The Visual World of Infants

Discovering what babies can see has been a formidable challenge, but research methods now provide an objective picture of their surprising visual abilities.

Russell D. Hamer

William James, the great 19th century philosopher and psychologist, once described the sensory-perceptual world of infants as a "blooming, buzzing confusion." The image James painted raises profound questions that are pragmatic, scientific, and philosophical: How can we know what infants see? Or how can we know what any beings see if they cannot tell us, via language or other unambiguous communicative gesture, of their internal experience?

Of course, James could not know what an infant's perceptual world was like. And for many decades after James, a series of myths and erroneous ideas about the sensory world of infants were propagated. Indeed, researchers as recently as the mid-1950s believed that newborn infants were unable to see patterns because of immaturities in the optics of the eye, the retina, and the visual cortex. Moreover, as recently as the 1970s, some physicians, including ophthalmologists, told new mothers that their newborn could see almost nothing, and was essentially blind.

Can we picture what the infant's visual world is like? If we were to adopt James's view, we might reasonably envision a newborn's perception of the world to be a sort of jumble, like a dynamic Jackson Pollock painting or a Picassoesque montage of deconstructed elements of objects—impoverished in color, spatial detail, and contrast, and without organized perceptual meaning. However, many neuroscientific findings and the results of carefully designed perceptual tests now give us good reason to believe that such a characterization is very far from the truth. The newborn infant's visual world is almost certainly neither a Jamesian confusion, nor a patternless haze, nor the equivalent of blindness. We have a high level of confidence that it is a highly organized (albeit immature), rapidly developing version of adult vision, rich in pattern, contrast, and color, and that it possesses some remarkable abilities for discrimination and complex pattern recognition. In addition, the methods used to study visual development have wide applicability across sensory modalities in humans as well as in other species.

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A Conceptual Breakthrough

The ultimate demonstration of vision is behavior that can be correlated in a systematic and reliable way with a visual stimulus. In testing adults, we have the luxury of being able to devise a reliable objective test requiring only that they correctly identify the letters on an eye chart. Objective quantification of a preverbal human's visual capacity, however, poses formidable challenges.

In the late 1950s and early 1960s, developmental psychologist Robert L. Fantz of Case Western Reserve University in Ohio began a systematic study of vision in infants using a method he called *preferential looking.* He observed infants viewing a pair of visual stimuli and recorded which stimulus the infants looked at, how many times they looked at each stimulus, and how long each look lasted. By this means, he quantified which patterns, and what features of the patterns, infants could perceive or perhaps "preferred." His observations clearly showed that infants "preferred" patterned versus unpatterned, homogeneous stimuli. This observation set the stage for powerful additional methods to be introduced.

In 1974 psychologist Davida Y. Teller of the University of Washington introduced a modification to the preferential looking technique that, although subtle, was conceptually profound. She changed the role of the adult observer from having an essentially subjective task to one with an objective outcome.

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A standard eye examination can tell researchers a lot about the normal anatomy of an infant's retina and optical system, but not what the infant actually sees. As infants are unable to verbally tell us what they see, researchers over the past 40 or so years have had to develop other methods and tools that key into an infant's natural looking behavior and body movements to objectively measure how much detail an infant can actually see.

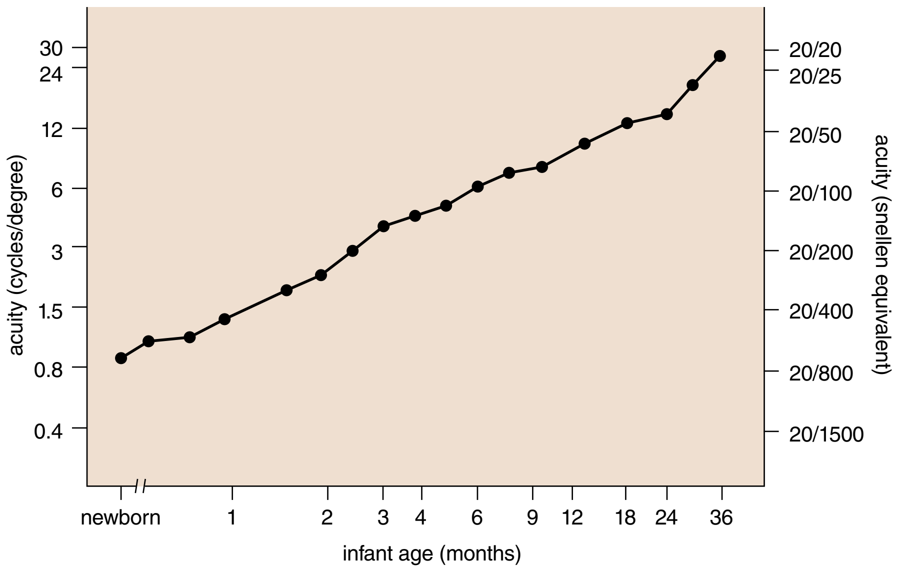
In Teller's experiment, an infant was held facing a large, uniform gray screen on which was presented a black-and-white bar grating pattern. The holder was shielded from viewing the grating. An adult observer, also blind to the grating location, was hidden behind the screen, and observed the infant through a central peephole. (*See a linked video of the procedure at www.americanscientist.org.*)

