The primary difference between them is that the revised cardioidal-strain transformation affects the size of an object in a way that is more in keeping with the effects of actual growth.




**RESULTS OF THE EXPERIMENT illustrated on page 140B are presented in this bar chart. The mean growth score for the cardioidal-strain transformation was closest to that of the actual growth sequence, with the spiral-strain transformation coming in not very far behind. None of the other prospective geometric transformations yielded a significantly greater score than that of the control sequence ("*No change*"). This basic pattern of results, suggesting that heads grow cardioidally, has since been replicated by the authors in a variety of other experiments.**

The analysis suggested above is of course oversimplified. Heads are not perfectly spherical and there are other sources of stress operating on the craniofacial complex besides the force of gravity. The resulting model can be thought of as a kind of ideal case, similar to analyzing a falling body without considering air resistance. Such a model can be quite useful if it helps one to appreciate the overall influences on craniofacial growth or provides one with a means of approximating the course of growth in any given individual.

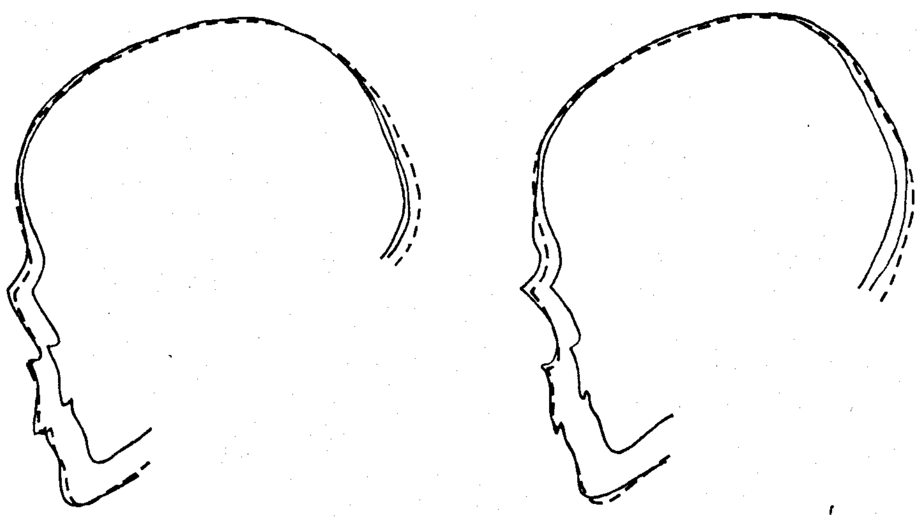
This brings us back to the question of what the relation is between growth and the perception of growth. We have already demonstrated that the cardioidal-strain transformation is a perceptually accurate model of growth, but is it accurate enough to satisfy the needs of a clinician, for example, in planning corrective treatment for patients with facial anomalies? We have begun experiments designed to answer this question.

Our procedure is quite simple. Working with the same series of longitudinal X rays of the skull that we used in our earlier perceptual experiments, we trace the outline of a young child's skull and try to predict how the skull will be shaped on reaching maturity. We then compare our prediction with an X-ray image of the same individual made during adulthood.

A fundamental issue that had to be addressed before we could make reliable predictions is that our model does not suggest precisely how to orient a head before applying a transformation. Although our earlier research has indicated that the cardioidal-strain transformation is perceived as growth over a considerable range of facial orientations, there is a noticeably large effect of orientation when the faces are compared on a point-to-point basis. It is therefore necessary to have a specific procedure for orienting a head so that different investigators can make the same predictions on different occasions. Our solution to this problem, arrived at through trial and error, is to orient each X-ray image over a sheet of polar graph paper. We are able to get satisfactory predictions by placing the tip of the chin at 160 degrees and placing the point where the bone at the base of the nostrils meets the rest of the skull at 125 degrees, so that the origin of the graph paper is midway between the two points where the skull intersects the horizontal axis.

