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The perception of growth in three dimensions

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During the past decade, there has been a considerable amount of research on how the age level of a human face is visually specified (Mark, Todd, & Shaw, 1981; Pittenger & Shaw, 1975a, 1975b; Pittenger, Shaw, & Mark, 1979; Todd, Mark, Shaw, & Pittenger, 1980). Most of the experiments reported to date have supported the hypothesis that morphological changes over the entire face and skull can be adequately described from infancy to adulthood by a single geometric transformation called cardioidal strain, and that human observers are specifically sensitive to that transformation in distinguishing growth from other styles of change such as weight gain, beard growth, or facial expression change. This research has also played an important role in the development of more general theories of human event perception by providing a demonstration that the perception of "slow" events, such as growth, can be governed by the same general principles as perception of "fast" events, such as a rolling wheel or a human gait (see, also, Todd, 1983).

One potential problem with this research, however, concerns the highly abstract and artificial stimuli used in most of the reported experiments. Previous studies have depicted human heads as two-dimensional profiles in silhouette, devoid of any internal detail. In contrast, an actual human face presents observers with far more detail about the facial surface and structure; and rarely do people look at faces only from the lateral (midsagittal) perspective. For cardioidal strain to constitute a useful description of perceptual information specifying craniofacial growth, it must be applicable to facial representations containing internal detail as well as other perspectives of the human head.

Our first attempt to address this problem involved changing the perspective in schematic line drawings from a side view to a front view. When this figure was subjected to cardioidal strain (See Figure 1), there were appropriate changes in perceived age level as revealed by a variety of psychophysical procedures. However, the faces used in these experiments were highly unnatural and artificial; they consisted only of a facial outline and neck without other facial detail. Many subjects remarked that "age level" seemed to be a less salient dimension of change than "weight" of the person. (The addition of eyes, nose, mouth, and eyebrows resulted in a slightly more natural representation when the face was transformed as a two-dimensional structure.)

In an effort to increase the perceptual salience of our displays, we then set out to apply our model to the entire surface of the head in three-dimensions. The first step in this process was to devise an appropriate revision of our transformation. The two-dimensional cardioidal strain (growth) transformation used in previous studies can be expressed in polar (north) coordinates as: $R' = R(1 - k \cos\theta)$, $\theta' = \theta$, where k is a free parameter increasing over time. In order to apply it to a three-dimensional data structure, we have adopted a similar transformation which can be expressed in spherical coordinates (R, θ, ϕ) as: $R' = R(1 - k \cos\theta)$, $\theta' = \theta$, $\phi' = \phi$. The motivation for this new equation was based on a hypothesis known as Wolff's law, which states that the growth of bone tissue is largely determined by the direction and magnitude of stress to which it is subjected. In accordance with this principle, we examined the effect of gravity on an idealized spherical system analogous to a growing human head (Todd & Mark, 1981; Todd et al., 1980). This analysis revealed that the pattern of gravitational stress is identical in all vertical cross-sections of the sphere passing through the central vertical axis (coincident with the direction of gravity).

Once we had extended the transformation to three dimensions, it was then necessary to acquire a data base representing a human head in three dimensions. This was obtained commercially through the Solid Photography Studio, a company that has developed a process for optical digitization of a solid object.

The stimuli in our experiment consisted of two computer-sculpted busts (Figure 2). A girl, age 15 years 1 month, was photographed by the Solid Photography Studio. From the three-dimensional data base generated by their digitization process, a computer-driven lathe carved a plastic bust of the girl (Figure 2, right). The original data base was then transformed using the three-dimensional cardioidal strain transformation to make the girl appear younger ($k = -.20$). From the transformed data structure, the computer carved a second bust (Figure 2, left). (The transformation was applied to make the girl appear younger, rather than older, to allow

