PERSPECTIVES: VISUAL SCIENCE

Close Encounters—An Artist Shows that Size Affects Shape

Denis G. Pelli

We easily recognize objects of all shapes and sizes, yet no one has any idea how we do it. It seems obvious that we must see shape in the same way regardless of size, otherwise we would recognize our friend or the letter "a" differently at each size or viewing distance (*1*). Yet the block portraits by the artist Chuck Close vividly show the size dependence of shape perception. When viewing any of Close's 1987–1997 portraits at their actual size (*2*), one can move forward and back, again and again, and the face, solid from afar, always collapses into flat marks when seen from near. The duality (solid from afar and flat from near) of these paintings shows that size affects the perception of shape, disproving the popular assumption that shape perception is size-independent. We have reproduced a recent Close block portrait, *Bill II* (1991), at one-third of its actual size (see figure, opposite page) to allow readers to experience the dramatic effect of size on what they perceive. Psychophysical measurements of observers viewing Close's block portraits reveal the importance of size, that the effect is visual (perception) not optical (physics), and that it involves a competition between the face and its constituent blocks to engage our perception of shape from shading.

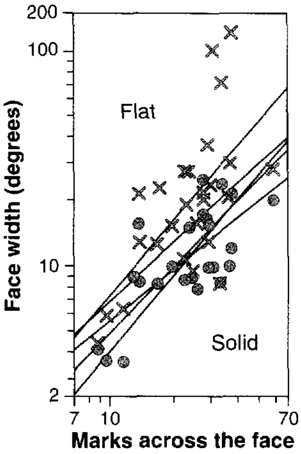
Aristotle (*3*) noted that shape perception could be independent of size only for sizes that are neither so huge as to exceed our visual field (~135° visual angle subtended at the eye) nor so tiny as to exceed our visual acuity (0.1°). As visual acuity (the fineness of vision) is largely determined by optics, the assumption among vision scientists has been that observers identify the shape of the (blurry) retinal image independently of its size. This age-old assumption seems to be supported by both common experience and priming experiments (in which the speed and accuracy of target identification are unaffected by the size difference between target and prime images) (*4*).

Nearly all of Close's paintings are of heads produced by photographing the subject, drawing a grid onto the photo and a similar grid onto the canvas, and meticulously copying one square at a time from photo to canvas (see cover, this issue). Seen from a great distance, the portrait is a visually accurate reproduction of the photo. In his earliest paintings, Close copied details within each square so that the original grid is not visible in the result, but since 1973 he has usually filled each square of the grid on his canvas with content that is independent of the original photo. Close refers to each filled square as a "mark."

In 1973, the scientists Harmon and Julesz published block portraits of Abraham Lincoln that were important in vision science (*5*). Their "critical-band" explanation of the block-portrait effect implicitly assumes size invariance and thus predicts that face recognition requires a certain number of marks per face independent of face size (but they only tested the effect at one small size). Close, too, showed his first block portrait (dot drawing) in 1973 (*6*). Unlike Close's recent work, the early block portraits by Close, and those by Harmon and Julesz, had small (<1 cm) blocks that viewers never approached closely enough to experience the full duality (*7*). Instead, viewers experienced only a weak one-time effect, elegantly described by Harmon: *"Viewed from close up, these 'block portraits' appear to be merely an assemblage of squares, . . . [but] once a face is perceived it becomes difficult not to see it, as if some kind of perceptual hysteresis prevented the image from once again dissolving into an abstract pattern of squares."*

There are well-known antecedents to block paintings such as the coarse "benday" screens used in Roy Lichtenstein's cartoons of the 1960s, Seurat's pointillist *A Sunday on the Grande Jatte* (1884–1886), and the ancient mosaics at Delos and Pompeii. However, none used coarse grids to render three-dimensional shape, so there is no duality. The mosaics and the pointillist grids are too fine to readily disintegrate into flat marks, and the benday screens are uniform, so that they are always flat at all distances. The only precedent for the duality of Close's recent heads may be the long-lost 4th century (B.C.E.) *skiagraphia* paintings by Apollodorus in which he achieved intermediate colors by juxtaposing large patches of unmixed colors that blended when viewed from a distance (*8*).