On each experimental trial, the grating was presented randomly on the left or right side of the screen. The observer's task was to use any of the infant's behaviors, such as eye or body-orienting movements, to make a forced-choice guess as to whether the grating was located on the left or the right. Thus, Teller dubbed her method *forced-choice preferential looking.*

The infant had a view of a large, gray screen with a grating on one side of the center and a patternless gray patch on the other side. The grating and plain patches were designed to have a luminance equal to that of the screen, so that if the infant's visual systems could not resolve the grating, there would be nothing to bias their looking and orienting behavior toward either side. But, because infants have strong (apparently innate) preference for patterned versus unpatterned stimuli, if they can resolve the grating, their behavior should reveal the location of the grating to the hidden observer behind the screen.

Teller's key innovation was to make sure each guess of the observer had an objective outcome—correct or incorrect—with a 0.5 probability of being correct by chance. If the adult correctly identified the randomized location of the grating for five trials in a row, for example, the probability of that happening by chance was $1/2^5$, or 0.031. Early studies generally presented each test stimulus 20 times (or more) to increase the statistical reliability of the results.

The concept underlying the approach was one of information transfer. As Teller characterized it, the information about the location of the grating would be "transmitted" through the infant's visual system to the perceptual and motor centers, which would "pass" the information to the observer via the infant's behavior. Teller described the idea in a 1979 paper: "If the observer's performance is above chance, it follows that the infant can discriminate that particular stimulus from its surrounding visual field. If the observer's performance is at chance, it follows that the information concerning the location of the stimulus was lost somewhere between the display and the observer, hope-



Visual acuity of infants is often measured in terms of the number of regularly spaced black-and-white grating bars an infant can reliably respond to. The finer the bars in the grating, the more cycles (pairs of black and white bars) per degree of visual angle there are (*left axis; all numbers in log scale*). Adult grating acuity is about 30 cycles per degree. Babies are born with an acuity of 1 to 2 cycles per degree, but rapidly mature to about half of an adult's level by the age of 2 years, and children reach adult acuity by the age of 3 to 5 years. (Adapted from D. Y. Teller and J. A. Movshon, *Vision Research* 26:1483.)

fully (but not necessarily) within the infant's sensory visual system."

To determine the visual acuity of an individual infant, the percentage of trials for which the observer correctly identified the location of the grating had to be measured for each of set of gratings with different bar widths (some too fine to see, others extremely visible) that encompassed the infant's visual threshold.

The resulting data were encouragingly systematic—for gratings with large bars, the adult observers' performance was always significantly above chance, and often nearly 100 percent of grating locations were correctly identified. For the finer gratings, the observer's performance dropped to chance performance (50 percent correct), and intermediate performance resulted when in-between bar widths were displayed.

Such a performance curve is called a *psychometric function* (*see figure on page 100*). The threshold bar width is estimated as the width where performance is significantly above chance, in this case being the bar width corresponding to 75 percent correct. When this procedure was used to test a large sample of infants of different ages, the thresholds shifted systematically from coarse gratings (low acuity) to finer gratings (higher acuity) with increasing infant age, mapping out a regular developmental sequence for grating acuity.

The forced-choice preferential looking procedure has valuable internal controls based on performance at either end of the psychometric function. Chance performance reassures us that the stimulus display did not have any detectable artifacts that would draw the infants' visual attention even if they could not see the grating. Performance at or near 100 percent correct shows that when the grating is above-threshold for the infant, the infant has the sensory and motor mechanisms adequate to do the task and orient to a visual stimulus.

