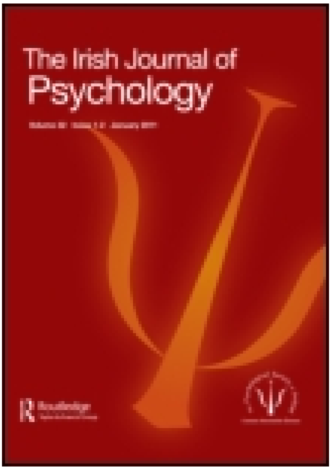

The Irish Journal of Psychology

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/riri20

Object Constancy in Face Processing: Intermediate Representations and Object Forms

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Published online: 13 Nov 2012.

To cite this article: Alan Johnston (1992) Object Constancy in Face Processing: Intermediate Representations and Object Forms, The Irish Journal of Psychology, 13:4, 426-439, DOI: 10.1080/03033910.1992.10557903

To link to this article: http://dx.doi.org/10.1080/03033910.1992.10557903

The Irish Journal of Psychology, 1992, 13, 4, 426—439

Object Constancy in Face Processing: Intermediate Representations and Object Forms

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Bruce (1988) has argued that face recognition mechanisms may utilise a description of the 3-dimensional surface of the face as well 2-dimensional pictorial information and that shading provides sufficient information to the extraction of the surface-based description. The present paper considers what kind of intermediate representation of surface shape might best serve the description of the face, in the context of the problem of object constancy under scalings and rotations of the object, and argues for a description based on measurements of local surface curvature. Failures of object constancy are attributed to the need to establish object forms through learning, in order to describe allowable global configurations of the face across and within individuals.

Object constancy in face processing

The retinal images contain perspective projections of the surfaces in the environment and undergo lawful changes as objects in the environment change their distance from the eye or undergo rotations around axes perpendicular or parallel to the image plane. It is a remarkable fact that we can recognise the identity of objects irrespective of the size changes and distortions introduced by perspective. Gibson (1979) reasoned that, in order to achieve object constancy, the visual system had to separate properties of the retinal images due to changes of the viewpoint from properties of the retinal images that were dependent on the nature of the object and, therefore, must be invariant, as we assume the object remains invariant. A similar argument can be applied to object constancy in the face of changes in the direction and nature of the illumination, which also has radical effects on the brightness distribution in the retinal images. Object constancy, then, is the result of the process by which we recover properties of the object from the properties of the retinal images. In Gibson's view we do not need to posit any special mechanisms to deal with the problem of object constancy.

In Marr and Nishihara's (1978) approach to object recognition, constancy results from the process of describing the object in a way which does not

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depend upon the viewpoint. They outlined how we might generate a view-invariant representation of objects by describing the shape of the object with reference to a coordinate system centred on the object rather than the viewer. However, faces tend to fall outside the scope of the model, which is primarily aimed at objects that can easily be decomposed into articulated component parts. Faces can be decomposed into facial features, but linguistic definitions tend to describe regions of the face rather than clearly defined boundaries. This is a problem for models of object representation which derive volumetric primitives from object or object component contours (Beiderman, 1987; Marr & Nishihara, 1978).

In addition, the face recognition literature provides some evidence of view dependent encoding which is difficult to accommodate within Marr and Nishihara's framework. Studies of recognition memory (Krouse, 1981; Logie, Baddeley & Woodhead, 1987) have shown preferences for full face or 3/4 views over profiles, although Bruce, Valentine and Baddeley (1987) found no effect of view on the speed of familiarity judgments. Bruce et al. did, however, report a preference for views in a face matching task for positive trials and unfamiliar faces. Perrett et al. (1985; 1991) described cells in the superior temporal sulcus (STS) which are selective for faces and which are tuned to particular orientations of the face, particularly full face or profile. However, both Perrett et al. (1991) and Hasselmo et al. (1989) also described cells which respond to faces uniformly for all views. Rotation in the image plane also disrupts face encoding. Inverted faces are more difficult to recognise than upright faces (Valentine, 1988; Yin, 1969, 1970). Faces are also more difficult to recognise when illuminated from below (Johnston, Hill & Carman, 1992). These observations indicate a departure from object constancy, but departures from the ideal case of complete invariance with respect to rigid transformations and lighting should not lead us to ignore the fact that face recognition is, nevertheless, fairly robust with respect to scalings and rotations of the target object and changes in illumination.

