BY **MIKE WOOD**

How bright is bright—Part 4

THIS IS THE FOURTH AND CONCLUDING INSTALLMENT in this series of articles dealing with the concepts of vision and perception and how the human eye and brain make assumptions about what we *see*. So far we have looked at brightness perception in both two and three dimensions and how those perceptions can often be incorrect. We also briefly looked at color vision.

This issue I want to delve further into our color vision. This is an area of our vision system that is often misunderstood; in fact, many schools still teach outdated theory that isn't entirely correct. The topic is incredibly complex with new discoveries still being made so we can really only scratch the surface here.

Classical color theory

What were you taught at school? I'm betting it was a classical three-color theory of color vision. Something along the lines that you have Red, Green and Blue receptors in your eye and that you perceive color based on unique combinations of those three signals. Right? Well, to a limited extent that's correct but it ignores the overwhelming influence of the brain. Although we do have three types of color sensors in the eye, to call them Red, Green and Blue is a severe over-simplification. In actuality the sensitivity curves of the three receptors overlap significantly as shown in **Figure 1**.

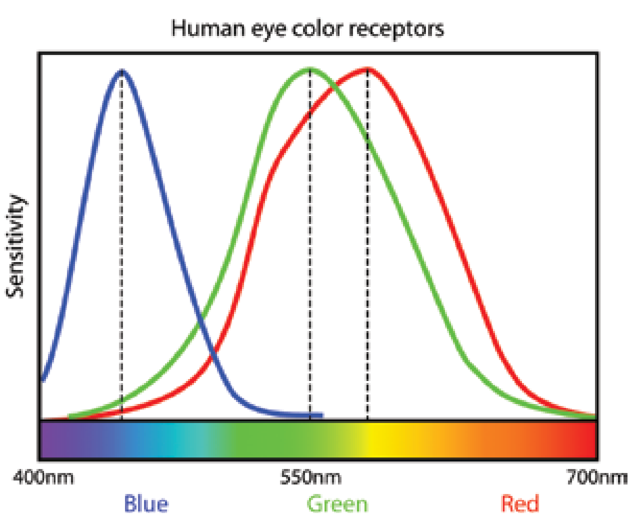

Figure 1 – Human eye color receptors

I've also shown a spectrum at the bottom and the wavelengths where we *see* the primary colors: Red, Green and Blue. Note that the Red and Green curves in particular almost completely overlap and that the peak sensitivity of the *Red* receptor is right at what we see as Yellow!

It's tempting to think from these curves, even though they do overlap, that we see color in the same way a color camera sees it by using the three values of Red, Green and Blue returned by the sensors to absolutely define a color. After all, I can go into Photoshop® and draw a square with colors R= 255, G=127 and B=0 and be confident that it will print and be seen as an amber color in **Figure 2** and look the same on my monitor, your monitor, and on paper.

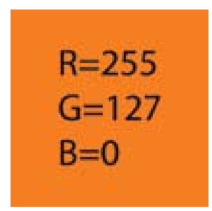

Figure 2 – Amber square

Color constancy

Unfortunately the human eye doesn't work that way; just because a color reflects light in those proportions does not mean that we will see it as amber. The way we perceive a color depends just as much on what is around it in the rest of our field of view as the wavelengths of light the object reflects.

We do not see color as absolutes; we see color only as referred to the rest of the scene. When an object looks red to us, that only means that it is red compared to the rest of your field of view, not that it actually *is* red.

The concept that all color vision is relative not absolute is a relatively recent one, well within our lifetimes (well, mine anyway!). In fact it wasn't until Dr. Edwin Land, the well known inventor of the Polaroid instant camera, really took this concept to heart and produced some convincing demonstrations in 1971 that it became widely accepted. Land's demonstrations illustrated that colors retain their perceived appearance even when the color of

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the illuminating light changes drastically. For example, a banana looks *yellow* no matter whether we view it in pure white daylight at midday, the light from a deep red sunset, or in warm artificial light. It also looks that same *yellow* if you look at it under a tree canopy where the light, and thus the banana's true color, is actually very green from the leaves.

This makes it a lot easier to forage for food, which is likely why this sense developed as it did, otherwise that same banana would look completely different at different times of day, in different weather conditions, and in light and shade. Perceiving colors as a constant makes our world a lot easier to understand.

