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M. C. TEICH, EDITOR

OPTICAL COMMUNICATIONS AND PSYCHOPHYSICS

William J. McGill
Columbia University
New York, New York

Ladies and gentlemen, let's make it informal. The President of the University usually arises on occasions like this and greets the group. He hasn't the faintest idea who they are or what they do, and he has no particular wisdom to give to them. And indeed, optical communications is not something I know a great deal about. But when I was a brand new shiny Assistant Professor back in the days when I was with the Lincoln Laboratory at M.I.T., I developed a rather formal interest in communication theory and in detection theory. There was a man named Dave Middleton who was at the Lincoln Laboratory in those days, and I subsequently read Middleton's book.[1] There was also Bill Davenport; you remember the book by Davenport and Root.[2] That work on detection theory attracted my attention because I was interested in the mechanisms by which the ear and the eye detect either minute stimuli or changes in the level of stimulation. Determining the nature of these mechanisms is the classical problem in what is called psychophysics. One would think -- and to a sophisticated group like this I almost do not need to say it -- that the most practical way to go about this process is to look at the mechanics of the receptor, to examine the nature of the neural processing system that lies behind it, and then to make a judgement about the nature of the processing system. But as you probably know, these systems are extraordinarily complex. Indeed the neurologists and the neuroanatomists have no idea what processes are in effect operating, and they look to those who study the detection behavior of the intact organism for some clue as to the nature of the message that is getting through. If one can determine the critical elements of stimulation, then one can draw some conclusions about the nature of the process.

Here at Columbia, around 1940, there was a celebrated piece of work done in visual detection by Selig Hecht, working with Shlaer and Pirenne, that resulted in a famous paper by Hecht, Shlaer and Pirenne.[3] In effect, what Hecht did was to make a number of simple calculations about the level of energy entering the eye in flashes of incandescent light delivered about 20° off foveal central sensitivity in the peripheral area of the eye. Their experiments were performed in the most sensitive part of the visual spectrum, the blue-green region. Hecht, first making basic measurements, determined that at the surface of the eye there were perhaps 100 photons entering it at the visual threshold. Calculating the losses through the ocular media and in the pattern of cells at the back of the retina, he then concluded that about 90% of this energy was lost. He couldn't make these measurements very precisely, but the 100 or so figure was right as was the rough 80% to 90% estimate. He then concluded that the energy in a flash at these low light levels must display appreciable statistics, and he therefore applied the Poisson model to the detection threshold of the eye. Hecht supposed that if some specific number (critical number) of photons were necessary for detection, he could draw the curve show ing the detectability of the flash as a function of the average energy in the flash. That paper, completed in 1942, had a profound impact on me, and on most people working in the study of visual sensitivity from the point of view of the intact behavior of the seeing organism. Indeed, very fine methods have been developed for doing this work in humans and also in animals.

From that day to this, people have concluded that in effect what one must be doing in the intact organism is looking directly through the whole visual system to events occurring in the eye itself, and that some number of photons, say 7 or so, integrated together within a narrow region of space and time, would summate enough to send a message to the brain that a stimulus had been detected. That idea now pervades all of visual theory. You can see at once that this is a noiseless conception of visual processing. Moreover, the critical number that needs to be summated was viewed by Hecht, Shlaer and Pirenne as almost an anatomical mechanism, whereas anybody who does experiments with humans recognizes that one can set that threshold. This may be achieved either by instructing the subject or by arranging a system of payoffs for various events.

When I began to read the detection theory literature, in particular the Lawson and Uhlenbeck[4] treatment of the ideal observer which minimizes errors, I began to see the possibility that there was a potential logical flaw in the Hecht-Shlaer-Pirenne argument. It's possible to look through the system from the back end, obtain the shape of the detection curve, find that the shape is identical to that of an integrated Poisson distribution with a critical number of the order of 7, and then conclude that you've determined the nature of the process. But, you haven't asked yourself what other potential systems would yield equivalent classes of data, because indeed you haven't made the basic measurements. There is nowhere in this whole line of argument that you actually make the measurement that there are 7 photons impinging on a particular point of the eye. The nearest you ever get to that is 100.