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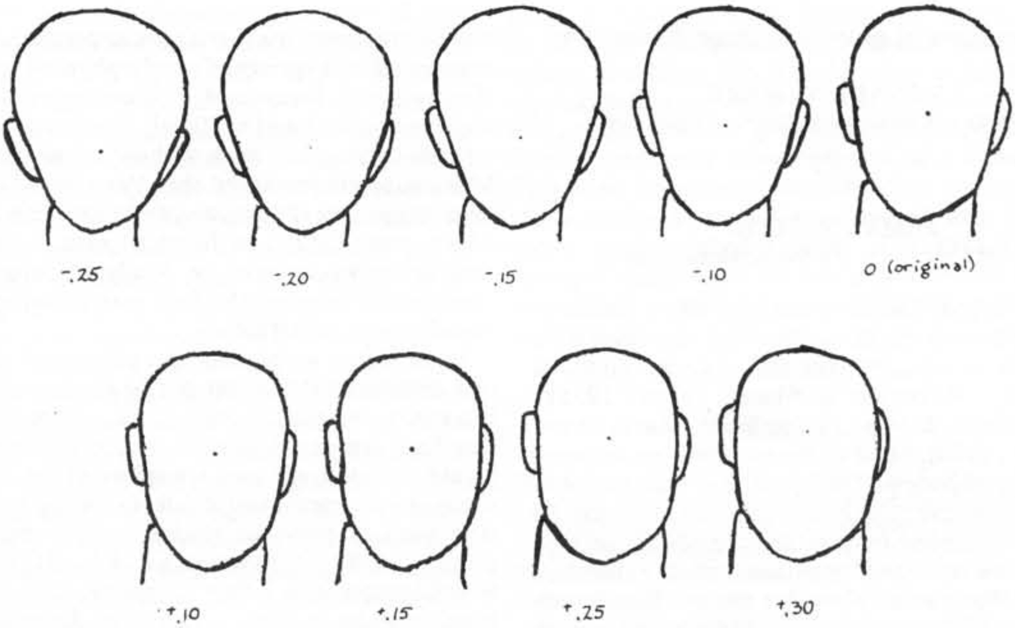

Figure 1. A series of human heads that were produced by transforming a coronal section with the cardioidal strain (growth) transformation. The value of the free parameter (k) of cardioidal strain used to produce the transformed head is given below. The original (untransformed) head is at the upper right (k = 0).

Figure 2. The two busts used in the current study. Right, the original bust of a girl, age 15 years, 1 month; left, the busts resulting from transformation of the original data structure by applying three-dimensional cardioidal strain to make the head appear younger.

us to evaluate the likeness of the transformed bust against the girl's earlier appearance.)

The two busts were shown to observers in a 15 × 18 ft room with overhead fluorescent lighting from a variety of perspectives. The subjects were told to look at each bust carefully and determine which bust was "older." They were then asked to estimate the age levels of the two busts to the nearest half-year.

The results of both tasks, shown in Table 1, provide a dramatic demonstration that the cardioidal strain transformation, when applied to a three-dimensional representation of a human head, produces appropriate changes in perceived age level. The results of the absolute age-judgment task are particularly interesting in this regard. The average age-level estimates were 6.23 years (SD = .89) for the younger bust and 14.54 years (SD = 1.47) for the older bust (Table 1). Since the child was 15.08 years old at the time the "older" bust was made, this latter result indicates that the computer process for sculpting the bust produces a satisfactory depiction of the child's age. Although the difference between subjects' age estimates and the child's actual age is statistically significant [$t(359) = 6.75$, $p < .001$], this difference is not overly meaningful, since it is based on the child's chronological age rather than a measure of her developmental age; perceived age should be more closely related to developmental age than chronological age.

Table 1
Results of the Ordinal Age Judgment and Absolute-Age Judgment Tasks

Number of Correct Ordinal Age Judgments	356
Percent of Total	98.9
Mean Absolute-Age Judgments for the Younger Bust	6.26
Standard Deviation	.89
Mean Absolute-Age Judgments for the Older Bust*	14.54
Standard Deviation	1.47

*Note–Total N = 360. *Actual age = 15.08.*

Evaluation of the age-level estimates of the younger bust is somewhat more tenuous because the value of the free parameter of the cardioidal strain transformation has not yet been correlated with particular age differences. Nonetheless, people who had known the child as a preschooler were impressed with the "likeness" of the transformed bust to the child at