Colors, unlike brightness or intensity, tend to remain constant in our vision system and are much less affected by the color of the illuminant than might be expected from the predictions of classical color theory. Land called these new concepts retinex theory (the word retinex was intended to show the close link in vision between the eye's retina and the brain's cortex) but the principle is now more usually referred to as color constancy.

Here's another example: if you are reading this article in your home or office lit with incandescent lamps then you are in a very warm, red light. Look out of the window or walk out of the door into daylight and you move into light which is extremely blue by comparison. Does everything look blue? No, your brain instantly re-calibrates and the white paper still looks white. Occasionally in a building a distant and small window can look very blue because your vision system is predominantly acclimatized to the warm internal lighting. But get close or look out of the window and that blueness instantly disappears. You have internal auto white balance but for every color instantaneously and selectively.

There are exceptions of course, some modern light sources such as fluorescent or discharge lamps have a poor spectral bandwidth and distort colors so much that we do see them as different. We know, for example, that the sweater we just looked at in the store under fluorescent light will likely look a different color in daylight—but these are man-made extremes affecting our vision system. The key points I'm trying to get across are:

1. Within limits, colors in a scene remain constant under different illumination.
2. An object's color is not an absolute but is determined by its color in relation to surrounding objects.

These two statements are different aspects of the same thing, although they may seem sometimes contradictory. How can colors be constant and look different at the same time? The point is that it's the color within a scene that's a constant, change the scene and you can change the color.

Now we know this, it goes some way to help describe some illusionary effects. To start with a simple example, **Figure 3** shows two colored rectangles with a central colored dot. The dots are the same color, although they don't look it. We see each dot's color as it relates to its surroundings, not as an absolute.

Figure 3 – Surrounding colors

A particularly strong, but still simple, example is shown in **Figure 4**; here we combine the brightness illusions we saw in earlier articles in this series with the effect on color of its surroundings. The red lines are all the same shade and brightness of red and the blue lines the same shade and brightness of blue. Even though half of them may look paler and chalkier, they aren't! You may need to fold the page to convince yourself of this.

The contrast and comparison with the surrounding areas confuses our color constancy system and we see the lines that are adjacent to black lines as both a lighter color and paler in intensity than those which are adjacent to white lines.

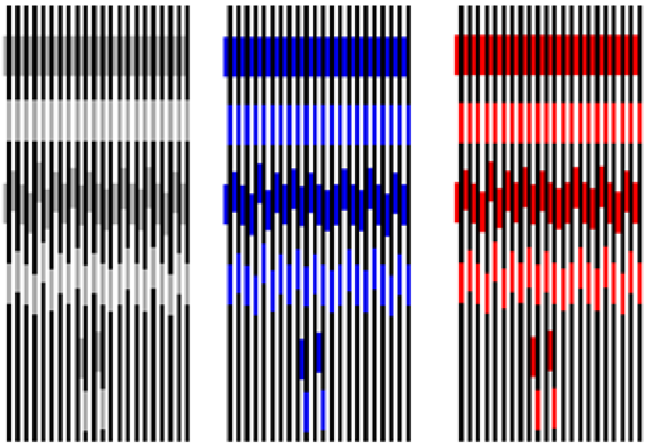

Figure 4 – White's illusion with colors

One more two dimensional example, **Figure 5** shows two faces of a Rubik's Cube structure with 25 squares in various colors. The version on the left is apparently illuminated in yellow light while the one on the right is illuminated in blue light. Our color constancy system agrees with this and sees both layouts as being essentially the same. However, they aren't the same. As the arrows indicate all the *yellow* squares on the right and all the *blue* squares on the left are actually grey squares and, what's more, both *blue* and *yellow* are the same grey. What's going on? Well, we've established that we see colors by comparing an object with its surroundings and the yellow (actually grey) squares on the right are more yellow than anything else in the scene as everything else is tinted blue. Thus we see them as yellow even though there is absolutely NO yellow light coming from them. In a real scene a yellow square illuminated with blue light may well reflect a neutral grey and still appear yellow, so we aren't cheating; this is a real life example.

