Images as Interstellar Messages[1]

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Introduction

Do images provide a foundation for interstellar communication that is relatively unambiguous? Is there something special about images that makes them a universal medium of communication, likely to be understood with little difficulty by extraterrestrial intelligences sufficiently advanced that they attempt to contact us via, say, radio or laser? This is the question we address in this chapter. It is natural to suppose pretheoretically that images are a particularly easy medium of communication, one that requires little if any interpretation. Our own subjective experience when we view images is that the process of seeing is usually effortless and almost instantaneous. Moreover, if we wish to create road signs that can be understood by drivers of different native languages, we use pictures rather than words, and the pictures are so effective that we trust them to guide the actions of drivers even in cases where a misinterpretation of a sign could have serious consequences. Since images communicate effortlessly to people of different native languages, then perhaps they can also communicate to extraterrestrials whose intelligence is sufficiently developed. Perhaps no Rosetta Stone of translation, or merely a cursory one, will be needed if we use images. The message of the image will be displayed relatively transparently in the image itself. Some such hope appears to underlie several attempts at extraterrestrial communication, such as the Pioneer 10 and 11 plaques, the Voyager recordings, the Arecibo message, the Evpatoria message, and the Encounter 2001 message (Drake and Sobel, 1992; Dutil, 2004; Sagan, 1978).

In evaluating this hope, we will be guided primarily by recent results in cognitive neuroscience and computational modeling of visual perception. There is now a large body

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of empirical research and mathematical modeling that describes the processes involved in the visual perception of an image by humans. This body of research has interesting implications for using images for communication with extraterrestrials.

The Passive Camera

A common view of visual perception is the passive camera theory. According to this theory, vision is a passive process of objectively recording whatever is in the environment in front of the observer. The eye, after all, has a design much like a camera, with a focusing lens and a recording surface, the retina, onto which the focused image is cast. As long as the eye is in good working order and properly focuses an image on the retina, all is well and visual perception will occur. According to the passive camera theory, so long as the extraterrestrials in question are sufficiently intelligent, e.g., so that they attempt to communicate with us via radio or laser, and so long as they have a sensory apparatus analogous to the eye in that it can record images in roughly the visible spectrum (400nm to 700nm), then we can be reasonably sanguine about communication via images. They will perceive the same objective image as we do, and can then proceed to decode that image to find the messages it contains. In many cases the message in the image will be fairly transparent, as when the bodies of male and female humans are depicted. In other cases, even though the image itself is perceived by the extraterrestrials much as it is perceived by us, they will still have some work to do because we have used some encoding scheme to pack nonvisual information into a visual format. But this is no more work than any human receiving the message would have to do.

Visual Construction

Although the passive camera theory is appealing, it is accepted by almost no serious vision researchers today. One reason is that roughly half of the brains cortex is engaged in visual perception. Approximately 50 billion neurons and tens of trillions of synapses are engaged each time you simply open your eyes and look. The entire occipital lobe, most of the temporal and parietal lobes, and large portions of the frontal lobe are engaged in vision. Why should half of our highest processing power be engaged by vision if visual perception is simply an objective recording process, as held by the passive camera theory? Certainly no manmade camera has such processing power attached to it, nor is such processing necessary for a camera to function normally. The dominant view among vision researchers today is the visual construction theory (Gregory, 1972; Hoffman, 1998; Knill and Richards, 1996; Marr, 1982). According to this theory, visual perception is fundamentally a sophisticated process of constructing visual scenes or visual interpretations that, in some sense, best account for the data available in an image. Visual perception is, at its core, a process of theory building, and what we see at any moment is the best theory that our visual system has constructed at that moment. The visual world we see at any moment is not an objective and passive recording of what is out there, but instead is a very active and subjective construction of a theory of what is out there, a theory that tries to account for the images one receives. In this regard, the processes of visual perception are much like the processes of scientific theory building, involving sophisticated inferences based on the data available. But there is one major difference: the inferences underlying visual perception, unlike scientific inferences, typically proceed without our conscious awareness of them.

The reason that half of the brains cortex is engaged in vision is that the variety and sophistication of the inferences involved in constructing visual interpretations of images requires vast computational resources.

The passive-camera theory of vision suggests that images could serve as a readily understood form of communication with extraterrestrials. The predictions of the visual-construction theory are not as obvious. To understand its predictions, we will need to explore the visual-construction theory in a bit more detail.

Visual Examples

Perhaps the easiest way to understand the visual-construction theory better is to look at some concrete examples. We will begin with the "blue patches" in Figure 21.1.