Perrett et al. (1991) proposed that view-dependent cells may support the recognition of facial orientation and that rotation-invariant cells may be constructed from view-dependent cells. Essentially, face recognition systems need to be duplicated for each of a number of views and then a superordinate system integrates over view. This is an attractive idea which finds support in the computer vision literature (Poggio & Edelman, 1990) and which does not require an explicit representation or description of 3-D shape like that put forward by Marr and Nishihara. Nevertheless, it is difficult to see how the approach could be generalised to account for other constancies, such as size and distance invariance, invariance for image rotation, lighting direction, and spatial position, all of which have been demonstrated in view-dependent cells (Hietanen, Perrett, Oram, Benson & Dittrich, 1992). We would have to argue that view invariance in some way poses special problems. Neither the object-centred approach nor the view-integration approach invokes intermediate surface-based representations in object recognition — the object recognition system operates on 2-D spatial patterns.

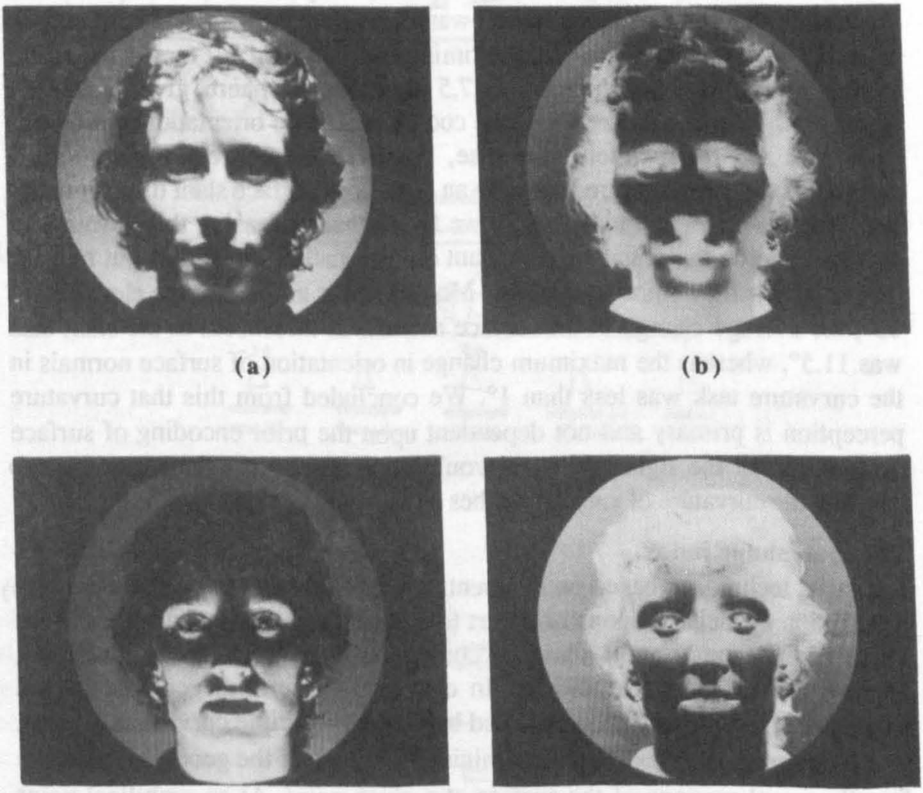
Surface descriptions and intermediate representations