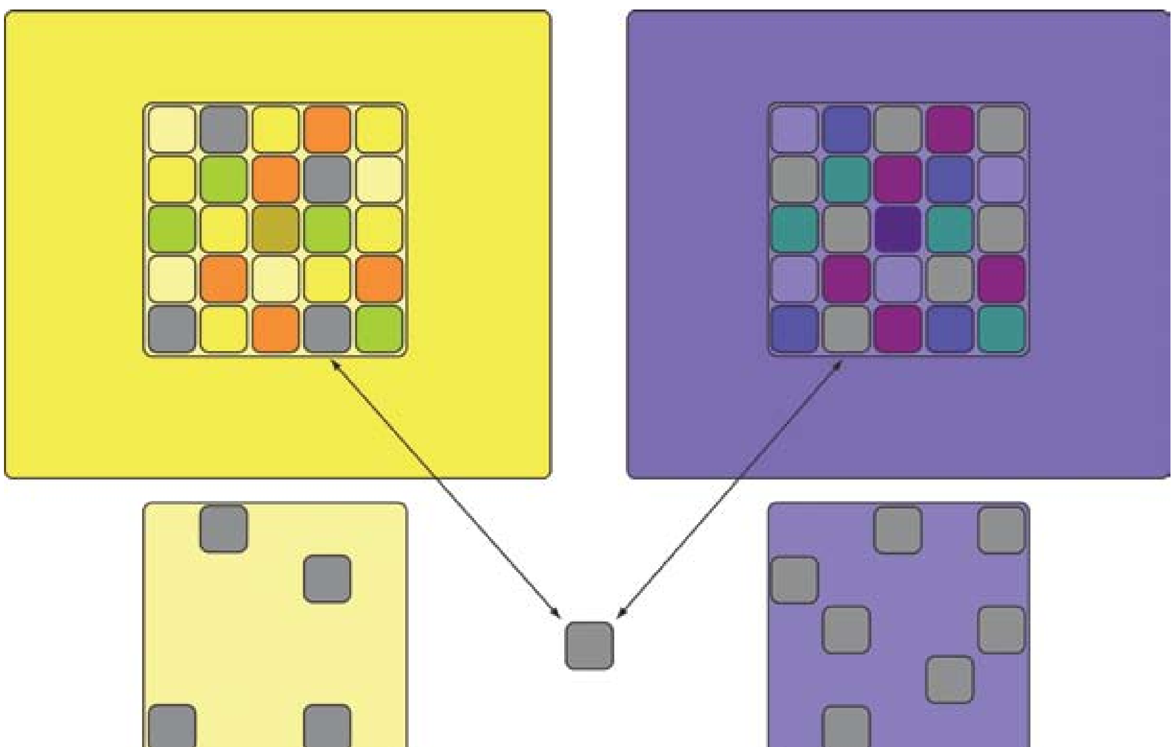

Figure 5 – 2D color constancy

Perceiving colors as a constant makes our world a lot easier to understand.

Color in three dimensions

As we saw with brightness illusions these effects are much stronger when seen on three dimensional objects. We live in a solid three dimensional world and we equate three dimensions with reality in a much stronger way than we do two dimensional pictures.

Let's take that same concept we see in **Figure 3** and look at it on solid objects.

Figure 6 is a 3D version of **Figure 3**. The central squares on each disc shaped object (the ones with the small black dot) are identical colors. (Note: I know some of what's coming is unbelievable but just trust me on this, they ARE identical.) We see the two objects as essentially similar apart from the lighting—we assume the left disc is lit with a reddish toned light while the right one is apparently lit with a bluish light. Once we've made that subconscious determination then we automatically compensate (through our

