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Empirical aspects of symmetry perception

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'Take it — to the limit — one more time'

The Eagles

This Special Issue is the second of a pair devoted to the human perception of symmetry relations, the first published collection of articles on this topic. As is evident from the preceding companion issue, the division that had to be made between theoretical and empirical approaches to the topic for the two issues is artificial, intended merely as a grouping principle for the papers submitted. The present contributions are those that emphasized empirical characterization of some aspect of symmetry perception, although many are placed in a clear theoretical framework.

Symmetry is a general concept that refers to any manner in which part of a pattern may be mapped on to another part (or the whole pattern onto itself). Symmetries of various kinds play a fundamental role in both the structure of the physical universe and, in a different form, our interactions with it on a human scale. Early art and architecture offer some insight into the role of symmetry in human perception, suggesting that repetition (translational symmetry) was perhaps the earliest to be aesthetically appreciated. This is evident as much as three thousand years ago in the ranks of repeated figures of terracotta warriors in the tomb of Emperor T'sin, the founder of China, in the repeated profiles of the Persian bas-reliefs of the era of King Xerxes, and in the wall-paintings of the Egyptian pyramids. Remarkably, the mirror symmetry of the human face was hardly ever depicted in this era, although the monumental architecture of its palaces and tombs are replete with both mirror symmetry in the structure of the buildings and repetition symmetry in their ornamentation such as colonnades and battlements. In general, then, symmetries of design have long been widely incorporated into human artefacts, as is amply documented in *Symmetries of Culture* by Washburn and Crowe (1988), for example.

WHY STUDY SYMMETRY PERCEPTION?

As the preponderance of papers in this issue attest, mirror symmetry is the type that seems to hold the most appeal for perceptual investigation, but does it offer a particular benefit for the analysis of pattern-recognition processes? Most studies in pattern recognition are based on a past memory of the recognized object and therefore deal with the nature of representation in memory. Symmetry perception is distinct, however, in that it is based on a comparison of representation in immediate perception rather than memory. A memory of one part of the image is not required to recognize the similarity of another part, although memory may be activated during the task. It is the representation of the matching patterns after taking the requisite symmetry transform into account that is the crucial aspect of the recognition process. The immediacy of this process in nonfamilar (randomly generated) images, as reported in the literature from Julesz (1966) to the present collection, militates against a significant role for memory in the task. Thus, the symmetry paradigm allows analysis of an aspect of complex pattern recognition that is difficult to access by other techniques.

There is significant evidence, reviewed in the contribution by Wagemans, that mirror symmetry has a special status in human perception in comparison with other types (such as translation or rotation symmetry). Why this should be the case may be evaluated in terms of the environment in which our visual system evolved. Mirror symmetry of the objects that we encounter usually betrays the presence of living organisms, for one of several reasons. Inanimate objects, consisting predominantly of rocks and geological formations, generally exhibit no particular symmetry. Crystals may be a special case in this regard, but even then it is rare to find an isolated object consisting of a single crystal with an identifiable symmetry axis. It is only on a non-human scale of analysis that inanimate objects are limited by symmetry constraints. Microscopically, of course, atoms have pervasive symmetries, although these are already delimited by the molecular level. Crystals then constitute an intermediate ('miniscopic'?) level at which the molecular symmetry is expressed in magnified form. On an astronomical scale, symmetry is resuscitated by the gravitational constraint in the form of pronounced spherical symmetry, together with examples of radial and spiral symmetry in conglomerations of astronomical objects.

Animals that move linearly through the environment always are formed with an axis of mirror symmetry aligned with their typical direction of movement. This design is an obvious adaptation to avoid asymmetries that might cause a bias from the axis of movement. Any tendency to drift to the left or right would create difficulties in orienting and navigating during reduced cue situations (locomoting at night or in tall grass, for example). It seems that it is the motion constraint that is the limiting factor (rather than some inherent genetic property, for example) because only external parts of moving organisms are symmetrical. Internal organs, such as brain, heart, liver, and intestines, may exhibit substantial asymmetry as long as the external envelope conforms to the constraint. It is interesting to note that the design of fast-moving vehicles such as cars and planes adheres to the same symmetry constraints, with exterior mirror symmetry but lateralized placement of internal components such as the steering wheel and driver. On the other hand, animals that do not locomote consistently through the environment, such as starfish and limpets, or that drift or pulse through it as do plankton and jellyfish, do not conform to the bilateral symmetry constraint but typically have either cylindrical or multifold symmetry.