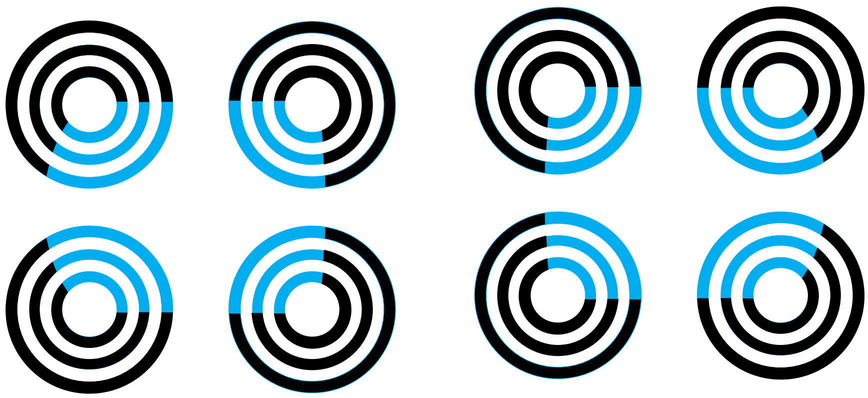

Figure 21.1. Blue patches.

When you look at this figure, you probably see two blue regions that are roughly rectangular. However, the only blue that is literally on the page is in the blue arcs of circles. The blue that you see filling in the rectangular regions is entirely constructed by your visual system. To check this, you can cover up the arcs, and you will see the blue disappear from the interior area. We often think of color as an objective property of objects that our eyes simply report to us. But this figure illustrates that in fact colors are constructions of our visual system. You might also notice that the blue rectangular regions have clear edges around them, even in the areas between the arcs of circles. Again, these edges are not literally on the page, as you can again verify by covering the arcs. These edges, and indeed all lines and edges that you perceive, are constructions of your visual system. A spectral photometer, a device for measuring light, would not report the edges or the blue interior that you see. Another example of how you create colors and edges is "The Shadow" interactive applet accessible online at

http://aris.ss.uci.edu/cogsci/personnel/hoffman/Applets/index.html.

This applet lets you interactively change the parameters of a moving display to let you experience a wide range of colors constructed by your visual system. It also illustrates that we create the motions that we see.

The blue-patches figure is also a stereogram. You can fuse the left and right sides of the figure, by crossing your eyes or using a stereo viewer, and you will see a ghostly blue cylinder, in three dimensions, floating above black circles. Again, the three-dimensional shape of the cylinder and its ghostly blue color are both constructions of your visual system, not literally painted on the page. And in fact any time you see the world and its objects in three –dimensions, you are constructing all the depth that you see. The images at the eyes are only two-dimensional. To see depth, to see a third dimension, requires sophisticated inferences by your visual system.

Another example of visual constructions is the "mixed-colors" display first devised by Jan Koenderink (Figure 21.2).

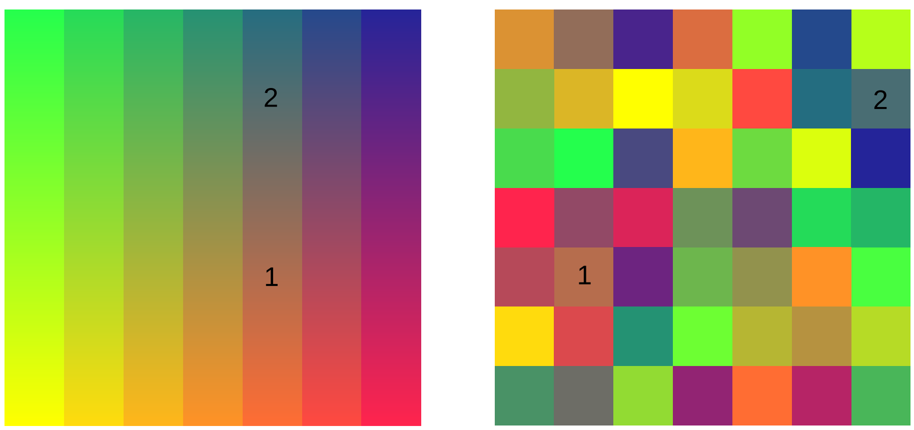

Figure 21.2. Mixed colors.

On the left is an array of 49 colored squares, arranged to vary systematically in their chromatic properties. Notice that these squares seem to be illuminated by colored lights, such as a yellow light from the bottom left corner. The squares are not perfectly flat, but seem to be slightly scalloped, either convex or concave. Moreover, each square seems to be darker at one side and lighter at the other. Now on the right is the same array of 49 colored squares, just randomly rearranged. Exactly the same 49 patches of ink are used on the right side as the left. But notice how different your visual construction is. The squares on the right seem to be illuminated by a single white light source, rather than several colored light sources. The squares look perfectly flat, not scalloped in depth. They are of uniform brightness, not lighter on one side than the other. And there appear to be browns and tans on the right that do not appear on the left. What this figure illustrates is that the visual system not only creates the colors that we see, but that it does so in coordination with the three-dimensional shapes and light sources that it constructs. The constructions of the visual system can be quite sophisticated, which is why billions of neurons are required. An interactive version of the mixed-squares figure is available online as the "Color Grids" at the same URL given above for "The Shadow," and it allows one to explore in more detail how the visual system constructs colors in coordination with depth and light sources.