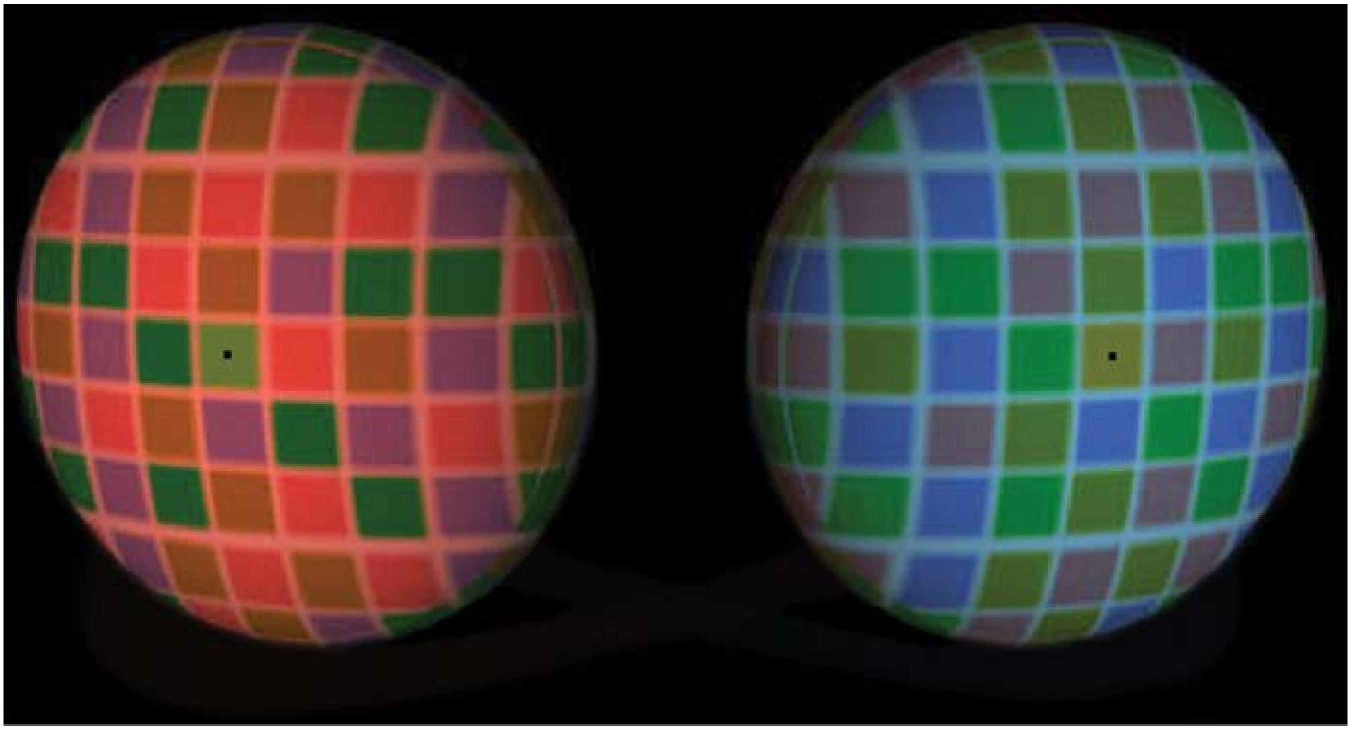

Figure 6 – 3D color constancy © Dale Purves and R. Beau Lotto 2002

color constancy system) for the apparent differences in colors reaching our eye. In the case of red squares (there is one to the right of the central square in each case) that compensation means that we see them all as red, no matter which color is illuminating them. Similarly for the blue squares, green squares, and so on. The central squares are actually the same color on both discs (unlike all the other squares which aren't) but our vision system still applies the same compensation so we end up with them apparently looking very different! I *cannot* make them look the same, even though I know they are. Just to check for you, gentle but skeptical reader, I scrutinized **Figure 6** in Photoshop and confirmed that they are exactly the same color: R=100, G=116, B=18.

Although **Figure 6** has some subtle elements of 3D in it, let's take it another step. As with the black and white images we looked at in previous articles, the addition of three dimensions tells our brain that we are in the real world and so we make real world assumptions. **Figure 8** (see next page) is perhaps the most stunning example of this that I've ever seen and I know you are going to have a hard time believing your eyes!

