

Biological aspects of vision processing

Harish Tella

Our path towards understanding how the human visual system processes stimuli begins with signal detection theory. It provides a framework of perception that is probabilistic (Wickens, Hollands, Banbury, & Parasuraman, 2013). A particular stimulus is competing for attention with all other stimuli. Signal detection theory frames this as signal versus noise. The probability that a particular signal will be detected depends on its strength relative to the background noise—the greater the strength, the greater the likelihood of detection. In the visual design arena, our signals are particular visual features that we want to arrive at the user's attention, and noise is either other unrelated visual stimuli or stimuli that may be mistaken as our feature (McNicol, 1972). With an understanding of the visual system, one can modulate the signal strength of visual stimuli and thereby increase the likelihood that the user detects the desired features (Ware, 2013). It is the goal of this paper to outline our systems of visual processing and thereby demonstrate a means for modulating the strength of visual stimuli. This paper will then conclude by applying this understanding to a design case, the Boss GT-3 guitar effects processor.

The bioelectrical processing of light begins when it hits the retina at the back of eyeball. The retina is an array of rod and cone photoreceptor cells that convert incoming light into electrical nerve impulses. There is only one type of rod cell, and it functions only in low-light conditions. There are three types of cone cells, however, each with different sensitivities towards different frequencies of light. (Haber & Hershenson, 1973). The varying sensitivity functions of the three types of cone cells allow us to distinguish between all of the different frequencies or hues of light in the visible spectrum (Schnapf, Kraft, & Baylor, 1987). However, these cone cells only function during daylight conditions. As the amount of light decreases, we rely more heavily on our rod cells, which are unable to provide us with color vision (Haber & Hershenson, 1973).

The neuronal wiring within the retina is multilayered, but at a high-level, it begins with photoreceptors at the back surface of the eye and ends with the ganglion cells in front. The path between photoreceptors and ganglion cells is mediated by a set of interneurons consisting of bipolar cells, amacrine cells, and horizontal cells (Dowling & Boycott, 1966). The connectivity scheme of these interneurons is complex, but what is important is the nature of the signal that arrives at the ganglion cells.

According to Curcio, Sloan, Kalina, & Hendrickson (1990), we have, on average, one hundred million photoreceptor cells. However, we have fewer than one million ganglion cells (Haber & Hershenson, 1973). The interneuronal wiring serves to reduce the signal of these one hundred million photoreceptors down to the outputs of just one million ganglion cells. This is accomplished by wiring the signals of many adjacent photoreceptors into one ganglion cell assigning it a receptive field. A ganglion cell's receptive field is the area of the retinal surface where changes in the incoming light produce

changes in the electrical output of the corresponding ganglion cell. However, the arrangement of this receptive field is unusual and has important consequences (Dowling & Boycott, 1966).

According to Dowling and Bowcott (1966), the receptive field is arranged into two concentric circular regions. If the ganglion cell is an on-center cell, one of two types of ganglion cells, changes of light within the central circular region will cause an excitatory response. Changes in light in the outer circular region will cause an inhibitory response. Simultaneous changes in both regions will only cause a small excitatory response (Dowling & Boycott, 1966). Steady state stimuli produce no response. The other type of ganglion cell, off-center, simply has effects of the inner and outer regions reversed. The net effect of this organization is that our eyes only see change and, in fact, exaggerate it (Haber & Hershenon, 1973).

Taking an example of this exaggeration effect from Haber and Hershenon (1973), let us say the eye just landed on a bright object. The ganglion cells with receptive fields completely on the bright object will be slightly excited as both their inner and outer regions are being stimulated. As we move towards the object's edge, there will be receptive fields that have their center on the bright object but some of their inhibitory outer regions will be off the bright object. The respective ganglion cells are less inhibited overall and produce a stronger excitatory response than those ganglion cells with both their fields fully on the object. This results in an exaggerated edge, and it is the basis for numerous visual illusions (Haber & Hershenon, 1973).

Although we have 4 types of photoreceptors and their connections to ganglion cells are complex, Hurvich and Jameson (1957) demonstrate that the information that arrives at our perceptual centers is reduced into three channels: a luminance channel and 2 color channels, red-green and yellow-blue. These channels work mostly independently, and input from all three channels come together to form our picture of the world. However each channel's perceptual limits differ (Mullen, 1985). These differences will be covered, but first we must formally understand what is meant by intensity.

The measurable strength of emitted light is called luminosity, however this quantity is not what we perceive. The eye's photoreceptor mosaic, as a whole, is more sensitive to certain frequencies of light and less sensitive to others. This variation of sensitivity has been measured and captured in the human spectral sensitivity function, $V(\lambda)$. It allows us to scale the luminosity of light at different wavelengths to their perceived intensities (Haber & Hershenon, 1973). It turns out that at equal luminosities, green light at 555nm is perceived most intensely, while blue light at 480nm is only perceived 20% as intensely as green light (Haber & Hershenon, 1973; Beare and Siegel, 1967). This is all to make clear that perceptual intensity is not the same as the luminosity of light.