Sometimes your visual system constructs more than one theory to account for the images it has received. In this case, your perception becomes multistable, as you switch from perceiving one theory to another. An example of this is the "subjective Necker cube" (Figure 21.3), first devised by Bradley and Petry (1977).

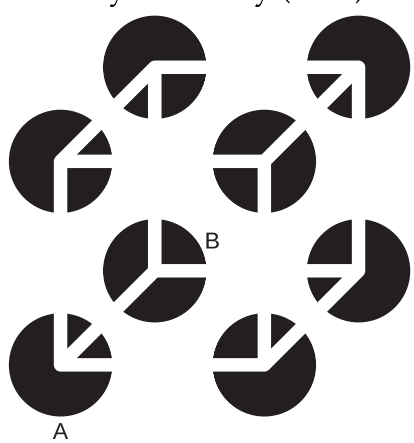

Figure 21.3. Subjective Necker cube.

Perhaps you see a ghostly three-dimensional cube floating in front of black disks? Of course the page is flat, so the three-dimensional cube you see is entirely your construction. If you look a bit longer, you might notice that the cube flips, and you see a different cube floating in front of the disks. One cube has the corner labeled "A" in front, the other cube has the corner labeled "B" in front. Which cube is there when you dont look: The cube with "A" in front or the cube with "B" in front? The answer must be that neither cube is there, since there is no cube at all until your visual system constructs one. The key point of the visual construction theory is that this is also true of every object and every visual property that you experience visually in everyday life: It isnt there until you look and your visual system then constructs it for you.

If you look again at the subjective Necker cube, you might notice the ghostly-looking lines that extend between the black disks. These lines are entirely constructed by your visual system, and would not be reported by a photometer, since there is no luminance difference in the image for it to pick up. But in fact all lines that you perceive are constructed by your visual system, even the lines that make up the letters of the words you are now reading. Lines are not available in the image at the retina. The reason is that the retina has a discrete array of photoreceptors that catch quanta of light. This is the starting point of vision. It is not a continuous surface, but a discrete array. Any continuous visual objects or properties that you perceive, such as lines, edges, and surfaces, must be constructed by your visual system from the discrete information available at the retina. One might think, for instance, that an image as simple as a silhouetted black object on a white background would be readily perceived as such by any sufficiently intelligent extraterrestrials. However, even the silhouettes that we see are the end result of quite sophisticated inferential processes that might not be shared by all intelligent extraterrestrials.

If you look once more at the subjective Necker cube, you can think of the black disks as holes in a sheet of paper, and behind that paper, through the holes, you see a cube. Notice that the new cube you now see does not look ghostly, but solid, even though you cant see all of the lines of the cube. The ghostliness or solidity of the lines is your visual construction. Also note that you can again see two different cubes through the holes, one with corner “A” in front and one with corner “B” in front. That makes four different theories your visual system has constructed for this single image. An interactive version of this subjective Necker cube, which rotates in three dimensions, is available online as “The Rotating Cube” at the same web address as “The Shadow,” given above. In this online version you can see six, not just four, interpretations. In the extra two interpretations, half of the cube is in front of the sheet of paper, and the other half is behind the sheet of paper, and yet the cube does not rip the paper as it rotates.

Neuropsychological Examples

Further evidence that human vision constructs our visual perceptions comes from case studies of subjects with brain damage. It appears that distinct areas of the brains visual cortex are particularly important for distinct visual constructions, and damage to an area can lead to very specific impairments in our visual constructions.

It appears, for instance, that regions of the lingual and fusiform gyri are important for the construction of color. Strokes that damages these gyri of the left hemisphere can leave people with a condition called hemiachromatopsia. Their vision and cognition can be entirely normal, except that they cannot see any colors to the right of their fixation point. An apple that looks red when shown in the left visual field suddenly looks gray as it is moved to the right visual field. The reason is that the left hemisphere of the brain constructs the right half of our visual world, and the right hemisphere constructs the left half of our visual world. Damage to the color- constructing cortex on the left hemisphere therefore results in loss of color perception in the right visual world. If the color-constructing cortices of both hemispheres are damaged, one loses color in the entire visual field, a condition called achromatopsia. In at least one reported case of achromatopsia, the person not only lost the ability to perceive colors, but also the ability to imagine or dream in color (Sacks, 1987). This is understandable in light of brain-imaging studies that indicate that the same areas of visual cortex that are engaged in perception are also engaged in imagination (O'Craven & Kanwisher, 2000).