Bruce (1988) pointed out that, although much of the research on face recognition uses pictures of faces as stimuli, faces are 3-dimensional objects rather than 2-dimensional images, and encoding the face may require some form of surface-based or volumetric-based description of the 3-dimensional structure. Bruce has argued strongly for the importance of shading as a source of information about the 3-dimensional structure of the face. Evidence for the existence of a surfaced-based description comes from the effects of lighting direction and inversion on face recognition (Johnston et al., 1992). Faces are more difficult to recognise when turned upside down; however, Johnston et al. showed that the face inversion effect was reduced for faces illuminated from below the chin in comparison with faces illuminated from the front or from above the head. An image-based account of the effects of lighting on face recognition would predict that lighting direction and face orientation effects would be independent.

Johnston et al. (1992) interpreted the interaction between illumination direction and face orientation as reflecting difficulties in the recovery of the 3-dimensional shape of the surface of the face. Inverting a picture of a scene can alter the perception of surface geometry, as is demonstrated in the well known 'crater illusion' (Gibson, 1950). In the crater illusion, rotating a picture of a cratered landscape also involves the rotation of the direction of the prevailing illumination. After inversion, the craters are interpreted as protrusions. It would appear that, in general, the visual system arrives at an interpretation of the surface geometry of a scene which is consistent with illumination from above by a single light source (Ramachandran, 1988). We can expect perceptual conflict in the interpretation of faces illuminated from below, because the image is incompatible with one or other of two real-world constraints which the visual system may be using to derive the 3-dimensional shape of the face — that objects are normally illuminated from above and that objects are normally globally convex. This conflict would not be present in faces illuminated from the chin presented upside-down. However, the inversion effect was also found for faces illuminated from the front, demonstrating that the associated changes in the apparent direction of illumination when pictures of faces are inverted is not the sole cause of the inversion effect.

Difficulties in the recognition of faces presented as photographic negatives also indicate a role for shading in the construction of surface-based codes (Cavanagh & Leclerc, 1989; Pearson, Hanna & Martinez, 1990). Generating a photographic negative only changes the sign of the brightness values relative to the mean level; it does not change location of iso-phote contours or the magnitudes of the brightness gradients. This manipulation does, however, radically disrupt the recovery of shape from shading, because the resulting brightness values may not be consistent with the effects of illumination on any possible 3-dimensional surface (Horn, 1990). The negatives of faces illuminated from the chin are easier to interpret as faces, possibly because the apparent direction of illumination is now from above and the brightness distribution in the resulting image is more consistent with that generated by a globally convex face under natural lighting conditions (see Figure 1).

Figure 1. A face: (a) illuminated from above; (b) a photographic negative of the picture in (a); (c) the same face illuminated from below the chin; and (d) the photographic negative corresponding to (c).



(a) (b) (c) (d)

Note. Photographs from "Recognising faces: Effects of lighting direction, inversion and brightness reversal" by Johnston, A., Hill, H. & Carman, N., 1992, *Perception*, 21, p. 371. Copyright Pion Ltd. Reproduced with permission.