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With the introduction of this technique, the characterization of infants' visual development joined the domain of the modern, objective psychophysics traditionally used to study sensory capacity in cooperative, linguistically competent adult observers.

Mapping Out Acuity

Between the mid-1970s and mid-1990s, research coming out of labs worldwide, including Teller's, used the forced-choice preferential looking method to establish reliable, objective norms for the development of visual acuity in humans and nonhuman primates.

Grating acuity is measured in terms of spatial frequency, in units of cycles per degree. A *cycle* is one repeat of a pair of the light and dark grating bars, and a *degree* is a measure of bar size in terms of visual angle. One degree of visual angle encompasses 60 *arcminutes* (one arcminute equal to 1/60th of a degree). The individual line-strokes of the 20/20 letters on the widely used Snellen eye chart encompass 1 arcminute, which is the width of each bar in a grating with a spatial frequency of 30 cycles per degree. The line-strokes of the big "E" on an eye chart (for 20/200 vision) are 10 times larger, or 10 arcminutes, corresponding to a grating with spatial frequency of 3 cycles per degree. As acuity improves with age, infants can see gratings with smaller and smaller bar widths (or higher and higher spatial frequency).

The fractions in a Snellen eye chart, originally developed by Dutch ophthalmologist Herman Snellen in 1862, quantify someone's acuity compared to the average normal adult acuity of 20/20. For example, consider a person with 20/200 acuity. The fraction means that smallest letters he or she can read from 20 feet (the numerator) could be read by someone with normal acuity from 200 feet (the denominator).

Data shows that newborn healthy infants have pattern vision starting with an acuity of 1 to 2 cycles per degree. Acuity increases steadily and rapidly over the first 1 to 2 years of life, achieving 12 cycles per degree by the age of 1 year. So a 3-month old, on average, has an acuity of 3 cycles per degree, a 6-month old's acuity is 6 cycles per degree, and so on until about 18 months to 2 years of age. Behavioral grating acuity reaches adult levels by the age of 3 to 5 years.

Acuity in Perspective

Although a 3-month-old's acuity of 3 cycles per degree of visual angle (the equivalent of 20/200 vision) seems quite poor compared with that of an adult, consider what an acuity of 20/200 permits one to see. If an infant could read, the 20/200 "E" on an eye chart would be readable at a distance of about 6 meters. If you hold up your thumb at arm's length, it is about 2 degrees of visual angle, or about 12 times wider than the line-strokes of that big "E." In other words, an infant in your arms can easily see the important features of your face: your eyes, nose, lips, and smile. The baby can also see his or her own hands, fingers, feet, and toes. The irises of your eyes (which are about 1.3 centimeters in diameter) would be visible from 4.5 meters; your whole eye would be visible from about 12 meters; your mouth would be visible from about 22 meters. The baby could see something the apparent size of the Moon, which is visually about three times larger than the line strokes of the big "E" on the eye chart. It's also the about the same size as a 70-meter long Boeing 747 aircraft when it is 24 kilometers away.

But can infants focus on objects that distant? From the time of Fantz's early studies in the 1950s and 1960s, it was widely believed that young infants could only focus up to 18 to 25 centimeters in front of their faces—and this myth is still propagated today in popular books and on websites on parenting and development. However, the viewing distance of the stimuli in most of the forced-choice preferential looking studies has been 50 to 100 centimeters, or more in some cases, and these thresholds are considered to be lower-bound estimates.

If an infant could focus optically no further than 18 centimeters, for example, and the gratings were presented at 50 centimeters, the image of the grating reaching the retina would be out of focus by about 3.6 diopters, which would reduce the acuity of an adult by 4 to 5 lines on the eye chart. This