Just as there are certain regions of the cortex that are particularly important for the construction of color, there are also regions that are particularly important for the construction of motion. One such region is the middle temporal area, or MT. A stroke that damages MT on the right hemisphere can leave a person unable to see motion in the left visual field, but still able to see motion in the right visual field, a condition called hemi-akinetopsia. A stroke that sufficiently damages MT on both hemispheres leaves a person unable to see motion at all, a condition called akinetopsia. At best such a person sees motion as though the world were illuminated with a strobe light. One woman who suffered from akinetopsia reported that she could not pour tea from a pot into a cup, because the stream of tea looked frozen in space to her, and she could not see the level of tea rise in the cup (Hess et al., 1989). The neuropsychological examples we have just considered for the perception of color and motion indicate that the visual system constructs these low-level visual properties. But there are many neuropsychological cases that demonstrate that the visual system constructs high-level visual properties as well. There are, for instance, regions in the lateral fusiform gyrus that appear to be specialized for the construction of the identity of faces. A stroke that damages these regions can leave a person normal in every respect except that they cannot recognize faces, even their own face seen in a mirror, a condition called prosopagnosia. They can still recognize facial expressions, since the region of cortex that is particularly important in the construction of facial expressions is not the lateral fusiform gyrus, but the superior temporal sulcus. However, a stroke to the superior temporal sulcus that does not damage the lateral fusiform gyrus can leave a person unable to recognize facial expressions, though able to recognize facial identities.

The Logical Necessity

The visual and neuropsychological examples just discussed might be reasonably strong evidence that human vision does indeed construct the visual scenes that it perceives. But one might wonder if this is just a contingent fact about the human species. Perhaps as we evolve further we will not need to rely on visual constructions, but will be able to see reality objectively. If so, then perhaps we might assume that many extraterrestrials that are advanced enough to communicate with us via radio or laser are also sufficiently advanced that they no longer rely on visual constructions. In this case, the passive-camera theory might still be valid as a model of their visual systems, even if it is not valid as a model of ours. And this would again suggest that images might serve as a universal form of communication with these extraterrestrials. There are two problems with this argument. First, human vision relies on construction not out of weakness or immaturity, but out of logical necessity. And second, there is no reason to suppose that any turn in evolution would remove this logical necessity. Lets consider these briefly in turn. The image at the retina is couched in a restricted language: the number of quantum catches at discrete locations on a two-dimensional surface. However, our perception of visual scenes is couched in a much richer language: lines, edges, colors, textures, objects, motions, patterns of shading, and three-dimensional shapes. The retinal image provides the fundamental source of premises for visual inferences whose conclusions are our perceptions of visual scenes. Since the language of the premises is impoverished relative to the language of the conclusions, these visual inferences must be nondemonstrative, i.e., must involve background assumptions or constraints. To take one concrete example, the retinal image is two-dimensional but our perception of visual scenes is three-dimensional. The mathematical problem of inferring a three-dimensional scene from two-dimensional premises is clearly mathematically ill-posed: There are countless three-dimensional interpretations compatible with and projecting onto a given two-dimensional image. This problem cannot be solved unless one is allowed further assumptions to constrain it. These assumptions are at the heart of the constructive processes that underlie our visual perceptions. Similar arguments hold for our perceptions of lines, edges, motions, colors, textures, and objects. In each case, constructive processes are required, not because of some inadequacy of the human visual system, but out of logical necessity.

However, given that this logical necessity stems from the mismatch in richness of the retinal premises and the visual conclusions, one might wonder if this necessity might be eliminated by further evolution. Perhaps it is just an accident of our evolution that we are now in the unfortunate position that we are required, by logic, to construct our visual perceptions. Perhaps with further evolution this logical necessity will be removed.

The only way for this to happen is for the language of retinal premises to be as rich as the language of visual scenes. The retina would have to evolve to do more than catch merely quanta of light. It would have to "catch" three-dimensional surfaces and objects. And no one has any idea how to do this. All we know how to do is to catch light, and from the light to infer objects. Wishing to catch objects directly seems to be a category error. Its not simply that we dont have the technology at present to do this, but rather that the wish itself is nonsensical.

From these considerations we conclude that extraterrestrials, no matter how advanced their evolution, must construct their visual worlds no less than we do. We will not find extraterrestrials so privileged that they see reality unadorned. All of us must see only what we can construct.