A striking feature of vertebrate animals is that, with rare exceptions such as fingers, they have no symmetries other than bilateral (absence of radial, rotational, repetitive, etc.). Almost every part of a vertebrate animal differs from every other except for its symmetrical mate on the other side (excluding, ironically, for the skeletal structure, which has strong repetition symmetries that are hidden by the musculature). Gardner (1964) has explained this predominance of mirror symmetry by reference to the forces that tend to disrupt the perfect spherical symmetry of the single cell; the vertical force of gravity and the fore and aft asymmetry of the motion direction. On this view, the prevalence of mirror symmetry is a default result of the absence of a perturbing force; since there are no lateral asymmetries in the locomoting environment, there is nothing to induce a lateral asymmetry. But the same argument would predict mirror symmetry for the internal organs, and probably also cylindrical symmetry for fish, who are essentially immune from gravitational pull. It also would make it difficult to explain the total lack of symmetry in amoebae and many other single-celled organisms. Thus, it seems that organismic symmetries may betray the operation of some active symmetrizing principle, such as the adaptive value of mirror symmetry for unbiased motion, rather than a default state to which organisms tend in the absence of asymmetric forces. The spherical symmetry often found in single-celled organisms would be attributable to the symmetrizing force of surface tension, as for bubbles in general.

Insects and invertebrate animals share the universality of a vertical symmetry axis but also exhibit manifold examples of repetition symmetry, such as the repeated thoracic segments of the centipede, the repeated leg and antennae segments of most insects, spiders, and crustaceans, and the multiple 'arms' of the octopus and squid. It is interesting that this repetition strikes us as inhuman and perhaps repulsive. It may be that some of the aversive quality of Hallowe'en skeletons derives from the way they reveal this insect-like quality of our repetitive bone structure.

Another prevalent feature of animals is that their long-distance sense organs are located close to the front as defined by their direction of movement. This arrangement implies that they become perceptually mirror-symmetric when facing in the direction of an observer. This orientation is one of high significance to the observer because it implies that the perceived organism has the observer at the centre of its sensory input, i.e. that it is maximally sensitive to the observer's presence. The significance may be either positive or negative according to whether the organism represents a threat or an advantage, but either role is maximized at the point of perceived symmetry. For example, a tiger passing by may be of concern, but when it turns to exhibit its proverbial symmetry by facing you, it is time to take action! Similarly, when the face of a human companion is turned to its position of full symmetry, the implication is strong that that person is maximally aware of your gestural signals. This association of perceived mirror symmetry with the maximal likelihood of another consciousness being focused on oneself may help to account for the perceptual specialization for mirror symmetry and our fascination with it.

The plant kingdom also exhibits widespread mirror symmetry, but for a different reason. In plants, accurate symmetry is a local principle determining, for example, the shapes of leaves and petals rather than of the plant as a whole. In this case, mirror symmetry seems to be just one of many types of symmetry constraint that have evolved in the design of plants, perhaps based on the principle of economy of design. Just as it is ontologically efficient to replicate the design of one petal around the circumference of a flower, efficiency is gained by using the same template for both sides of a petal or a leaf. In addition, plants often have a rough cylindrical symmetry imposed by gravitational constraints, which appears as a bilateral symmetry when viewed from the side. This cylindrical symmetry appears in many aspects of plant structure, elaborated into helical and rotational symmetries. In addition, the replication of similar elements such as leaves all over the plant provides a prevalent example of repetition symmetry throughout the plant kingdom. The growth of such elements of plant structure from small to large also provides extensive examples of scale symmetry in plants. This diverse array of symmetries seen in plants may be a reflection of the varieties of symmetry evident in diatoms, the microscopic constituents of ocean vegetation, which exhibit bilateral, triangular, and higher multiaxial symmetries in an astonishing display of crystalline regularity.