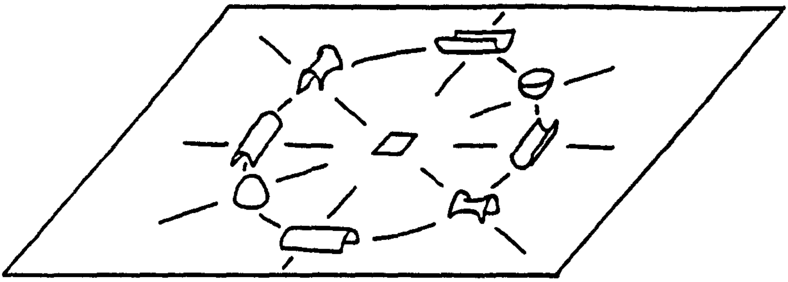
The observation that the generation of a surface-based description may be an important stage in face processing leads to questions about what kind of intermediate representation or structural description would best serve face recognition. We might first consider a description of facial shape in terms of surface distance and surface orientation — Marr's 2.5-D sketch (Marr & Nishihara, 1978). But this description would change as the object changes its distance or rotates around an axis in 3-D space. In addition, our ability to encode or discriminate changes in surface orientation for surfaces defined by shading is rather poor (Johnston & Passmore, 1992; Mingolla & Todd, 1986). This has led Todd and Reichel (1989) to propose that we can only recover ordinal depth relations from shaded images. However, Johnston et al. (1991) have recently shown that we can make precise judgements of surface curvature. Curvature discrimination thresholds were measured in a forced-choice task in which subjects were asked to decide whether a surface patch on a shaded sphere was more curved or less curved than the main body of the sphere. The Weber fraction for curvature discrimination was found to be around 0.11, from which it can be calculated that we can discriminate a change of 3.7 mm in the radius of curvature of a surface patch on a 7.5 cm diameter sphere, given a viewing distance of 75 cm. It is likely that the coding of surface orientation and surface curvature are independent, because, when we compared discrimination thresholds for the curvature task with an analogous surface slant discrimination task (Johnston & Passmore, 1992), we found that increasing the elevation of the light source increased surface-slant discrimination thresholds but reduced curvature discrimination thresholds. Moreover, for a light source elevation of 65°, the average change in the surface normals at thresholds in the slant task was 11.5°, whereas the maximum change in orientation of surface normals in the curvature task was less than 1°. We concluded from this that curvature perception is primary and not dependent upon the prior encoding of surface orientation. In the light of this it would be useful to consider how best to describe the curvature of surface patches on the face.

The local shape index

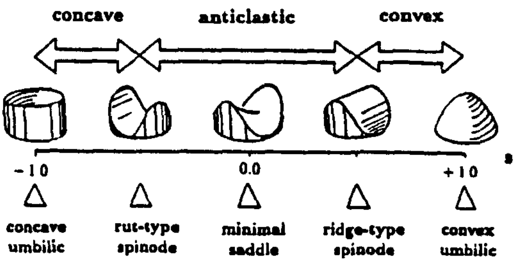
Recently, techniques based on differential geometry have been applied to the description of facial shape in an effort to describe and evaluate changes in the shape of the face brought about by corrective surgery (Coombes, Richards, Linney, Bruce & Fright, 1992). In classical differential geometry, local variation in surface shape is captured by the two principle curvatures (k_1,k_2), which describe the maximum and minimum values of the geodesic curvature for all normal sections of the surface at a given point. At an umbilical point the geodesic curvature is identical for all normal sections, otherwise the sections giving rise to the curvature extrema are orthogonal. Coombes at al. (1992) subdivided the space parameterised by the mean and Gaussian curvature (the mean and product of the two principles curvatures) into regions, in order

Figure 2. Koenderink (1990) described local shape in terms of all possible combinations of the values of the two principle curvatures through a point on a surface patch. In (a) curvedness increases from the origin and local shape changes systematically around the iso-curvedness circle. In (b) we see that gradual changes from convex umbilic to concave umbilic regions can be scaled into the range 1 to -1, and in (c) a log polar mapping provides an orthographic representation of shape and curvedness where units of curvedness are specified as equal units on a log scale.

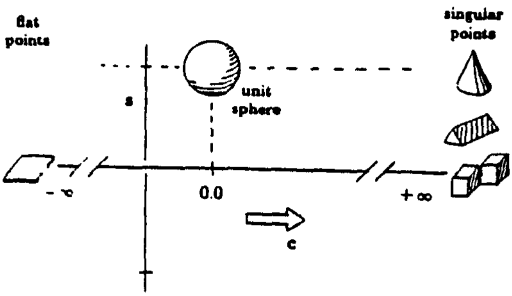
(a)



(b)



(c)



Note. From *Solid Shape* by J. J. Koenderink, 1990. Cambridge, MA: MIT Press. Copyright MIT Press. Reproduced with permission.

to define qualitative surface types like valleys, peaks, ridges and saddle ridges. This allows the production of maps of the face for particular surface types.