Rules of Construction

If extraterrestrials must, like us, construct their visual worlds, then what does this entail about using images as a universal form of communication between them and us? The answer depends, in part, on our respective rules of visual construction.

The human visual system does not construct visual worlds haphazardly. It has an adaptive set of rules that guide and constrain its visual constructions (Hoffman, 1998). These rules are not explicit rules that some homunculus in the visual system is consciously reading and obeying. Instead, these rules are implicit in the computational processes instantiated in the neural hardware of the brain. Moreover, these rules are generally not clean, simple, and without exception, but function in many cases more like heuristics that interact and that can be overridden, when necessary, by other rules.

Many rules interact, for instance, in our construction of the three-dimensional depth that we experience. One such rule is at work in our perception of depth from visual motion. It is possible for a person to see depth even with just one eye, and the depth one sees is particularly compelling if there is motion. This is something you can check while driving. Simply cover one eye (when it is safe!) and notice that you still have a good impression of the depth of the world around you simply because of your motion. If you try this same experiment while standing still and looking at the bare limbs of a tree in winter, you will find that it is hard to decide which limbs are closer to you than others until you move. One rule the visual system uses to construct depth is the "rigidity rule": If the two-dimensional motions of features in the visual image are consistent with being the projections of features on a rigid three-dimensional object, then construct that rigid three-dimensional object as the interpretation of the visual motion. An object is rigid if the three-dimensional interpoint distances of all its features remain constant over time as the object moves. Shimon Ullman proved that, with very little visual information, this rigidity rule is mathematically sufficient to guarantee that false rigid interpretations will almost never occur, and that if there is a correct rigid interpretation it will be unique (Ullman, 1979). The equations involved are simple and easy to program into a computer to allow it to "see" three-dimensional structure from image motions. The performance of the rigidity rule, and of other computer-vision implementations of other rules, can be compared to human performance as measured by psychophysical experiments, and the rules used by the computer can then be modified to model human performance better. In this way, vision researchers successively refine their models of the interacting rules that underlie our visual constructions.

What implications do these rules have for communication with extraterrestrials via images? If we share with certain extraterrestrials the same rules of visual construction, then we can expect that these extraterrestrials will see the same visual interpretations of images that we do. This would be a tremendous aid in using images as unambiguous vehicles of communication. So a key question is this: Is it likely that extraterrestrials advanced enough to communicate with us via laser signals or radio waves also share our rules of visual construction?

Evolution of Rules

To evaluate whether extraterrestrials might share our rules of visual construction, we need to understand how we acquire these rules, and how they vary among species on Earth. Our rules of visual construction are an adaptive response to our environment that depend on our genetic endowment and the particular visual stimuli that we encounter in our development. Ones genetic endowment constrains ones capacity to learn visual rules of construction as one grows and develops. Those whose genetic endowment permits the learning of visual rules that are better adapted to their particular ecological niche in the environment are more likely to succeed in surviving to the point of having offspring. In this way, our rules of visual construction evolve and adapt to our niche in the environment.

There are many niches occupied by many species on Earth, and consequently, many varieties of visual systems across these species. Much work remains to assess the rules of visual construction of these species and to compare them. But it would appear that there can be large differences in the rules of visual construction between species, and even striking differences within a species.

Looking across species, we find that different species see different visual realities, and these realities can seem alien to us. The Python molurus, for instance, uses infrared to target fast-moving prey. Where we see light, they see heat. Even in the dark, with no visual information, they accurately locate and strike small prey. The visual world of your cat is alien from your own. Cats have no color vision and see only shades of gray. Their visual acuity is terrible: instead of 20/20 it is roughly 20/400. What is it like to see through the eyes of a cat? They live in a colorless world of fuzzy forms where motion is the defining property. You and your cat might inhabit the same room, but you don't inhabit the same visual reality. The same is true for the humble honeybee: the visual system of the honeybee, unlike the human visual system, can see the polarization of sunlight and can use it for navigation (Horridge, 1991).

Because of the light-scattering properties of water, fish vision is specialized for contrast and increased sensitivity rather than for acuity or resolution. Human vision is specialized more for acuity and resolution, and is inferior to fish vision in measures of contrast and sensitivity (Northmore, 1977; Northmore & Dvorak, 1979).

The visual systems of mammals are fundamentally different from those of nonmammals, in that mammals have a highly developed visual pathway passing from the retina to the thalamus and to the neocortex, whereas nonmammalians rely primarily on a pathway from the retina to the optic tectum. The bottleneck theory of visual evolution proposes that early in evolution mammals had the same reliance on a tectal pathway as nonmammals (Masterton & Glendenning, 1978). The presence of predatory reptiles forced these mammals to live in nocturnal or subterranean habitats, causing some adaptive atrophy of their visual systems. When the predatory reptiles became extinct, the mammals emerged to occupy diurnal habitats, and their visual systems adaptively increased in size and power. But since their neocortex had already developed during their nocturnal evolution, the new development of the visual system took advantage of the newly available neocortex, leading to a large thalamocortical pathway. Whether or not the details of this theory are correct, it illustrates that the particular history of selective pressures experienced by a species can lead to profound divergence in the evolution of its visual system.