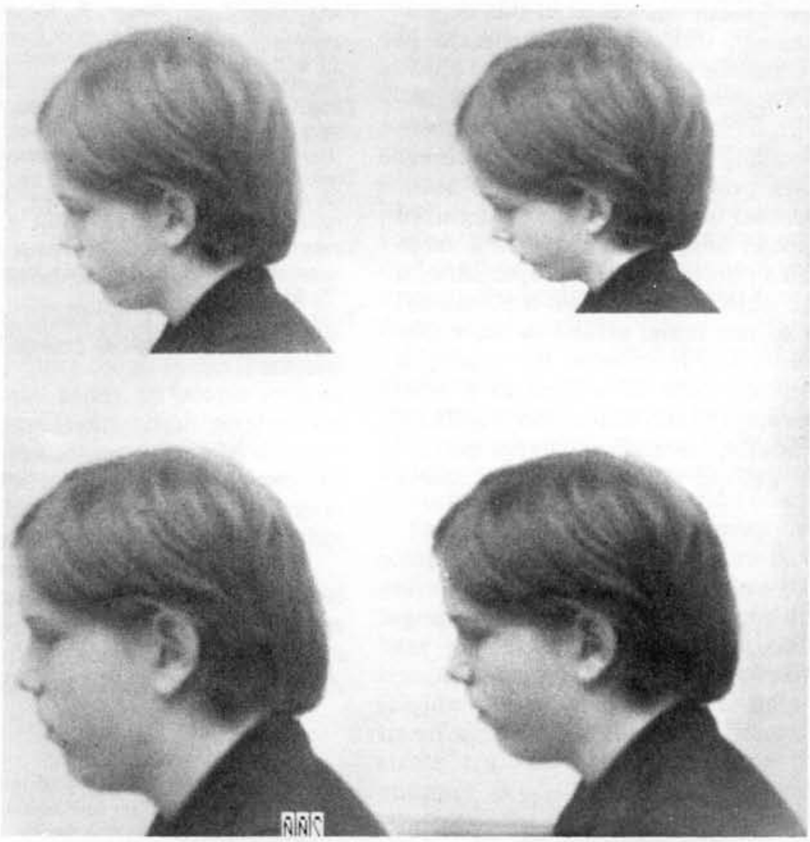

Figure 3. A series of transformed photographs produced by applying cardioidal strain transformation to the actual photograph of a 12-year-old boy (lower right). The transformation producing the photographs on the upper row was intended to make the boy appear increasingly younger (left to right); the transformation producing the photograph at the lower left was intended to make the boy appear older.

about age "5" years. Both parents, an older sibling, and several friends, however, have noted an important difference. As a 5-year-old, the girl did have considerably more "baby fat" than had been depicted in the transformed bust. This is interesting, because the growth transformation does not model the forces responsible for changes in the amount of fat tissue in the face. The biomechanical analysis motivating our generalization of cardioidal strain to three dimensions suggests that this transformation models only the effects of gravitational stress. As other forces play significant roles in shaping the human face, it comes as little surprise that the cardioidal strain transformation did not account for at least one significant dynamic component of facial change. This observation suggests a possible explanation for the small discrepancy between subject's age-level judgments of the younger bust (mean = 6.26 years) and the age estimates (around 5 years) of family and close friends: To participants in the experiment, the absence of "baby fat" on the craniofacial structure of a 5-year-old could have made the child appear somewhat older than family and friends remembered her.

The process for generating a three-dimensional representation of a human head used in this experiment is, unfortunately, unlikely to be repeated in future research because of its prohibitive cost. However, the success of this initial study and the importance of the problem encourages us to explore other means for working with more natural representations and multiple perspectives of a human head. One promising method involves the use of digitized shaded (photographic) images presented on a video monitor. Although a photograph is a projection of a three-dimensional object onto a two-dimensional plane, the results of our initial efforts indicate that the perspective distortion introduced by treating a photographic representation of a face as a two-dimensional object is not overly serious (see Figure 3).

To summarize briefly, research on change perception has typically utilized highly artificial displays (e.g., point-light, stick figures, etc.), necessitated, in part, by limitations of computer graphics technology available for transforming a more natural representation in real time. The current study, however, shows that our growth model is applicable to a three-dimensional representation of a human head. This is an important demonstration in light of previous studies of craniofacial growth that have used more impoverished stimuli. The present results strongly suggest that the findings based on these impoverished stimuli can be generalized to more complex and natural representations of the human head.

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