Early in my thinking about this, around the time I came to Columbia in the early 1950's, I got the idea that there might be some gold to be mined in statistical decision theory and in the detection theory that was then developing, for the study of this Hecht-Shlaer-Pirenne model. Perhaps it was not as simple as it purported to be and as most vision theorists felt it to be. But my own competence was not as directly in the study of vision as it was in the study of audition, and I began to ruminate about the same sort of problems in the auditory case. Here, what you have is a burst of pure tone at say 1000 Hz, of the order of 100 msec in duration, imbedded in broadband noise. The purpose of the broadband noise is as a masker. The ear has a marvelous property: you can train an observer to pay attention, as it were, only to the frequency region in which a tone is likely to occur. You can have a lot of fun with this detection process by training the person to listen to 1000 Hz and then presenting 1800 Hz to see whether he detects it. You can then measure the width of this band that is determined by processes that we label attention, but are not understood at all.

I finally began to try to formulate some logical machinery for doing this kind of detection experiment. I had, in fact, been reading a variety of not very well thought out papers in the psychological literature. A number of these claimed that the ear had the properties of an ideal detector. The problem was that the psychologists who were writing these papers did not describe the nature of the "ideal", and thus you didn't have any conception of the kind of processing going on. I did a simple piece of extrapolation of a paper by Peterson, Birdsall and Fox[5] on ideal detection, and discovered that if you have a sinusoid in wideband noise, and if you are looking at an ideal detector to detect the energy, that indeed all you have is the bandwidth of the energy detector matched to the bandwidth of the system. But no psychologist understood or thought through what that meant, that indeed the ideal detector might be something as simple and primitive as an energy detector.

I then tried to think through how this process might work, and conceived the notion that you would have a train of impulses coming up from the basilar membrane of the ear, generated by this band in which events were being detected. This train of impulses had an undetermined character. I then ran into a paper by Cox and Smith[6] which suggested that if you had trains of random activity, or indeed trains of periodic activity provided that they are not mutually divisible, and you smear them together, then the limiting distribution of the superposition is the Poisson form. It is, I think, one of the most elegant varieties of the central limit theorem that I've seen, but rather than being an additive theorem, it's a superposition theorem. The idea then would be that you would have these individual neurons, or pathways, or lanes of traffic. On each one, the events were occurring according to some form. The essential point is that there are supposedly many of these and that a detector sitting up a little bit higher than the ear would look at the energy coming through and would count impulses. The observer would then attempt to determine from the count whether or not a new stimulus was present.

It seemed to me to be the most primitive kind of detector that perhaps nature had devised for animal species at a very early stage in their development so that they could protect themselves in a predatory environment. With the superposition theorem and the Poisson form, what I tried to do from the extrapolation of the work of Peterson, Birdsall and Fox[5], and Rice[7] was to calculate the energy distribution in a short burst of band-limited noise; it turns out to be central chi-square. And then the energy distribution in a short burst of band-limited noise with a sinusoid added to it, and that turns out to be non-central chi-square. Thus one has all of the components necessary to calculate what energy fluctuations like this would do if they were driving a Poisson process, where the mean rate was determined by the energy of the input. First I calculated these doubly-stochastic counting distributions that I had never seen before and published them.[8] The purpose of this paper was to do the analysis -- to try to develop the detection formulation and to show that all of the data that I was able to identify, and that I was able to get myself, in the auditory detection of sinusoids in noise were really consistent with the notion that the "ideal" in this instance was the simplest detector known to the mind of man, namely an energy detector. It worked out rather well. In fact, if the auditory detection system is looking at those counting data rather than at the energy, it turns out that you can't tell the difference. One is a simple discrete image of the other, and the macroscopic detection properties of the two systems are essentially the same. That was very important to me because it suggested the nature of the mechanism.

I speculated at that point that maybe the Hecht-Shlaer-Pirenne process works the same way; that you have a photon distribution which in effect is driving a rate of nerve impulses. Then, perhaps, the mind's eye is looking not at the energy impinging on the eye but rather at the flow of information up the optic nerve. What was interesting about the problem is that in the auditory case, the counting distribution for a Poisson process driven by a chi-square process has a form quite different from the original Poisson process (it has much more variance). In the visual case, on the other hand, the counting distribution is a Poisson process being driven by another Poisson process, and there is not appreciable departure from the original Poisson form. I published these results[8] and was right in the midst of the most exciting research streak of my life, with everything falling into place, these distributions falling out in beautiful form, and people writing to me from remote parts of the world, when serious problems arose on the (University of California) San Diego campus. I was appointed the Chairman of a Search Committee to find a new Chancellor, and became involved in another kind of life in which I deal with political pressures, student unrest, and academic administration. Eventually, in 1970, I wound up here at Columbia. That operating part of my life in San Diego came to a sudden halt about 1969.