There is not only divergence in the evolution of vision between species, but also within the human species itself. The behavioral genetics of human vision is in its infancy, but there is already at least one striking case of divergence. Most of us have three distinct photoreceptor types in the eye, sometimes casually called the red, green, and blue photoreceptors or, more technically, the L, M, and S photoreceptors. These three photoreceptor types allow us a three-dimensional range of color experience (e.g., for colored disks against a gray background). The gene that codes for the photopigment of the red photoreceptor is on the X chromosome. Women get two chances at getting the correct gene, since they have two X chromosomes, but men get only one chance at getting the correct gene. For this reason there are far more red-green color-blind men than women. Now among normal men there are two different alleles of the red photopigment gene, which differ at position 180 in the nucleotide sequence. This leads to a single amino acid difference in the photopigments, with about 62 percent of men having serine and 38 percent having alanine. These two versions of the red photopigment differ in their peak sensitivity to light by about 4 nanometers, which is large enough that these two groups of men make different color matches in the red end of the color spectrum. A single nucleotide difference in the DNA leads to a measurable change in conscious visual experience.

Women are even more interesting. About one woman in five gets one version of the red photoreceptor gene on one of her X chromosomes, and the other version on her other X chromosome. Both are expressed, and the woman has four different kinds of photoreceptors rather than the usual three in her retina. In careful experiments testing their color perception, these women give evidence of being able to see a wider range of colors than the rest of us (Jameson, Highnote, and Wassserman, 2001). If you try to imagine a new color, a moment of effort will convince you that you cannot. But these women can actually see colors that the rest of us cannot even imagine. Not only are their eyes different from the rest of us, in that they have an extra photoreceptor type, but the wiring of their visual system itself, and the concomitant rules for constructing colors, must be different from ours. Where our world of color experience is three-dimensional, theirs appears to be four-dimensional. Only by careful psychophysical experimentation over a period of years will we begin to be able to translate between the color experiences of these women and the rest of us.

So, do extraterrestrials have the same rules of visual construction that we do? This is unlikely, given the wide divergence in evolution of vision between species here on Earth, and the newly accumulating evidence of divergence in vision even between members of the human species. The species on Earth at least share the same planet, and therefore have some commonality in the selective pressures to which their visual systems must adapt. Even so, their visual systems are widely divergent. We must expect even wider divergence when we consider intelligent species from other planets.

Cognitive Interpretations of Images

Once a visual interpretation of an image has been constructed via the rules of visual construction, there still remains a later stage in which a cognitive interpretation is given to the visual construction. Suppose that you view an image, and in consequence your rules of visual construction lead you to construct a burnt and windblown landscape scene with a large mushroom-shaped cloud of dust rising above it. The cognitive interpretation you might give is that this depicts a nuclear blast. If you lived in the nineteenth century or earlier, or if you were raised in a remote jungle of Papua New Guinea, you probably would not give this interpretation. The cognitive interpretations that we give to our visual constructions of images depend not only on the images themselves, but also and quite heavily, on the cultural milieu in which we are raised. And in some cases, the message that we want to communicate via an image is primarily the culturally-conditioned interpretation that we attach to the image.

If visual evolution is divergent, cultural evolution is probably more divergent. It is unlikely that intelligent extraterrestrials share our rules of visual construction, and even more unlikely that they share our culturally-dependent rules of cognitive interpretation.

This issue arose in considerations of the images to be included in the Voyager record. Carl Sagan comments that some writers criticized this record for not including images of the ugly side of human life, such as famines and nuclear explosions. But creators of the record debated intensely whether an image of a nuclear explosion might be misinterpreted by extraterrestrials as a threat (Sagan, 1978). Similarly, they debated whether an image of humans with outstretched arms might be interpreted not as a gesture of welcome, but instead as a statement of aggrandizement.

These examples illustrate that the potential diversity in rules of cognitive interpretation of images is at least as great as the potential diversity in rules of visual construction. Given that we find such diversity in the cultural conditioning underlying such cognitive interpretations within just one species on one planet, it is surely in the cards that there will be even more diversity, and therefore more potential for miscommunication, as we expand our horizons to other planets.