The Chuck Close retrospective (*2*) exhibits scores of block portraits, half in color (like *Bill II*) and half in black and white, with a wide range of marks across the face (5 to 21), face size (2 to 200 cm), mark size (0.5 to 9 cm), and mark type. This variety allowed us to undertake a parametric investigation of the size dependence of shape perception. We used a psychophysical "nose test" to measure the transition from flat to solid in 33 Close portraits. While looking at the painting, the observer is asked to move forward and backward to find the viewing distance at which the nose emerges from the canvas. (The instructions emphasize the bridge of the nose to minimize the effect of the nostrils, which Close usually renders with detail exceeding that of the grid.) From afar, the nose (illuminated from the side) appears to stick out from the canvas. As the viewer approaches, the nose suddenly collapses, becoming a flat patch of unevenly colored skin. The transition is abrupt. The observer is asked to find the transition point, and the critical distance is measured from the observer's eye to the painting. Clearly, size does matter because the face is perceived differently at different sizes (viewing distances).



The nose test. The critical face width of Close's portraits plotted against the number of marks across the face. The regression lines, one for each of five observers (accounting for half of the variance), are plots of the results for judging nose emergence on each of the 33 gridded portraits from the Chuck Close retrospective (except the *Keith/Six Drawings Series*) (*2*). X and O are raw data for two observers. Size independence predicts a vertical line. All five lines have log-log slopes close to 1 (mean 1.0, SD ± 0.2), showing that the perceived shape does depend on size.

When viewing all possible block portraits there is a division into two domains: The face is seen as flat in one domain and solid in the other. We mapped the boundary dividing the two domains to reveal how size affects shape. For a given painting, the num-

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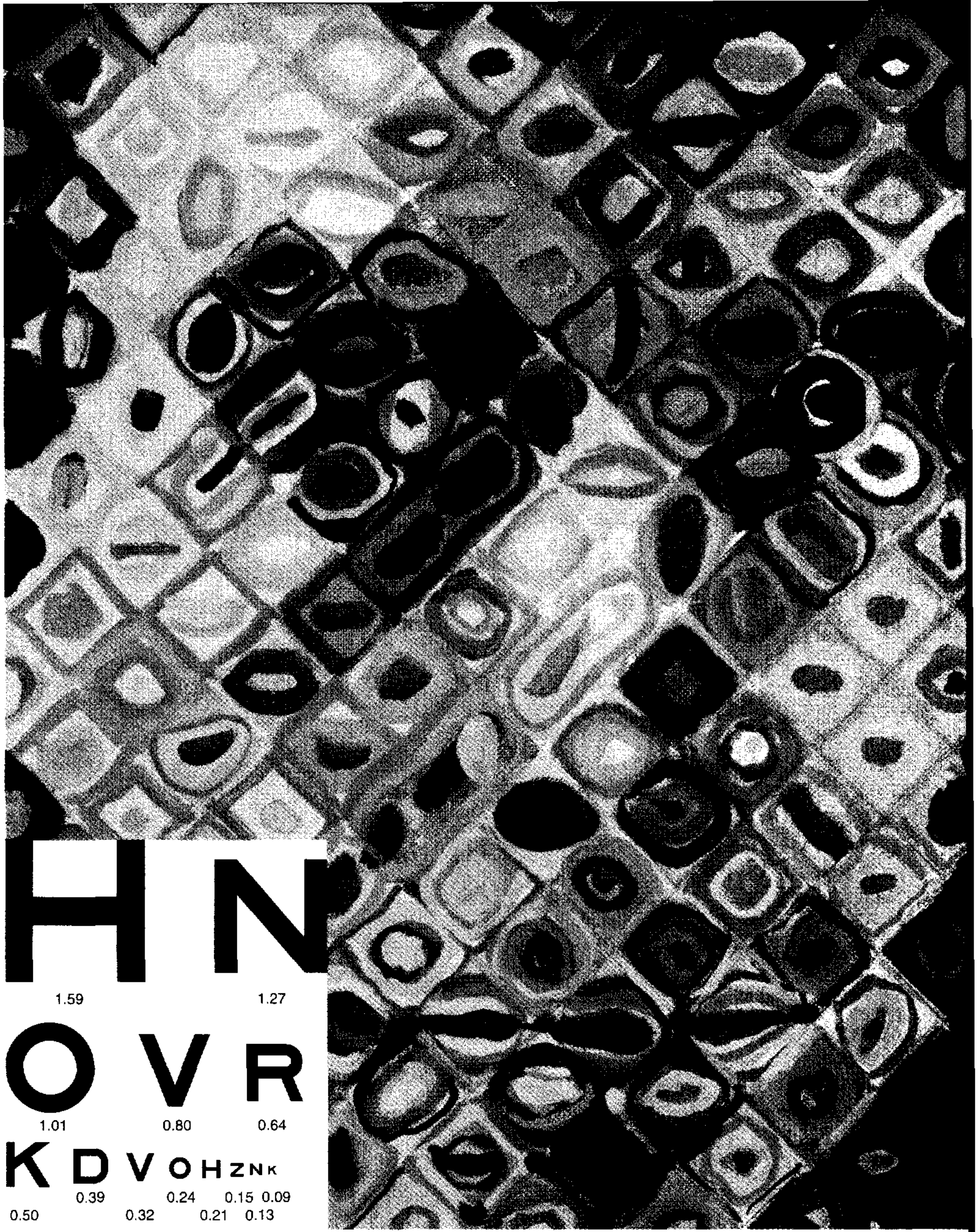
ber of marks across the face is fixed. The critical face width in degrees is the angle subtended by the face at the critical viewing distance. We plotted critical face width against the number of marks across the face. The five solid lines represent the results from the viewing of 33 block portraits by five observers (see figure, opposite page). There are obvious differences between observers, presumably because each must set his or her own internal criterion for nose emergence. If shape perception were size-independent, the plot would be a vertical line. Instead, the modest positive slopes indicate that people need more marks to see the nose stick out on larger faces. The five lines have slopes close to 1, demonstrating that critical face width is proportional to number of marks across the face. From the slope of the lines it is clear that the mark size (face width in degrees divided by number of marks across the face) is constant. So, it is the critical mark size (roughly 0.3°) that divides the flat from the solid domain. Portraits are seen as flat when marks are larger than 0.3°, and solid when marks are smaller than 0.3°, for faces of all sizes.