With an understanding of intensity, we can examine the differences between our perceptual channels. The luminance channel delivers information on variations in intensity regardless of the hue of the light, while the color channels deliver variation in intensity only along a yellow-blue spectrum or a

red-green spectrum (Mullen, 1985). The luminance channel is the most important of the three visual perceptual channels as it has many special roles that the color channels do not (Ware, 2013). We will address one of these roles, edge detection. Additionally, we will look at the difference in sensitivity between these channels.

People can generally detect weaker signals on the luminosity channel than on the color channels. A weak signal in this context means visual stimuli with weak intensity contrast and also small visual field size (Mullen, 1985). We will take a look at what is meant by intensity contrast, and then we will cover the contrast sensitivity function, which will provide a formal basis for this claim.

Intensity contrast is the relative difference in intensity between two stimuli. Two stimuli that have a very low intensity contrast are difficult to distinguish as separate. In addition, as two contrasting stimuli are made smaller—meaning as they occupy smaller and smaller areas of the visual field—it becomes increasingly hard to distinguish them (Ware, 2013). The limits of our ability to detect ever weaker contrast differences at ever smaller sizes has been mapped out by showing observers sinusoidal wave patterns of decreasing intensity contrast and increasing frequency (Mullen, 1985). Van Nes and Bouman (1967) have even done this with different frequencies of light with the same end results. This mapping of our perceptual limits is called the contrast sensitivity function, and it is particularly the sensitivity function for the luminance channel (Mullen, 1985).

Mullen (1985) has carried out a similar mapping process for the red-green and yellow-blue color channels. However, instead of using a sinusoidal pattern of varying intensity, a sinusoidal pattern of red-green or yellow-blue is used, and the overall intensity of the pattern is modulated. During these experiments, great care is taken to maintain isoluminant colors in order to only produce contrast on the color channels. The resulting contrast sensitivity functions of red-green channel and the yellow-blue channel allow us to make comparisons of sensitivity between all the channels. Mullen (1985) found that for the majority of spatial frequencies tested, humans can resolve smaller contrast changes on the luminance channel than on the color channels. In addition, human limits for resolving very small contrast changes are much higher on the luminance channel than on the color channel—at about 32-33 cycles/deg. versus 11-12 cycles/deg. for the color channels (Mullen, 1985). This ability to discern small and weak contrast differences is a good predictor for our ability to find small targets at a distance (Ginsburg, Evans, Sekule, & Harp, 1982).

Next, we will address the luminance channel's role in edge detection. Experiments by Gregory (1977) have shown that the luminance channel acts as the authoritative source for shape and boundary information. When a red line is projected on a green background with no luminance contrast between the two, the red appears to be bouncing around slightly, and phantom parallel lines appear in black and white. This implies that the visual system is having trouble settling on a precise location for the line without a luminance difference to aid it. Other images, such as the Frasier spiral, completely lose their form when

all luminance difference is removed. The important takeaway is luminosity contrast is needed to reliably communicate information about edges and boundaries (Gregory, 1977).

Finally, it is useful to understand that these three vision channels are opponent processes. This means that on the yellow-blue channel, for example, we cannot experience a visual sensation that is both yellow and blue. Hurvich and Jameson (1957) have shown how one can mix increasing amounts of blue into a yellow stimulus without it ever appearing yellow-blue to an observer. The opponent nature of these channels gives rise to contrast enhancement similar to the edge enhancement described before. Stimuli on opposite poles of these channels will appear more highly contrasting than they actually are when they are juxtaposed. (Hurvich & Jameson, 1957).

With the relevant elements of the visual perceptual system in place, we can approach our design case of the Boss GT-3 guitar effects processor. This device is targeted towards professional electric guitar players who wish to apply electronic effects to their playing. According to Boss Corporation (1998), the player presses one of four pedals marked 1 through 4 using his foot. This selects a patch, which instantly changes the sound of the guitar according to predefined settings. The player can also press the bank-up and bank-down switches, which cycle through groups of four patches that get mapped to the pedals labeled 1 through 4. The player moves the large black pedal on the right with precision to modulate certain parameters depending on the particular patch. The device also has a small display, a variety of settings buttons, and a settings wheel (Boss Corporation, 1998).

It is important to understand the context in which this device is used. Many professional musicians find themselves playing in the poorly lit environments of bars or clubs. The lighting at these venues is designed to be moody and not to provide good visibility. There may not be a proper stage or any dedicated light setup, and the musicians have to make do with the environment as it is. It is in this context that we will evaluate the design choices of GT-3.