Implications for Interstellar Messages

What implications does the modern theory of visual perception have for using images as universal media for communication with appropriately intelligent extraterrestrials? What we see in an image depends on (1) the rules of construction of our visual systems, (2) the aspects of the scene that our sensoria (e.g., the eye and retina) can respond to, and (3) the higher cognitive interpretations that we give to our visual constructions. To assume that an image would be given the same interpretation by an extraterrestrial as it would by us, is to assume that the extraterrestrial would (1) use rules of construction similar to ours, (2) that its sensoria would respond to physical aspects of the external world similar to those that our eyes do, and (3) that their higher cognitive interpretations of their visual constructions would be similar to ours. These assumptions are probably false. They don't hold across different intelligent species on earth, and there is little reason to expect that they hold across different solar systems. Evolutionary arguments will not allow us to conclude that intelligent extraterrestrials will share our rules of visual and cognitive construction to an extent sufficient to permit communication via images. Natural selection does not force different species to the same rules of visual or cognitive construction. It only "makes sure" that the rules of construction employed by a species will guide its behavior successfully enough to reproduce before dying. Just as there are many different ecological niches, there are many different rules of construction that will allow a species to survive successfully. So evolutionary arguments would, if anything, suggest that extraterrestrials have rules of visual and cognitive construction that are different from ours, since they have faced environments and selection pressures that are different from ours. Furthermore, assuming that the extraterrestrials are intelligent enough to send electromagnetic signals does not in any way alter this conclusion. Having that level of intelligence does not logically imply, nor does it increase the probability, that they share our rules of visual and cognitive construction. The selective pressures primarily responsible for shaping the visual and cognitive rules of construction for a given species need not be the same as the selective pressures primarily responsible for shaping its intelligence to grow to the point that it understands theoretically how to send signals at radio or optical frequencies. Indeed, human vision was substantially as it is today many millennia before any member of the human species sent the first radio signal. And species, such as the macaque monkey, whose visual systems are remarkably similar to ours, are unlikely to develop a theoretical understanding of electromagnetic radiation for many millennia to come.

How to Communicate?

So how will we communicate via images with an extraterrestrial? The problem is much like the problem we have in understanding the visual perceptions of other species, such as the shrew. We have had to do years of experiments, comparing human and shrew overt and brain-activity responses to various visual stimuli. And we are still far from truly understanding how shrews see, and our level of understanding of how shrews communicate with each other is still quite rudimentary. We would probably have to do similar years of hard work to understand and translate between our visual worlds and the visual worlds of an extraterrestrial. We would have to decipher their rules of visual construction by the same arduous process by which we are still trying to decipher our own rules of visual construction. And we still have a long way to go to understand our own rules. Only then would we be able to make images that communicate to the extraterrestrial in a way that we want. But in fact this process is likely to be more difficult with extraterrestrials than with humans and other terrestrial animals. We have ready access to terrestrial life, but in the most likely scenarios we will not have ready access to extraterrestrial intelligence, and will have to conduct our research at a distance. On earth we use the cooperation of humans and coercion of other species to conduct the necessary controlled experiments. We also use uncontrolled field studies when necessary, but their utility is limited simply because they are uncontrolled. With intelligent extraterrestrials at a distance, coercion is impossible and, even if possible, undesirable. Cooperation would require a substantial level of interspecies understanding. Until such understanding is established, uncontrolled field studies, such as analyzing whatever signals we happen to receive from the extraterrestrials and sending back signals of our own, is the best we can do. Progress along these lines will necessarily be orders of magnitudes slower than would be possible with controlled experimental studies.

Common Rules

Given that evolutionary arguments cannot assure us that intelligent extraterrestrials will use rules of visual construction similar to ours, are there other directions we might look for similarities between our rules? This is an important question to consider, since any similarities that we might find could provide a critical initial step in understanding the whole system of rules employed by an intelligent extraterrestrial.

One possibility is to look for principles of visual construction that are based entirely on fundamental mathematical principles (Narens, 1997). Since such principles are true in all ecological niches, principles of vision based solely on these mathematical principles might be universal across intelligent species. One example of such a principle is the generic-views principle: Reject any interpretation of an image that entails a nongeneric view. A nongeneric view is a view that is unstable, in the sense that small perturbations of the viewing position would lead to qualitative changes in the topological or metrical structure of the image. Consider, for instance, an image that is blank except for a single straight-line segment. A possible three-dimensional interpretation is that one is viewing a sinusoidally wiggling curve, but from just the right viewing angle so that it happens to project to a straight line in the image. This interpretation is nongeneric, because if it were true, a small change in viewing position would lead to a qualitative change in the image: If you moved your head slightly, the straight line would suddenly appear wiggly. It follows, then, from the generic-views principle that straight lines in an image must be interpreted as straight lines in three dimensions. It is also easy to show that the principle entails that three lines that intersect in a single point in an image must be interpreted as intersecting in a single point in three dimensions. Many other specific rules of visual construction follow from the generic-views principle (Hoffman, 1998).