The type of mark used may account for much of the residual scatter of the points about the lines in the graph. Close has tried many types of mark, and they affect the critical distance at which the nose collapses. The *Keith/Six Drawings Series* (1979) of Close portraits are all the same size, based on the same photograph and grid, but use very different marks (watercolor dots, fingerprints, ink stick scribbles, and white Conté crayon) and have different critical mark sizes, ranging from 0.2° to 0.7°.



Faces are but a gallery of pictures. *Bill II* (1991), a block portrait by Chuck Close, reduced to one-third of its actual size and cropped. Compare its appearance from near and far (>5 m) or compare it with the tiny copy of *Bill II* (see opposite page, top). Ignore the pupils, nostrils, and the line between the lips, which have much higher resolution than the 1.3-cm grid that represents the rest of the face. Below each letter in the eye chart is a number indicating its size (the observer's acuity) as a fraction of a mark (a filled square of the painting's grid). (Oil on canvas, 92.4 x 76.2 cm. Photograph by Bill Jacobson.)

COURTESY OF PACEWILDENSTEIN

But can the size effects of Close's paintings be explained by simple optics? Vision scientists, taking size independence for granted, have supposed that increasing the viewing distance reveals the face simply because it increases the blur, wiping out the grid. By taking off one's glasses (or putting on someone else's), one can blur the image (remove the grid) and the face is revealed, as viewers of Close's paintings often discover for themselves. But, whereas one could (at least in principle) walk far enough away from a block portrait to achieve the same blur as the wrong glasses provide at short distances, in fact, the size effects that are most salient in the Close exhibition occur over modest distances (<6 m) at which the eye's blur is only a fraction of a mark. Readers can try this for themselves by finding the points of nose emergence with and without their glasses, and comparing the appearance of *Bill II* and their visual acuity (size of smallest readable letter) between the two conditions. Defocus (blur) reveals the nose only when it completely smears out the grid, at an acuity of about one mark (see acuity scale on figure, this page). But when the observer simply increases viewing distance, without defocus, the grid is still apparent when the nose pops out, at an acuity of about a quarter mark.

