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Publication Date
1993

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Working Paper
1993

UCTC No. 207

The University of California Transportation Center
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1. SUMMARY

The research of Bloch in the nineteenth century laid the groundwork for the Blondel-Rey Law of visual integration, a law that lies at the heart of warning signal specification methods. That early research suggested that the eye is a perfect integrator up to some temporal limit. Recent vision research casts doubt on this simple model of temporal integration. In this paper we show several examples of data that undermine the simple integration idea., and which require a multiple parallel channel replacement. A nested standards strategy is proposed to accommodate the new insights while retaining earlier systems and methods.

2. INTRODUCTION

Visible warning signals serve an important purpose in many applications. In order to improve designs and to set standards, it is first necessary to have an understanding of the role played by the visual nervous system in detecting light. The main purpose of this paper is to enumerate several reasons for revising our classical view that the eye is a perfect integrator.

Bloch's Law[1] of perfect temporal integration is an analogy to the Bunsen Roscoe Law of photochemistry. It states that the product of intensity of a brief flash of light, times the time it is on, is a constant at threshold.

$$\Delta I \times T = C \tag{1}$$

Beyond Bloch's integrating time, usually taken as 0.1sec, threshold declines only modestly as duration increases until, for long durations, threshold is a constant. A simple two-limbed approximation to this threshold function obeys Bloch's law for short durations and obeys the relation that threshold is constant for longer durations.

The Blondel-Rey law[2] is a simple way of summarizing this two-limbed function. It states that the product of a flash intensity times its duration is equal to the asymptotic threshold value times the sum of the duration plus a "visual response time constant", a.

$$\Delta I \times T = \Delta I_\infty \times [T + a] \tag{2}$$

In an ideal two-limbed function the constant is twice the value of the eye's integrating time which is the value of flash duration at which the two limbs join. In practical application, the idiosyncratic time course of light sources must be taken into account, for their intensity is rarely a rectangular function of time. In this case, one integrates the intensity as a function of time over the period, T, when the source can be on, with the resulting relation[3].

$$\Delta I_\infty \times [T + a] = \int_T \Delta I(t)dt \tag{3}$$

It will be apparent that temporal integration by the eye is intrinsically interwoven into the foregoing relations. But is that what the eye really does?

3. DOUBLE FLASH DETECTION

If the eye simply integrates, then two homogeneous flashes should behave as their sum, provided they are spaced closely enough in time to be within the integrating time of the eye. Rashbass[4] described experiments of this sort with very surprising results. Two flashes within the integrating time of the eye were adjusted in relative intensity and also polarity. Then a threshold for the combination was found. The stimulus combinations that achieved threshold visibility were plotted in a two-space where each axis represented the stimulus intensity of each flash respectively. (Negative values correspond to a dimming from a background level.) The expectation for a system that simply integrates light is a pair of straight lines inclined at -45DEG and passing through the points on the two axes representing single stimulus presentation. Data depart markedly from this prediction. Data points fall not on two straight parallel lines but rather upon an ellipse. The ellipse can be inclined in much the same direction as the parallel lines as Fig. 1 shows, especially when the flashes are close together in time, or it can be inclined orthogonal to these lines. Ellipse shape seems to be a strong function of the interval separating these two flashes. Note that even when the entire two flash sequence falls within the measured integrating time with this apparatus, the data depart strongly from the simple integration shape.

Rashbass' study employed very large (17deg diameter) targets with 1msec duration. One might argue that the pertinence to warning signals, which are far smaller in size, is not demonstrated. For that reason, I report here a repetition[5] of the Rashbass experiment with 1'x4" rectangular targets with precisely the same result.

The practical implication of these studies is this: when multiple flashes are used, as is increasingly true with strobe type lamps, separating flashes by times in the range of 30-80msec, considered by many to be within the eye's integrating time, can cause signal detectability decrements of as much as 50%. (making the second of two flashes essentially superfluous).