A final class of objects in our developmental (rather than evolutionary) environment constitutes those of human construction. These artefacts often have extensive symmetries, both for practical and aesthetic reasons. Much of the constructed world is characterized by the two-fold symmetry of the elaborated rectangle, but all types of symmetry have found their place. The practical reasons for such symmetries include stability and rigidity requirements, the constraints of machine production (particularly promoting circular symmetry) and the need to match the symmetry of the human body in objects that constitute furniture. Aesthetic reasons for symmetry also may derive from a variety of sources. One is the aforesaid symmetry of the natural environment, whose properties often are reflected in constructed objects to appeal to the perceptual specializations that have developed in this environment. A second is a resonance with the inherent symmetries of the optics, retina, and cortical projection of the visual system, which has circular symmetry overlaid with a mirror symmetry. Designs such as those of Persian carpets may be particularly appealing because they harmonize with such symmetries. Lastly, symmetries may be represented as an aesthetic exploration of the combinatoric possibilities of design elements (Washburn and Crowe, 1988), visual structure for its own sake rather than for any relation to the inner or outer environment. Thus, symmetries of all kinds may be present in constructed objects, with an emphasis on two-fold symmetry.

In summary, varieties of symmetry tend to distinguish the components of our perceptual environment according to a simple scheme:

vertebrate animal:	mirror symmetry;
invertebrate animal:	mirror and repetition symmetry;
vegetable:	multiple symmetries (emphasizing repetition, scale, cylindrical, helical, and multifold);
mineral:	none (at the macroscopic scale);
constructed:	multiple symmetries (emphasizing two-fold).

THE STUDY OF SYMMETRY PERCEPTION

In general, the empirical study of symmetry perception employs the same array of techniques as other perceptual tasks. Of course, most types of visual stimulus may be used for the study of symmetry, although reduced stimuli such as horizontal or vertical sinusoidal gratings do not permit a meaningful symmetry manipulation. The typical approach from the earliest studies has been to use non-familiar or randomized shapes on which the symmetry transforms are imposed. This approach was taken to its logical extreme by Julesz (1966, 1970), who introduced the computerized random-dot field as the base stimulus for symmetry manipulations and showed that symmetry could be perceived preattentively from very brief presentations. Many other variants have been utilized, including filtered random textures, dynamic random textures and random polygons, in addition to familiar images such as faces and outline figures.

Except for the use of eye-movement patterns to investigate symmetry (Locher and Nodine, 1987), the experimental techniques employed all involve methods of pushing the visual system to its performance limit in order to quantify the characteristics of the perceptual processing. Limiting the time available for processing the presence of symmetry defines the *reaction time* task that has found common use. Determining the percent correct discrimination for a brief exposure constitutes the *accuracy* task. Reducing the stimulus to the minimum duration at which the symmetry can be detected (with unlimited response time) defines the *duration threshold* task. Reducing the stimulus to the minimum contrast for the detection of symmetry defines the *contrast threshold* task. The accuracy in setting the orientation of the symmetry axis defines the *orientation discrimination* task, introduced for the study of symmetry by Wenderoth in this issue. Each task has a role to play in exploring the properties of symmetry processing.

A revealing task that has not commonly been used in perceptual experiments is to introduce positional noise into the pattern elements until the symmetry is detectably degraded, or until its presence is just discriminable from a pure noise stimulus, defining types of *pattern discrimination* task employed by Bruce and Morgan (1975) and Barlow and Reeves (1979). Another task that was introduced for the study of stereopsis (Julesz and Tyler, 1976) but has been adapted to symmetry perception is the transition reciprocity paradigm, which addresses whether the change from stimulus A to stimulus B is perceptually equivalent to the change from stimulus B to stimulus A. The failure of this equivalence is evidence for a characteristic neural bias in processing the pattern information, requiring the definition of a neurally relevant definition of the available information, termed 'neurontropy'. A corresponding definition of the information available for symmetry perception has been termed 'symmetropy' (Yodogawa, 1982), although he did not investigate transition reciprocity under this measure.