To unequivocally conclude that perceived shape depends on the size per se of the retinal image, we tested a condition in which the retinal image changes only in size. We compared critical distances while looking through either a 1- or 2-mm pinhole; these artificial pupils are sufficiently small to make the eye diffraction-limited (the quality of the image depends only on pupil size) (*9*). The eye's blur with the 1-mm pupil is twice as big as, but otherwise identical to, its blur with the 2-mm pupil. (The retinal illuminances are equated by adding a 25% transmission neutral density filter to the 2-mm pupil.) If we perceived the retinal image's shape independently of its size, then the critical image size should double when we double the blur. In fact, we find that the critical image sizes are identical, showing that retinal image size, not blur, determines the perceived shape.

Observers must see marks both substantially larger and smaller than 0.3° to experience duality. To collapse reliably, a portrait composed of 0.4-cm marks (like Harmon and Julesz's Lincoln) must be viewed from less than 40 cm, closer than most viewers will come. For 2-cm marks, or larger, as in Close's recent 1987–97 portraits (see cover, this issue) that distance is at least 2 m, which most viewers cross as they approach. Some forms of camouflage, like a tiger's stripes, may break up the animal's shape only when seen from very near. Most perception textbooks show a spotted Dalmatian, initially lost in a background of spotty shadows, but which usually appears quickly and never goes away (like Harmon's description of seeing Lincoln with small blocks) (*10*). I find that the Dalmatian, like a block portrait, does break up reliably into mere flat spots when enlarged (or approached) to make the spot spacing exceed 0.3°.

Testing a wide range of sizes revealed that the division between seeing a block portrait as flat or solid occurs at a critical mark size of 0.3° (which is independent of the number of marks per face). This refutes the size invariance of shape perception and Harmon and Julesz's critical-band theory of the block-portrait effect. It seems that the blocks (or their edges) (*11*) compete with the face to capture the visual shape-from-shading process. The size and type of the marks determine their power of attraction. This competition is bottom-up, determined by the stimulus, not top-down, controlled by the observer. Close concedes that, painting at arm's length, even he cannot see the face unless he backs away (*2*).

One might suppose that Close was a naïve artist, obsessed by grids, who innocently produced the coarsely gridded paintings that we use here to reveal the size dependence of shape perception. In fact, Close has devoted his career to studying just that: *"The self portrait from 1967–68 is the first portrait head that I painted. . . . The idea was to make something that was so large that it could not be readily seen as a whole and force the viewer to scan the image in a Brobdingnagian way, as if they were Gulliver's Lilliputians crawling over the surface of the face, falling into a nostril and tripping over a mustache hair"* (*2*). He was more thorough than his scientific colleagues; the size of the marks in his block portraits increased by 15% per year from 1973 (0.4 cm) to 1997 (9 cm). He made sure that exhibitions of his work would convey the idea, canceling a retrospective that could not provide long viewing distances. So credit Chuck Close with discovering this size-dependent breakdown of our ability to extract shape from shading, well within the bounds of our visual field and acuity.

References and Notes

1. In 1886, Ernst Mach wrote, "Some forty years ago, in a society of physicists and physiologists, I proposed for discussion the question, why geometrically similar figures were also optically [visually] similar. I remember quite well the attitude taken with regard to this question, which was accounted not only superfluous, but even ludicrous" [*The Analysis of Sensations*, translated by C. M. Williams and S. Waterlow (Routledge/Thoemes, London, 1996), p. 109].
2. Chuck Close exhibition organized by Robert Storr, Museum of Modern Art, New York City, 26 February to 26 May 1998. The exhibition is at the Hayward Gallery, London, 22 July to 19 September, 1999. All relevant paintings, except *Maggie*, are reproduced in the catalog [R. Storr, *Chuck Close* (Museum of Modern Art, New York, 1998)]. The Close quote is from recorded narration provided at the exhibition.
3. "Beauty depends on size and order; hence an extremely minute creature could not be beautiful, for our vision becomes blurred as it approaches the point of imperceptibility, nor could an utterly huge creature be beautiful, for, unable to take it in all at once, the viewer finds that its unity and wholeness have escaped his field of vision" [*Aristotle's Poetics*, translated by J. Hutton (Norton, New York, 1982), chapter 7].
4. E. E. Cooper, I. Biederman, J. E. Hummel, *Can. J. Psychol.* **46**, 191 (1992). Unlike identification, judging whether one has seen a particular object before is size-specific. For discussion of the size question, see www.visionscience.com/mail/cvnet/1998/0307.html.
5. L. D. Harmon and B. Julesz, *Science* **180**, 1194 (1973); L. D. Harmon, *Sci. Am.* **229** (no. 5), 71 (1973); in O. J. Grusser and R. K. Klinke (Eds.), *Pattern Recognition in Biological and Technical Systems* (Springer-Verlag, New York, 1971), pp. 196–219.
6. *Keith/1,280*, exhibited at the Bykert Gallery, New York City, 20 October to 15 November 1973.
7. Harmon (1971) includes a face with 0.4-cm squares. The blocks are 0.4 cm in Harmon and Julesz's (1973) Lincoln (cover of *Science*), 0.8 cm in Harmon's (1973) George Washington (cover of *Scientific American*), and 1.0 cm in his Mona Lisa. Close's *Keith/1,280* (1973) is made up of dots on a 0.4-cm grid.
8. E. C. Keuls [*Plato and Greek Painting* (Brill, Leiden, Netherlands, 1978)], on the basis of texts by Plato and Aristotle.
9. F. W. Campbell and R. W. Gubisch, *J. Physiol.* **186**, 558 (1966).
10. Dalmatian photo by R. C. James, in R. L. Gregory, *The Intelligent Eye* (McGraw-Hill, New York, 1973), p. 14.
11. M. C. Morrone, D. C. Burr, J. Ross, *Nature* **305**, 226 (1983).
12. I thank S. Bernardete for Greek citations and D. R. Williams for suggesting the artificial pupil. Supported by the National Eye Institute.