After an X ray is properly oriented a continuum of transformed skull outlines is generated with successively larger values of the revised cardioidal-strain transformation. The resulting family of forms constitutes a predicted path of craniofacial growth. According to our model, an individual might grow at varying rates at different times, but barring some unexpected trauma, the direction of growth should always follow the predicted path. This hypothesis can be tested by comparing the predicted skull outlines for any given individual with an actual X-ray image made at maturity. The results of this procedure for two typical subjects are presented in the illustration below. It should be clear from the figure that our cardioidal model of craniofacial growth is able to generate surprisingly accurate predictions.

There are several important clinical applications that could eventually result from this research. A major problem confronting cosmetologists, orthodontists and oral surgeons is their present inability to predict how a given med-



**REVISED CARDIOIDAL-STRAIN TRANSFORMATION was tested by fitting it to tracings of actual X-ray pictures made of the same person at different ages. The colored outlines at the left were traced from the X-ray pictures of a female at the ages of seven and 22; the colored outlines at the right were traced from the X-ray pictures of a male at the ages of eight and 19. The broken black outlines are the transformed versions of the younger profile of each person. The values of the revised cardioidal-strain transformation were chosen so that the transformed younger profile in each case would be as similar as possible to the actual older profile.**

ical treatment will interact with normal growth processes. For this reason individuals who suffer from craniofacial abnormalities must often wait until they reach maturity before corrective treatment can be started. The ability to predict growth may also provide clinicians with a useful tool for the diagnosis of craniofacial abnormalities. If a human head is normally constrained to grow along a cardioidal path, then significant deviations from the path are likely to indicate that normal growth processes have somehow gone awry. By comparing a patient's actual craniofacial development with the predicted cardioidal path, a clinician could gain important insights about the underlying causes of abnormal growth and could reasonably assess what the patient would have looked like under more normal conditions. The latter information would be particularly useful for establishing the goals of corrective treatment.

There are many other issues that must be resolved before we fully understand the overall regularities of craniofacial growth and the ability to perceive growth as a distinct type of change. One such issue that we are currently investigating is the pattern of growth in other parts of the body in relation to the head. The first biologist to study this problem with a transformational approach was P. B. Medawar. In 1944 he reported a geometric transformation that adequately describes the changes in human body proportions observed from infancy to adulthood. Our own research in this area has been primarily concerned with demonstrating the perceptual salience of Medawar's transformation as an abstract type of change. Our results so far indicate that Medawar's transformation is similar to cardioidal strain in that it is perceived as growth even when it is applied to unfamiliar objects.

Another related issue that we are currently investigating is the apparent similarity between growth and evolution. In the course of our perceptual research we were surprised to discover that by reversing a sign in the revised cardioidal-strain transformation it is possible to produce a pattern of change closely resembling evolution [*see bottom illustration on page 3*]. Observers have frequently noted that the innermost profile looks something like a Neanderthal man, whereas the outermost profile looks like a futuristic being such as one might see in a science-fiction motion picture. Since both growth and evolution can apparently be described by a single geometric transformation, it seems reasonable to speculate that both processes are affected by the same influences. Such speculations may eventually help in gaining an understanding of why evolutionary change is perceived to be a continuous process that, like growth, moves inexorably along a specific path of morphological change.


## The Authors

JAMES T. TODD, LEONARD S. MARK, ROBERT E. SHAW and JOHN B. PITTENGER are experimental psychologists with a common interest in the role of perception in human behavior. Todd, Mark and Shaw are at the University of Connecticut, Todd and Mark as research associates and Shaw as professor of psychology. Todd, who received his Ph.D. in experimental psychology from the University of Connecticut in 1977, has worked as a computer-programming consultant for the University of Connecticut Health Center and the New York University Medical Center; he describes his main research topic as "mathematical modeling of the optical stimulation that supports complex activities such as catching baseballs or driving a car." Mark, who also holds a Ph.D. in experimental psychology from Connecticut (1979), wrote his dissertation on "A Transformational Approach toward Understanding the Perception of Craniofacial Growth" (the subject of the present article). Shaw, the senior member of the group, obtained his Ph.D. in psychology from Vanderbilt University in 1965. He taught at the University of Minnesota and at Cornell University before joining the Connecticut faculty in 1976. Pittenger is a member of the psychology department at the University of Arkansas at Little Rock. His Ph.D. is from the University of Minnesota (1971).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