While using this device, the player's principle concern is selecting patches with the pedals labeled 1 through 4 and actuating the large modulation pedal. It is these actions that must be done with accuracy so the sound output by the device is as the player intends. Hitting the wrong patch pedal or not landing on the modulation pedal properly can result in a jarring sound much worse than hitting a wrong note. These pedals should be highly visible in order to prevent this mistake. However, they are not.

The particular blue of the device case has low intensity making it near to black in appearance. This provides little luminance contrast between black pedals and the blue case. In fact, the situation is even worse. The border between the black patch-selection pedals and the blue case does not actually define the portions of the patch-selection pedals that the player presses. It is actually a smaller black section within the black pedal that the player presses. In low-light conditions, the player relying on his color-insensitive rod cells will have trouble seeing the pedal boundaries due to the lack of luminance contrast. It is also this very luminance contrast that he depends on for edge detection.

The solution is to intentionally add luminance contrast to better define the location of the pedals. This can be done with the addition of a white border around the periphery of the pedals. Our rod cells can easily pick up on the sharp luminance contrast between pure-black and pure-white, even in low-light conditions. Additionally this black-and-white contrast arrives on our luminance channel, which we use for boundary and edge detection. All of this working to give the player the clearest indication of where these pedal surfaces are located.

On a positive note, this product has a number of good design decisions as well. Firstly, the yellow text on a dark-blue or black background is a good choice. This particular yellow has a strong luminance contrast with the background giving it good visibility under poor lighting. With the text on the case, there is also contrast on the yellow-blue color channel, and the effect of opponent-process enhancement increases visibility even further. In addition, the size of the numbers and symbols labeling the pedals is appropriate for reading from standing distance.

The last attribute I would like to address is the device's screen. During a performance, a player will primarily use it to see which bank of effects is selected. Two numbers on the screen indicate the selected bank. The screen emits green light with high luminance contrast. These positives are for visibility, particularly the green light, to which our eyes are most sensitive. However, the display is small. The human contrast sensitivity function demonstrates that even strong contrast becomes hard to distinguish as the size is diminished. Therefore, I recommend a separate screen showing only the bank number with a text size similar to the numbers labeling the pedals.

This case makes clear the importance of considering luminance contrast and field size of key visual features of a product that is often used in poor lighting. The natures of our photoreceptors, perceptual channels, and their perceptual limits have all been brought forward as support. May this new awareness lead you to more human-centered designs in the future.



Bank number on screen is small.



High-contrast screen with green light.



In poor lighting, boundary between black features and blue case are hard to distinguish.

References

- Beare, A. C., & Siegel, M. H. (1967). Color name as a function of wavelength and instruction. *Attention, Perception, & Psychophysics*, 2(11), 521–527.
- Boss Corporation. (1998). *GT-3: Owner's Manual*. Retrieved from https://static.roland.com/assets/media/pdf/GT-3_OM.pdf
- Curcio, C. A., Sloan, K. R., Kalina, R. E., & Hendrickson, A. E. (1990). Human photoreceptor topography. *Journal of Comparative Neurology*, 292(4), 497–523.
- Dowling, J., & Boycott, B. (1966). Organization of the primate retina: electron microscopy. *Proceedings of the Royal Society of London B: Biological Sciences*, 166(1002), 80–111.
- Ginsburg, A. P., Evans, D. W., Sekule, R., & Harp, S. A. (1982). CONTRAST SENSITIVITY PREDICTS PILOTS' PERFORMANCE IN AIRCRAFT SIMULATORS. *Optometry & Vision Science*, 59(1), 105–108.
- Gregory, R. L. (1977). Vision with isoluminant colour contrast: 1. A projection technique and observations. *Perception*, 6(1), 113–119.
- Haber, R. N., & Hershenson, M. (1973). *The psychology of visual perception*. Oxford, England: Holt, Rinehart & Winston.
- Hurvich, L. M., & Jameson, D. (1957). An opponent-process theory of color vision. *Psychological Review*, 64(6p1), 384.
- McNicol, D. (1972). *A primer of signal detection theory*. London: Allen and Unwin.
- Mullen, K. T. (1985). The contrast sensitivity of human colour vision to red-green and blue-yellow chromatic gratings. *The Journal of Physiology*, 359(1), 381–400.
- Schnapf, J. L., Kraft, T. W., & Baylor, D. A. (1987). Spectral sensitivity of human cone photoreceptors. *Nature*, 325(6103), 439–441. <https://doi.org/10.1038/325439a0>
- Van Nes, F. L., & Bouman, M. A. (1967). Spatial modulation transfer in the human eye. *JOSA*, 57(3), 401–406.
- Ware, C. (2013). *Information visualization: perception for design* (Third edition). Waltham, MA: Morgan Kaufmann.
- Wickens, C. D., Hollands, J. G., Banbury, S., & Parasuraman, R. (2013). *Engineering psychology and human performance* (Fourth edition). Boston: Pearson.