However, this is one of a number of ways in which we can represent second-order variation in surface geometry. Koenderink (1990) described a novel parameter space which has the advantage that it separates changes in local shape from changes in scale (see Figure 2). Koenderink's local shape parameters (R,S) can be thought of as polar coordinates in the k_1,k_2-plane. The first parameter of the local shape index, 'shape' (S), indexes all possible combinations of relative values for the two principal curvatures (k_1,k_2) with the root mean square (RMS) of the principal curvatures held constant. The second parameter, 'curvedness' (R), is defined as the RMS of the principal curvatures and describes the scale of the changes.

The form of the representation of surface variation has important consequences for the stability of the description under simple transformations and, therefore, for the attainment of object constancy. A surface description, in terms of range or distance, changes under rotation, scaling and translation in depth. The orientation of a surface patch changes if you rotate the object or the reference frame, but is not affected by a scaling transformation. A description in terms of surface orientation is scale invariant, but a description in terms of surface height is not.

As curvature is a property of the surface, it is invariant under rotations and translation (Lehky & Sejnowski, 1990), but, as Koenderink (1990) pointed out, a description of surfaces in terms of mean curvature does not capture the invariance of shape under transformations in scale. A sphere of any size is spherical but its mean curvature varies as the inverse of its radius. However, the local shape parameter, S, the relative magnitude of the principle curvatures, is scale invariant. The scale of the changes in surface curvature is captured by the 'curvedness' parameter. These relationships are summarised in Table 1.

As the relative curvedness of regions on an object are more important for describing shape than the absolute values of curvedness, which only reflect the spatial scale of the changes, it would be appropriate to describe curvedness in logarithmic units. This has the advantage of making proportions explicit, and because it is a relative scale, it removes the need for an absolute metric (Koenderink, 1990). Koenderink pointed out that the k_1,k_2 plane can be conveniently transformed using a conformal logarithmic polar mapping to construct a rectangular grid with shape described along one axis and curvedness along the other (see Figure 2). Curvedness is now properly represented in logarithmic units. If 'curvedness' was represented logarithmically in the human visual system we would expect Weber fractions for curvature discrimination to be constant. In fact curvature discrimination thresholds do obey Weber's Law (Johnston et al., 1991). The Weber law for curvature from shading supports global shape constancy over changes in scale or changes in

Table 1. Summary of whether particular surface descriptors remain invariant under a given transformation (indicated by an 'I').

	Translation in depth	Scaling	2-D rotation	3-D rotation
Range				
Height	I		I	I
Orientation	I	I		
Mean curvature	I		I	I
'S'	I	I	I	I
'R'	I		I	I

Note. 'S' is an index of all possible combinations of relative values for the two principal curvatures of a surface with the root mean square of the principal curvatures held constant; 'R' is defined as the RMS of the principal curvatures and describes the scale of the changes (Koenderink, 1990).

depth, as a small change in surface curvature will be equally discriminable over a wide range of scales and this observation provides some psychological validity for the logarithmic scaling of Koenderink's local shape index.

Koenderink's local shape space has much to recommend it as a putative model of the representation of local shape in the human visual system and as a basis for the structural description of objects. The recovery of properties of the surface, which are relative and surface-based, and therefore invariant with respect to transformation and scaling, would seem to be an important intermediate stage in object recognition. A rotation, translation or scaling of an object would not change the value of the local shape parameter. This would allow the identification of corresponding regions on the surface in preserved and transformed images, supporting the computation of the nature and magnitude of the transformation. Thus, indices of local surface geometry might be combined with surface markings and object boundaries in the computation of shape from stereo or shape from motion. The separation of shape from scale and the logarithmic scaling of the curvedness parameter would also seem to be important. A magnification of the retinal image of an object would result in a simple decrement of the value of the curvedness parameter at all points on the object. However, an intrinsic image containing local shape information falls short of a global description of the shape of an object — a problem which is considered next.