The first paper in the present set, by Wagemans, provides an overview of the principal issues that have been addressed in the literature on mirror-symmetry perception. He concludes that mirror symmetry can be detected by a preattentive mechanism but that attention also plays a role in determining the axis of symmetry processing. Pairwise comparison across the symmetry axis seems to be important but symmetry perception is robust to perturbations of various kinds, particularly when supported by multiple axes of symmetry in the image. Longer-range mechanisms are implicated by the discriminability of stimuli with symmetry information removed from the region of the axis.

Three papers address issues of the image-processing mechanisms for mirror symmetry. The paper by Labonté, Shapira, Cohen, and Faubert is a predominantly theoretical development of the relative roles of local and global information in symmetry processing, nicely validated by experimental results. Space limitations precluded its inclusion in the companion issue (*Spatial Vision*, Vol. 8.4) that would have been its natural home, but its results accord well with the properties of symmetry-processing mechanisms that are revealed by the other papers here.

Wenderoth explores the effects of the outline versus the interior content of sparse random-dot arrays. While the outline played a minor role in enhancing symmetry detection, it was not required and had no significant effect on the differences between axis orientations that themselves were restricted to central presentation of the symmetry. Similar results were found in a novel orientation discrimination paradigm, in which the orientation threshold for tilt of the symmetry axis was remarkably precise.

The study by Tyler, Hardage and Miller concentrates on the precise form of the sensitivity to symmetry with distance from the symmetry axis. Rather than showing the progressive decline characteristic of a simple distance mechanism processing the symmetry information, the study reveals a 'head, shoulders and skirts' pattern implying the operation of a few discrete mechanisms in detecting static symmetry, with a much wider spatial range than for dynamic symmetry targets.

Four papers focus on the role of reference frames of diverse kinds on the perception of pattern symmetries. Quinlan studies the effect of the reference frame defined by the symmetric scene itself, by presenting pairs of polygons in combinations of the symmetries of the polygons themselves and between the members of the pair. To account for the pattern of results, the author proposes that the axis defined by the global orientation of the pair sets up a frame of reference for judgement of the local symmetry, with a preference for a vertical symmetry axis. An alternative model of shape matching after spatial transformation was not supported because there were significant differences between performance on horizontal and vertical symmetry axes.

Leone, Lipshits, McIntyre and Gurfinkel take the study of the gravitational control of the symmetry axis preference into space, with an experiment on the Russian space station MIR. The vertical axis preference persists during this prolonged microgravity exposure, suggesting that the gravitational cue is not required to maintain a vertical reference frame.

Szlyk, Rock and Fisher determine the effects of perceived lateral surface slant on the detectability of symmetry under the same slant transform. They find that the observers judged object symmetry within the frame of reference of the slanted surface rather than the retinal symmetry of the projected image, if there were sufficient cues to the surface slant. The results imply that symmetry is evaluated beyond the stage of perceptual shape constancy for objects in the world.

Passmore and Johnston are concerned with the converse paradigm, the effects of texture properties on the perceived vertical slant of the texture gradient. For this study, they use a different kind of symmetry relation, that of textures that are self-similar under size scaling (the fractal property), which is a characteristic of many textures in the real world. They find that the symmetry relations in such textures do not preclude perception of the slant of a texture gradient, although it is degraded in proportion to the departure from uniform statistics.

CONCLUSION

Perhaps the most apposite conclusion is that there is no conclusion to research in the field. Papers such as those in the present set constitute more of a freeze-frame of current activities in the field of symmetry perception rather than any kind of unified approach. One interesting aspect of the collection is the connection between the experimental and the computational approaches, which promises to be an increasing feature of sensory research in general. Development of sophisticated analytic models should not be allowed to obscure the fact that very little is known as yet about the details of human symmetry perception. Instead, the models may provide a driving force for the formulation of new empirical studies to assess the mechanisms proposed, leading to an augmented exploration of symmetry perception. As in all fields, only by taking the models to their predictive limit can their validity be tested against the perceptual reality.

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