This is a three dimensional version of **Figure 5**, once again we have two Rubik's cubes; one illuminated by a yellow light, the other

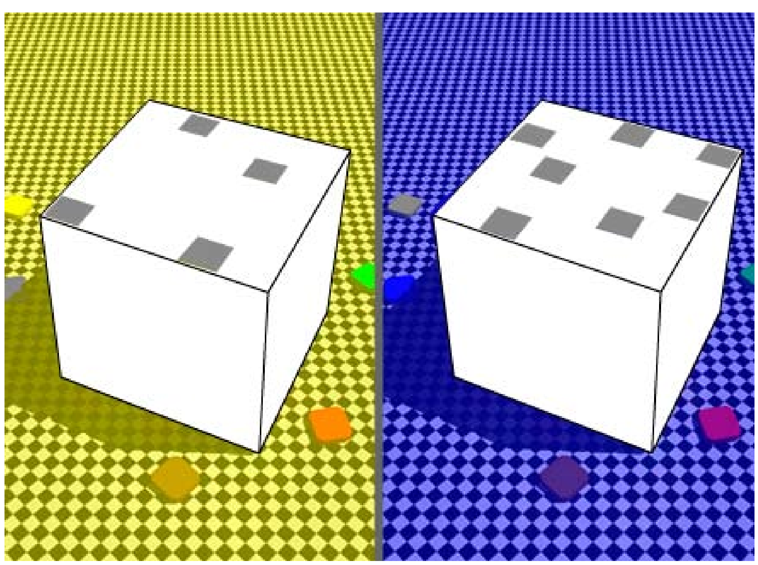

Figure 7 – Masked image

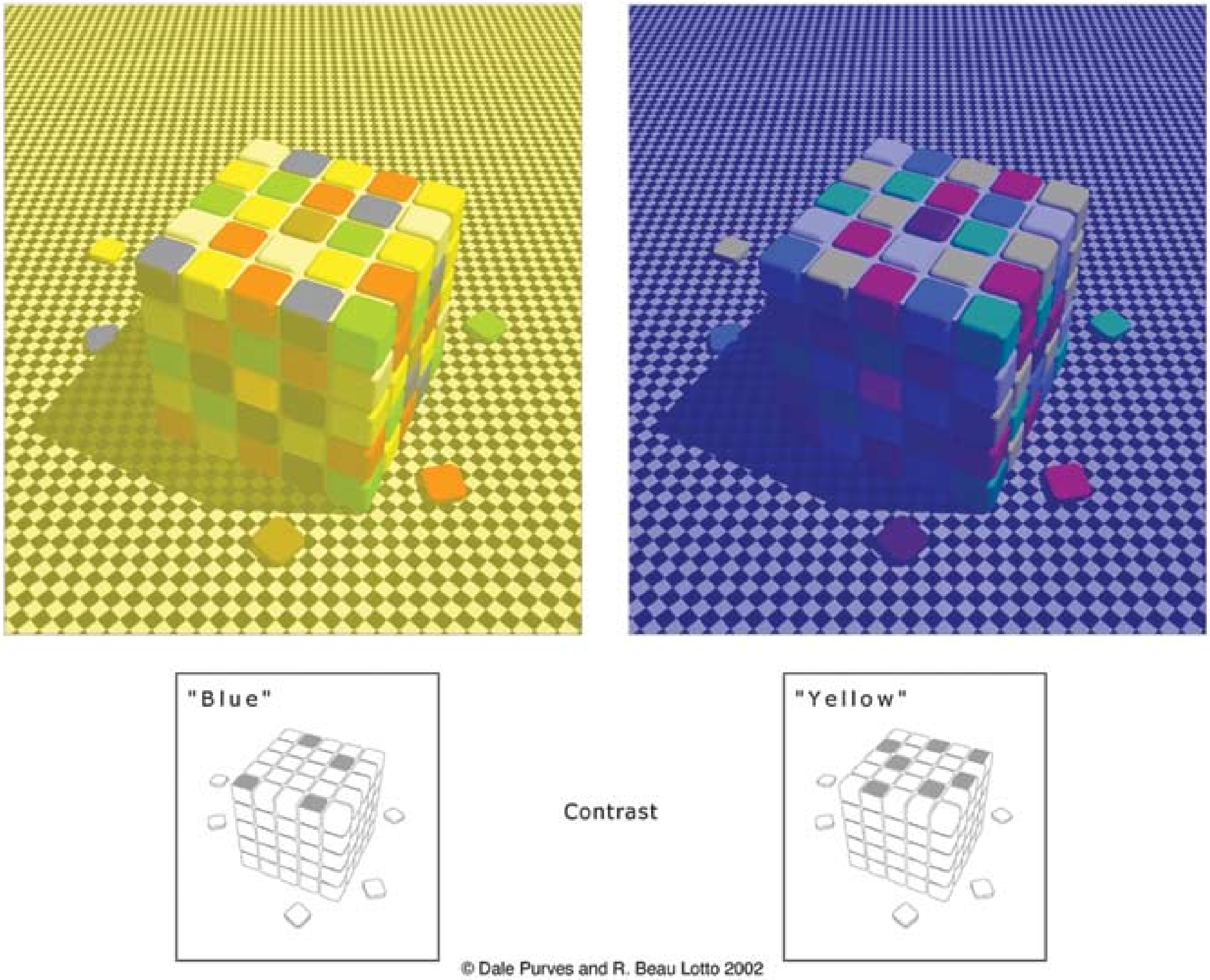

Figure 8 – 3D color contrast

with blue. This time the perception of color is undeniable. Even though the four *blue* squares on the top surface in the left image and the seven *yellow* squares in the right image are actually eleven completely identical grey squares I defy you to see them that way. The ones on the left *ARE* blue and those on the right *ARE* yellow, at least to my vision system and, I suspect, to yours. Look at them with a TV camera though and it would, correctly, see them as a boring grey. The thumbnail images below the main squares show the positions of the grey squares and **Figure 7** (see previous page) shows a masked version of the image, without the surrounding colored tiles, so we can see them as they really are. I can just about persuade myself that all the squares are grey but cannot persuade myself that the *yellow* and *blue* are actually the *same* grey. In the interests of continued skepticism I resorted once again to Photoshop to persuade me that all eleven truly are a R=135, G=135, B=135 grey.

We can use the same cubes to further demonstrate color constancy. Take a look at **Figure 9** (see next page) but, this time, examine the red squares on both top faces. They are all red aren't they? Well, actually they aren't. As the thumbnails show the red squares on the left are actually orange while those on the right are purple. We have an innate understanding that something red lit with a blue light will look purple so we allow for that, similarly we know that a red object lit with yellow light will look orange so we compensate again. To add to the effect we make the tacit assumption that we are seeing the same cube, just lit in different colors, this further reinforces our assumptions that we are looking at the same red tiles in different colored lights.

Color on stage

Think of what this means on a stage when we use color. We know from experience that, on a live stage, we can use quite bright colors in what might appear to be an unnatural manner to illustrate or enhance a mood without destroying the authenticity of the scene. Color constancy is our friend and explains why we get away with it and the audience still sees a real scene. Their vision systems allow for our excesses and still let them see objects as natural and real, albeit with a color cast. Try and repeat this on television though and you may have problems. The audience may be watching in a bright room lit in multiple colors that you have no control over. It's those colors that will predominate in their vision and so your coloring on the screen may suddenly look unnatural.