PERSPECTIVES: GEOPHYSICS

Hawaiian Plume Dynamics

John Lassiter

The Hawaiian Islands have long shaped geologists' views about Earth's interior. The apparently fixed position of the Hawaiian "hot spot" led to the theory that deep-seated plumes of hot, buoyant mantle were responsible for ocean island volcanism at Hawaii and many other ocean island chains (*1*). Chemical and isotopic differences between ocean island basalts and mid-ocean ridge basalts have long been used by geochemists to constrain models of mantle convection and the chemical evolution of Earth (*2–4*). In this issue, Blichert-Toft *et al.* (*5*) present evidence from hafnium isotopes suggesting that ancient deep ocean (pelagic) sediments are present in the source of some Hawaiian lavas. Important in its own right, this result also suggests that combined geochemical and seismologic study of the Hawaiian "plume" may help resolve one of the most important and long-standing questions in earth science: whether convection of Earth's mantle is layered.

Evidence for layered mantle convection comes primarily from geochemistry. Mass balance appears to require that a substantial portion of Earth's mantle is less depleted in elements concentrated in the continental crust [such as large-ion lithophile (LIL) elements] than the highly depleted upper mantle sampled at mid-ocean ridges (*2, 4*). Rare gas isotope distributions, especially for Ar and He, also suggest that part of Earth's mantle retains a large fraction of its primordial gas budget, as well as a large fraction of the ^{40}Ar produced by the decay of ^{40}K (*3, 4*). To have preserved this reservoir for the age of the Earth, the reservoir must remain convectively isolated from the upper mantle, where the processes of crust formation at mid-ocean ridges and island arcs have stripped a large fraction of the initial rare gas and LIL elements. A reasonable location for this gas- and LIL-rich reservoir is therefore the lower mantle. The change in mantle mineralogy that occurs at a depth of 660 km, indicated by a seismic discontinuity, was long believed to act as a barrier to convection, blocking transfer of cold downwelling slabs or hot upwelling plumes. The 660-km discontinuity was therefore thought to mark the boundary between a depleted upper mantle and a more primitive lower mantle (*6, 7*).

This model is not consistent with recent seismic tomographic images, which are widely interpreted as indicating that many subducting slabs do not stop at the 660-km discontinuity, but continue to descend deep into Earth's interior (*8, 9*). If a substantial fraction of subducted slabs have penetrated into the lower mantle for much of Earth history, significant long-lived chemical layering is difficult to preserve (*10*). However, seismic tomography can only provide a snapshot of the current thermal structure of the mantle. Earth has been slowly cooling for the past 4.5 billion years, and there is no a priori reason why mantle convection could not have been layered for most of the geologic past even if today such layering appears to have broken down (*4*).

The mounting evidence for ancient recycled crust and sediments in the Hawaiian plume suggests how seismologists and geochemists can combine forces to constrain the

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