It seems likely that some rules of visual construction based on the generic-views principle would be used by intelligent extraterrestrials simply because this principle is based entirely on fundamental mathematics. However, which specific rules of visual construction, based on the generic-views principle, are used by the extraterrestrials will depend on their ecological niche. But the assumption that some of their specific rules of construction follow from the generic-views principle might help us more quickly decipher their rules. Indeed some such assumptions may be the only way to decipher their rules if we are restricted to long-distance message sending, rather than direct contact.

Conclusion

Visual perception is not a passive process of objective recording, but an active process of subjective construction. The particular rules of visual construction used by a species reflect the adaptive history of that species, and therefore vary widely from species to species. Even within the human species there are striking differences in rules of visual construction between individuals, with some women constructing a four-dimensional range of colors, while most of us construct only a three-dimensional range. Given this variation between and within species on a single planet, it is nearly certain that the variation in rules of visual construction will be even greater across planets. It is not safe, therefore, to assume that images intelligible to humans using human rules of visual construction will also be intelligible to intelligent extraterrestrial species using their own rules of visual construction. It is even less safe to assume that intelligent extraterrestrials will use the same rules of cognitive interpretation that we do. We should expect instead that even the simplest of images will be misinterpreted. Consequently, we should be prepared to engage in the systematic, and potentially time-consuming, process of psychophysical experimentation and theory building that will be required to understand the rules of visual construction of each extraterrestrial species that we encounter. Moreover we should be prepared for similar cross-species anthropological research to understand the rules of cognitive construction of each extraterrestrial species. Only then will we be able to construct images that communicate the messages we wish. And these images may look utterly alien to us. In the most likely scenarios, our contact with extraterrestrial intelligence will be at a great distance. In this case we will not be able to conduct the controlled experiments that are necessary to understand the rules of visual construction used by the extraterrestrials. We will be limited to uncontrolled field studies: analyzing whatever signals we receive from the extraterrestrials and sending signals in return. It will be tempting in this case to assume prematurely that we understand how the extraterrestrials perceive and interpret images and related signals. This could be a serious mistake. Even with species here on earth with which we have coexisted for millenia, we are repeatedly surprised by the results of our controlled experiments.

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Appendix

The visual-construction theory of vision described informally in this paper is the dominant theory among vision researchers today, and has been developed into an elegant mathematical formalism (Knill & Richards, 1996) and applied to perceptual evolution (Bennett et al., 2002; Geisler & Diehl, 2002). In this appendix, we briefly describe some elementary aspects of this formalism.

Visual perception can be modeled as decision making under uncertainty. The viewer is given a set of images, I, and from these images must infer a description of an external world, or "scene", S. The viewer would like to know the conditional probabilities $P(S|I)$ for various scenes S, but these are not, in general, directly available to the viewer. However Bayes rule tells us that $P(S|I) = P(I|S)P(S)/P(I)$. The term $P(I/S)$ is called the "likelihood function" by mathematicians, and the "rendering function" by vision researchers. It specifies for each possible scene, S, the probability of obtaining the given images, I. This is, in principle, computable by the viewer given a model of the image formation process, say perspective projection, and a model of the noise in this process, such as Gaussian noise. The term $P(S)$ is called the "prior probability" by mathematicians, and the "constraints" or "background assumptions" by vision researchers. It represents the assumptions built into the viewer by phylogenetic evolution and ontogenetic experience. An example would be the rigidity constraint we discussed earlier that allows for inferring three-dimensional structures from two-dimensional images. The term $P(I)$ can be viewed as simply a normalizing factor that can be ignored.

Once the viewer has computed $P(S/I)$ there still remains the issue of deciding which scene interpretation S to choose. What choice the viewer makes depends upon the utility, $U(S)$, the viewer associates with the various choices. For instance, for certain utility functions $U(S)$ it might be prudent to choose the maximum likelihood scene, i.e., the scene S that maximizes $P(S/I)$.

The rules of visual construction employed by a viewer depend on the internalized rendering function $P(S|I)$, the internalized constraints $P(S)$, and the internalized utilities $U(S)$. The particular forms of these functions depend on the evolutionary history of the organism and its pattern of visual experiences.

A fundamental problem for using visual images as a universal form of communication with extraterrestrials who are intelligent enough to communicate with us by electromagnetic signals is that there is no reason to expect on evolutionary grounds that the functions $P(S|I)$, $P(S)$, and $U(S)$ will be sufficiently similar that we will share similar rules of visual construction.

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