In the spring of 1974, I was asked, the way people do to be nice to the President of the University, to present a talk at the University Seminar on Mathematical Methods in the Social Sciences.[9] So I prepared all of the material on this curious psychophysical problem. The basic question is this inverse reasoning: from the data that the intact organism can detect, to the nature of the detection mechanism. I posed the problem just as I had posed it for you in the visual and auditory cases. Most of the people in the audience did not follow the presentation but there was one young fellow there with blond curly hair named Mal Teich who said, "You know, what you've put up there is very familiar to me. It's Mandel's formula[10] and the Poisson kernel is being driven by a non-central chi-square process. I've worked on that kind of problem in photon counting detection and laser communications, but I'm not sure that I get exactly the same result." So we went over to the office and talked to one another, and established a beautiful identity.[11] It took us some time to work out. For the Poisson process being driven by a noncentral chi-square process, there are at least four major notational systems that I've found in the literature--from Laguerre polynomials to combinatorials. I had chosen the combinatorials; the thing that was familiar to Mal was the Laguerre polynomial form. We had to decide whether or not these things moved one into the other, and indeed we were able to show that they did. That was quite exciting because first of all, here was someone who understood the core of the argument and had worked on it in another area. I then was introduced to a literature in which the modulating energy distribution can have arbitrary form, e.g., triangular.[12] The only one that I had ever really thought about is the one that occurs in nature for sinewaves buried in narrowband noise.

Suddenly, then, the circuit came full because if you can use a physical device to introduce an arbitrary modulation on the energy distribution, you can go a considerable step beyond Hecht, Shlaer and Pirenne who used incandescent light with its random characteristics. Thus, using modern sophisticated electro-optic devices with laser light, you have the opportunity to re-do this work in an extremely refined form. You can then attempt to determine what is, I think, the central question. And that is the extent to which you can look at the back end of the system, definitively through the system, and try to arrive at the description of the nature of the detection mechanism from its output. You do this experimentally by varying the light energy distribution and determining whether or not the system can track it. Mal, one or two people in the Department of Psychology, I, and his students have been now fussing with this problem for about the past three years. There is a considerable amount of basic experimental work to be done.

I don't know how to forecast the outcome yet, except to say that it is perfectly clear from all of the initial stages of this work that many input distributions have rather comparable outputs and that one cannot conclude in reverse form, as the psychologists have, that one is looking through the system to events occurring in the eye. The whole literature on energy detection and energy processing using arbitrary modulated light has become available in psychophysics for those of us interested in visual and auditory detection. Nowhere earlier was it known that this connection existed, because one set of arguments was stated in Laguerre polynomial form and the other set in combinatorial form. Of course it was simplicity itself, once it was understood that there might be a connection, for Mal and his students to work out all of the details of the relation.

I think that in the end there will be more than a paper on the nature of the identity. And I think that there is a beautiful kind of symmetry to the result, both physical and human symmetry. After all, Hecht, Shlaer and Pirenne did their work in Pupin Hall, and it was a Columbia effort. I was attracted to Hecht's work after I came here, largely because a number of Hecht's students had stayed on and moved over to Psychology. Indeed, despite all of the anguish of 1968, the political activity and the unhappy environment, the nature of Columbia as a University is evident--a place where two people from rather different disciplines could at some point find one another close at hand and speak to one another seriously enough so that the impact of one set of ideas on another could be felt in something more than trivial terms. The net result has been beneficial certainly to my discipline of psychophysics, and I rather think also to the physicists and engineers who have been working in this field of detection rather remote from the questions that are asked by neurophysiologists and psychologists as they examine the nature of the detection mechanisms in the eye and the ear. Thus the possibility exists that that field can be further fertilized from sources outside the discipline of psychology where far more quantitative sophistication regarding the nature of this reasoning exists.

I wish I could report the end of the story, but that will take some time. It is unusual, however, and certainly a little different from the ordinary report of the President of the University greeting a distinguished group who have come here for a Conference. I wanted you to hear about it because I think it's fascinating. Thank you very much for listening.

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