Object-centred descriptions and object forms

Marr and Nishihara (1978) considered three sets of criteria by which models of object recognition could be evaluated. The first set, accessibility and scope, are simply engineering criteria which consider how easily a description can be derived from the image and what classes of object should be considered to fall within the remit of the model. As we are as yet unable to say how the visual system recovers facial shape, it is difficult to determine what descriptions the visual system would find easy to derive and which would be more problematic. The uniqueness criterion indicates that the same object should not give rise to two or more separate descriptions, otherwise we would have an ambiguity which would require some resolution. In fact, it is, of course, possible to generate images which give rise to such ambiguous percepts and the visual system tends to alternate between the available interpretations. The third criterion, the stability/sensitivity criterion, is by far the most important. The stability/sensitivity dimension in part indexes the degree of precision with which the object is described. A stable description is one in which minor changes in the object do not affect the derived representation. Stable descriptions support generalisation across instances. A sensitive description changes with minor changes in the object and thus supports discrimination. The stability/sensitivity distinction is also related to Gibson's conceptualisation of the importance of persistence and change in object constancy. A representation which recruits primitives which are invariant under object transformations, like local shape, will be stable; however, we also need to be sensitive to the transformations. Partial descriptions of the object are, of necessity, more stable than complete descriptions of the object.

Structural descriptions of 3-dimensional shape of the kind outlined by Marr and Nishihara or Beiderman (1987) involve object decomposition into component parts. The component parts often take the guise of simple forms, like cylinders, cones or ellipsoids, plus parameters. This approach drastically reduces the number of pieces of information required to represent a surface or volume. However, not all objects can be decomposed in this way. Smooth rocks or 'potato shaped' objects cannot readily be segmented into component parts and the shape of a potato cannot be described in a simple fashion. More complex components, such as generalised cones, require the specification of a space curve for the axis, a curve for the cross section and a scaling factor which may change along the curve: in short, the equivalent of a full parametric description of the surface. A general bumpy ovoid shape could be described as a concatenation of superquadric surface patches (Pentland, 1986) but this would not provide any simplification over a description of the surface in terms of local shape. Although the shape of simple objects like ellipsoids can be made explicit, that is, we can detect the fact an ellipsoid is present in the image and we can attribute a quality 'ellipsoid' and the quantities which describe the major axes to a region, the same is not true of general objects. We have to consider that if a description of local surface curvature and, perhaps, local surface orientation and scale is the most general description that we can achieve for arbitrary shapes (and as we can recognise an arbitrary shape as remaining constant under various rigid transformations), we may not need to apply a more abstract description of shape in the cases where a more abstract representation in terms of simple object forms is intuitively possible.

An alternative approach is to generalise the idea of simple forms plus parameters into standard or average forms plus parameters. The advantage of this approach is that it can deal more effectively with invariance over nonrigid transformation of global shape. When a general object, like a stone or a potato, changes its shape, it changes its nature, unless, of course, the transformation has a simple structure and a global effect, like that brought about by a general elongation on some other simple affine mapping. For an object which can be said to have some abstract form, which can only change in regular and lawful ways, like the face, then it may be possible to separate the abstract form from the allowable transformations.

A problem with the idea of abstract forms is that it would require that a form needs to be stored for each class of objects. One way to simplify object forms and reduce the number of forms which need to be dealt with is to decompose the object into separate component parts. Objects may be decomposed into parts using geometrical considerations, like joining together points of extreme concavity (Marr & Nishihara, 1978). However, what constitutes a part of an object appears to have more to do with visual semantics — that is, our knowledge of the nature of objects — than immediate vision. In particular, an object or part of an object might be defined as those regions of the scene which transform coherently but which can vary independently of other regions. We can take the example of a teapot, which is composed of a bowl, a handle, a lid and a spout. Within broad limits each of these parts can take various forms to provide the variety of teapots that surround us. If the spout was always predictable from the bowl we might say that the teapot could be segmented into three parts. Although it would be quite possible to construct a teapot from two parts joined along a longitudinal section, in the way that a child's plastic toy is constructed, we would not perceptually segment an object in this way because, due to symmetry, both sides of a teapot co-vary. If we accept that the conjecture that objects are segmented into parts which can vary independently, then there are no a priori rules that can be applied, and the way that objects are parsed must depend upon prior experience with that class of objects. The mechanisms of object recognition will depend upon the visual diet.