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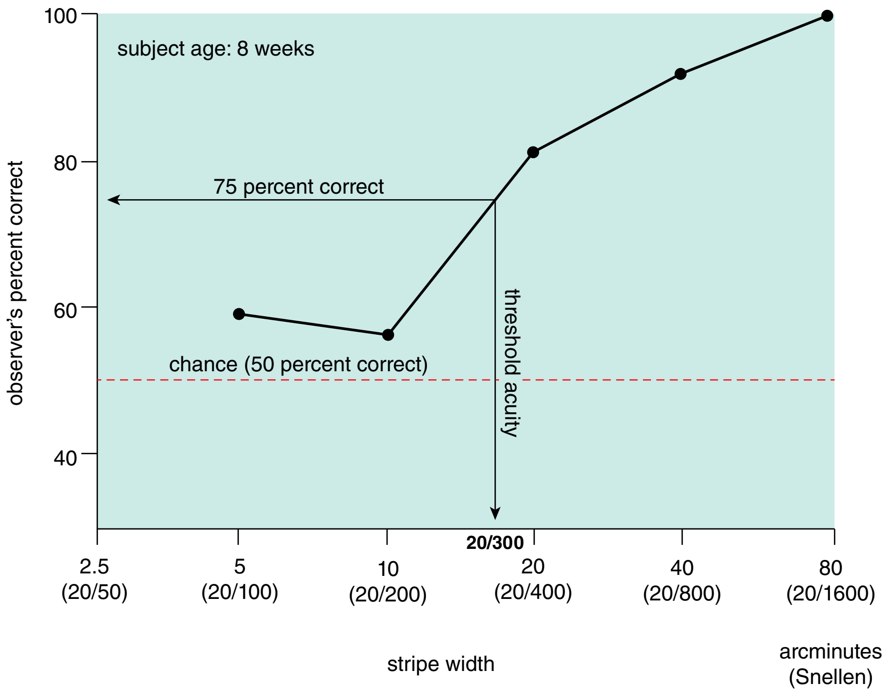
Parents are often told that their newborns require bold contrasts such as black and white patterns (*top*) and bright colors (*bottom*) to promote normal visual development. Although newborns are attracted to these strong stimuli, research has shown that their visual systems are capable of resolving much more subtle patterns and colors. Although infants aren't capable of verbalizing what they can see, we can nevertheless obtain objective estimates of their abilities using what's called the *forced-choice preferential looking method*, which takes advantage of infants' natural preferences to look at, and orient towards, patterned stimuli. In addition to acuity, it has been used to track development of sensitivity to visual contrast, color, motion, and other visual features, as well as development of other sensory modalities, such as hearing.

amount of defocus would mean that the "true" behavioral acuity (if optical blur were corrected) might be considerably higher than the measured acuity. Although researchers did not in fact know the plane of focus of the infants during testing, evidence from independent studies of this issue, including those by optometrists and neuroscientists Grazyna M. Tondel and T. Rowan Candy of Indiana University, suggest that by at least eight weeks of age, infants in these studies were capable of adjusting their focus to be appropriate to the test distances. Overall, the research indicates that infants have the capacity to focus on objects at virtually any distance, from infinity to very close to their own face, with relatively accurate control of focus starting at the age of about eight weeks, and improving thereafter. There is no compelling evidence, therefore, that the acuity values measured were severely underestimated as the result of impediments to optical focus.

The first year of life is an intense period of development, involving many complex neural and physical changes necessary to create the dynamic experience of vision.



An infant's visual acuity is estimated from a curve called a *psychometric function*, depicted here for an 8-week-old infant. The graph shows the observer's percent correct (*y-axis*) for each of five different gratings with bar widths of 5, 10, 20, 40, and 80 arcminutes, corresponding to Snellen eye chart values of 20/100, 20/200,20/400, 20/800, and 20/1600 (*x-axis*). For the coarse gratings, the observer's percent correct was highly significantly above chance performance (as high as 100 percent correct). For finer gratings, performance dropped to near chance (50 percent correct). The threshold bar width, or acuity, was defined as the bar width that would have yielded 75 percent correct. The acuity estimate for this 8-week old infant was 20/300, about 15 times worse than normal adult acuity of 20/20. (Adapted from D. Y. Teller, 1979.)

If the infants' optics are not limiting their acuity, what is? Anatomical evidence obtained from the retinas and brains of infant cadavers, along with physiological data from nonhuman species, and mathematical modeling of visual processing, all point to immaturities in the retina and the visual centers of the brain as the limiting factors in infants' visual sensitivity and acuity. The improvement in acuity tracks the maturation of the spatial processing abilities of the retina and brain. One example is the maturation of the *fovea,* the central part of the retina that is used to see patterns with very fine spatial detail. The infant fovea (which comprises about 4 degrees of visual angle) is functional, but has a lower density of photoreceptors packed into it. Over the first two years, the foveal cone density increases and the cells themselves assume adult form, with increased light-capturing ability and sensitivity. The visual acuity limit of adults closely matches the spacing of their foveal cone photoreceptors (approximately 1 arcminute), equivalent to the dimensions of the line strokes of the 20/20 eye chart letters and the separation between the strokes.