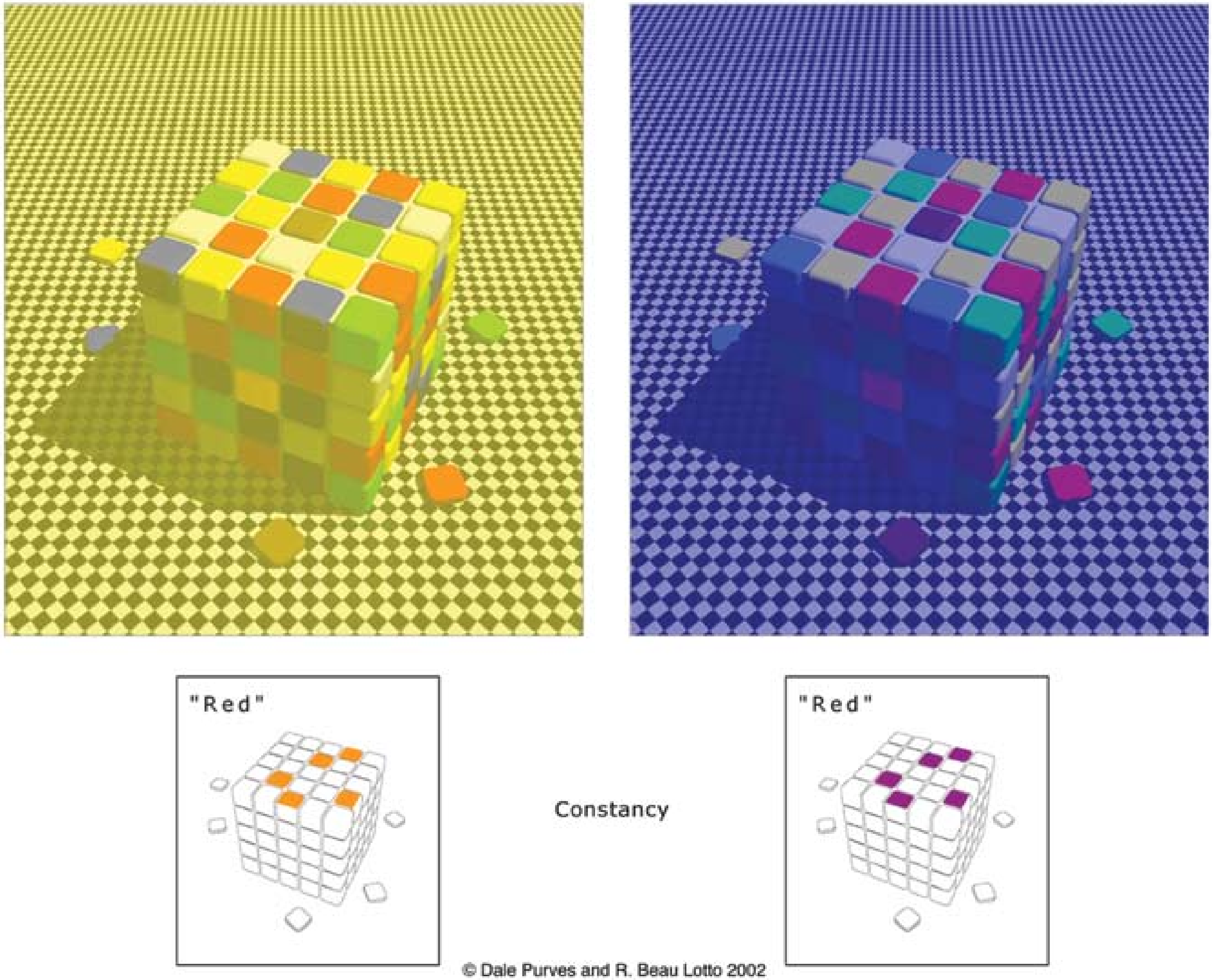

Figure 9 – Extreme color constancy in three dimensions

The *Protocol* editor allowed me to take over the front cover this issue so turn there for one last example; you will see the same cube only this time it's lit with white light. So, what's the problem this time? Just take a look at the dark brown square in the center of the top face, the orange one in the center of the front face and the mid brown loose tile on the table top. You guessed it, they are actually identical. The impression of the front face being in shadow informs our vision system that all the colors on that shadowed face should be perceptually lightened to see them as they really are. We thus lighten the mid brown to an orange. Similarly we perceptually darken the mid brown to a dark brown on the brightly lit top face and leave the table top one, illuminated to the scene average, alone. The loose tile shows you the color as it really is (whatever that means).

Well that about wraps it up. This series has partly been about how your vision system works and how perception is stronger than reality, and partly an excuse for me to show you some really cool illustrations! As fun as these are, and I do hope you found them so, there is a truth behind them that affects everything we do in our profession. The world is not what our light meters say or our cameras capture; the world is what we see. Color, shadow, brightness, darkness are all elements in our lighting design toolbox and they interact with our eyes and brain in a way that doesn't always follow directly logical or mathematical rules. It's that interaction between left brain and right brain, science and art, engineering and design, technology and flair, that excites me about this business. Color and vision is a passion of mine and I hope I've managed to pass a little of that passion on to you.

Thanks are once again due to Dale Purves MD, Director, Center for Cognitive Neuroscience at Duke University for permission to publish a number of these images. I highly recommend the book written by him and R. Beau Lotto entitled, Why We See What We Do *published by Sinauer Associates for further information on this fascinating topic. Their exciting work provided inspiration for this series of articles.*

Mike Wood is President of Mike Wood Consulting LLC which provides consulting support to companies within the entertainment industry on technology strategy, R&D, standards, and Intellectual Property. A 25-year veteran of the entertainment technology industry, Mike is the Treasurer and Immediate Past President of ESTA.