Failures of constancy: The inversion effect

When a face changes expression the surface of the face undergoes a reconfiguration. Yet the changes in local shape are not arbitrary; they are constrained by changes in the shape of the skull and the musculature. The changes in the face are correlated. In order to achieve constancy in face recognition we may parse the face into a standard face plus configuration. Here we take configuration to mean, not the disposition of features, but correlated changes in features and the facial surface which occur in an individual face or across faces. That is, the configuration of the face is a higher-order property which is extracted by detecting covariance in systematic changes in the face and which is lawfully related to underlying causes. Whereas object constancy for changes in size, rotation or illumination may be supported by the construction of a surface description which is invariant under changes in the scale or orientation of the object, it is likely that object constancy for nonrigid changes in shape depends on encoding the variation in the surfaces of objects and, thus, depends upon learning about visual configurations.

In the case of faces Brennan (1985) provided an important indication of how we might derive an object form. Brennan showed how we might arrive at an average line drawing of a face by averaging coordinates of key points on faces scaled to have the same interpupil distance. Caricatures can then be generated by scaling up the differences between individuals and the average face. In the case of 3-D facial shape, the average facial surface, which we may consider to be described in terms of Koenderink's local shape parameter, would constitute a form. For simple forms, like ellipsoids, the parameters describe the width and length, the principle dimensions along which ellipsoids vary. Variation in these parameters have various effects on the surface curvature. For the face form we would also hope for parameters which describe the principle dimensions along which faces vary and which lead to the multifarious changes seen in the surface of the face between and within individuals. These parameters will presumably have their physical support in the processes that control the shape of the skull and the dynamics of the facial musculature (Bruce, 1988; Pittenger & Shaw, 1975). Note that the average face should not be considered an 'ideal form' in the Platonic sense. It is simply a member of the class of objects that can be represented by changing the parameters of the form. Similarly there is no ideal ellipsoid — just a class of shapes that can be mapped onto each other by a simple transformation.

The face inversion effect provides evidence of a striking and puzzling lack of object constancy under image rotation. However, we can consider this failure in the light of the need to achieve object constancy under nonrigid changes in the face. The main difficulty in recognising an upside-down face appears to stem from problems in the recovery of the configuration of the face when inverted (Carey & Diamond, 1977; Young, Hellawell & Hay, 1987). For faces illuminated from the front we would not expect image rotation to affect the representation of the surface of the face, however, because, it is argued, the representation of the global shape or form of the face requires experience of how faces change, performance in face recognition tasks should reflect the nature of the visual diet.

Summary

The paper presents a two stage model for face description in order to address the problems of object constancy in face recognition. The first stage is the generation of an intermediate surface-based representation of local shape, based on Koenderink's local shape index (Koenderink, 1990), which encodes the relative magnitude of the principle curvatures of local surface patches. The second stage involves the establishment of a face form of a prototypical face which is parameterised in terms of the major sources of variation in the face. The parameters are thought of as indexing possible configuration of the form. The motive force of the form plus parameterisation stage is the achievement of object constancy under changes in configuration, brought about by nonrigid transformations and articulation of component parts. However, it is proposed that object forms and the range of variation in the form cannot be predetermined and therefore need to be established by learning about the nature of objects. This leads to a dependence on the visual diet and gives rise to orientation-dependent effects, like the face inversion effect, which compromise complete object constancy.

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