Looking Forward

The forced-choice preferential looking paradigm has had enormous influence not only on the study of visual development, but also on research into other sensory modalities, and the investigation of perceptual and cognitive development in humans and in animals. Within the domain of visual development, the paradigm was used to show that infants can resolve dark and light features of relatively low contrast, not just completely black and white. It was used in the first demonstrations that young infants have true color vision, and can detect more than just brightness differences. Both of these topics also remain the subject of persistent myths perpetuated to parents by popular books and articles, suggesting that infants can only see high-contrast patterns in black and white.

The first year of life is an intense period of development, involving many complex neural and physical changes necessary to create the dynamic experience of vision. But behavioral studies, augmented with complementary research using brain wave measures to follow the maturation of the visual cortex, have shown that, although infant vision is not as good as that of an adult, the visual experience of babies is quite rich and well-organized. It is certainly not a "blooming, buzzing," patternless confusion.

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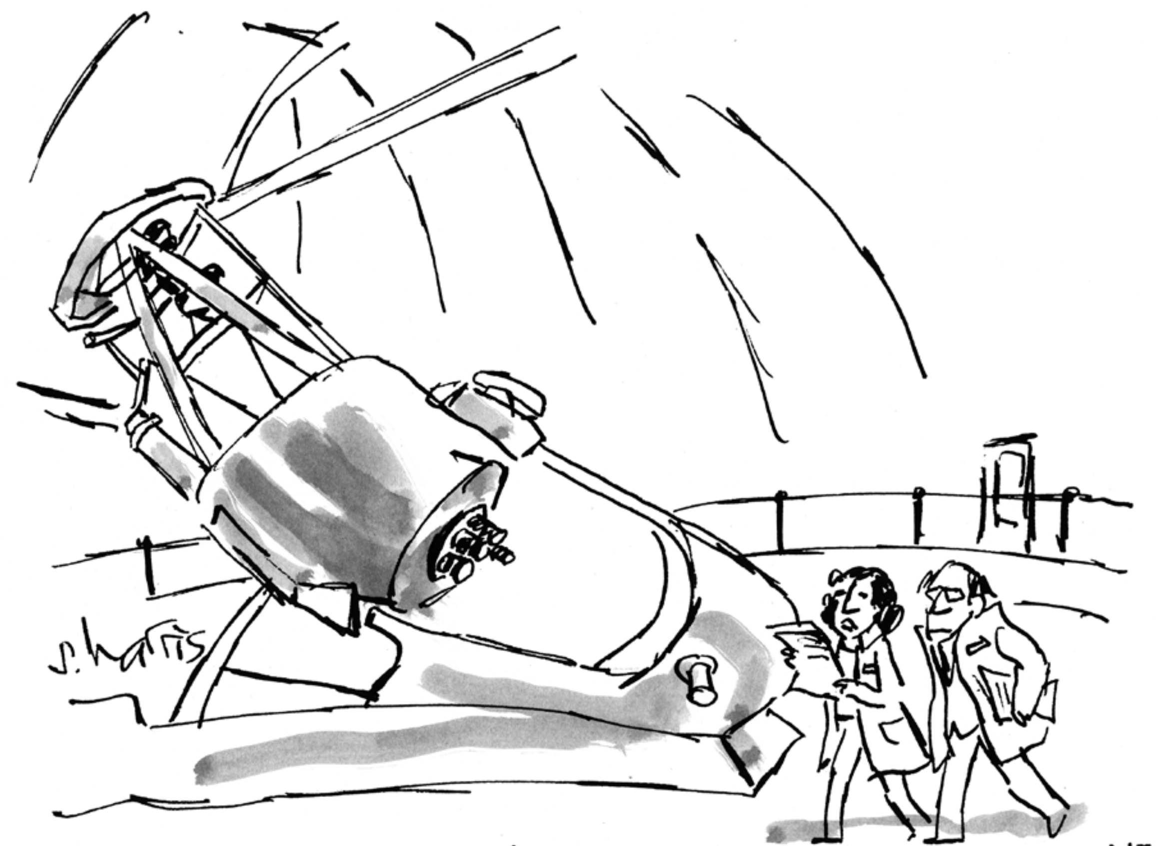

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