4. IMPOSSIBLE DISCRIMINATION

The second major finding to undermine the idea that the eye simply integrates photons up to the integration limit, was discovered by Zacks[6]. Simple integration predicts that if one of two equally detectable stimuli were presented within the integrating time of the eye, then observers should not be able to tell the difference between them. Zacks carefully measured the integrating time for his stimuli, then measured the discriminability of a long and a short duration flash of equal detectability. The discriminability was far above the predicted level of zero, indicating that the eye does not simply integrate photons. Zacks failed to do an important control however. It is possible that observers based their discrimination upon the apparent time of arrival of the flash. The longer lasting flashing would appear to arrive later and this might supply a basis for discrimination. We repeated Zacks' test with stimuli arranged so that their centroid coincided in time. In this way, apparent time of occurrence could not supply a cue to identification. Our results were essentially the same as his. We have also tested the discriminability of more complex stimuli and found non-trivial ability to identify stimuli which, on simple models, ought to appear to be identical[7]. It must be concluded therefore that simple integration is not the whole story.

5. WHAT NOISE REVEALS

Visual noise is not often considered an important consideration but it must be appreciated that any visual stimulus would be perfectly detectable without noise. A number of experiments that add a controlled amount of visual noise to the environs of a warning signal-like stimulus have been performed in the past two decades with interesting results.

Superimposed Noise Consider the case where luminance noise is superimposed upon the location where the warning signal can appear. In this case one expects little or no effect until that noise is roughly equal to the internal visual noise referred to the input. Experiments bear this out. Then, as noise is further increased one expects detectability to decline linearly with noise power, but that is not the finding. Detectability declines even more rapidly than predicted. This is interpreted to mean that the human observer is uncertain as to the parameters of the signal to be detected[8].

Adjacent Noise[9] Now consider the case where the experimenter moves the noise off to the side a bit, the luminance noise now falls adjacent to (on either side of) the warning signal location. In this case performance is also diminished by the presence of noise, indicating spatial summation processes that cross regions of retina larger than resolution capabilities would imply. One might think, however, that the effect could be due to stray light scattered onto the signal locus from the adjacent noise locii.

Consider this manipulation. Create noise sources such that one member of the pair is the polarity reversed version of the other. In other words, when the left noise spot is increasing in intensity, the right spot is declining in intensity symmetrically. The arithmetic sum of the two is always fixed at twice the background level. Now, one would think that the noise effect would go away because it would be averaged out due to scatter or it would be integrated and hence averaged in neural structures. But data show otherwise. The effect is heightened. Thresholds are raised even more than when the noise sources are identical. This result indicates to us that the neural pathway sensitive to the warning signal is sensitive to something else as well, because it shows the effect of the experimenter-introduced luminance noise. If we knew for certain what pathway this was we might be able to take steps toward optimizing the warning signal itself.

6. THEORETICAL CONSIDERATIONS

In the mid-1950's, the powerful techniques and insights of signal detection theory were brought to bear on the question of visual detection[10]. Two relevant insights arose from this work. First, Bloch's Law of temporal integration is a law of perfect integration only in circumstances where the internal noise of the eye limits detection. Second, when noise is considered, perfect integration is not represented by the parallel lines of Figure 1, but rather by a circle. Each of these points will be touched on briefly here.

Perfect Quantum Limited Integration When quantum fluctuations limit visual detection, as may be the case near absolute threshold under low light level conditions, then it can be shown that perfect temporal integration is represented by a relation that involves reciprocity between the threshold intensity and the square-root of flash duration[11]. This is sometimes termed Pieron's Law. In this case, Bloch's law is an expression of imperfect integration where the imperfection is the cumulation of excess photons outside the epoch in which the stimulus is flashed[12]. Then the simple idea of integration with limits specified by Bloch's Integrating time is no longer applicable. A full treatment requires consideration of both signal and noise. It is not clear, however, that this should provoke a change in standards specification.

Integration of Two Flashes In signal detection theory, the problem of integrating two flashes is more complex than simply adding them up. One must also add up the noise that coexists with each. In that case, and assuming that the two samples of noise are independent, it is straightforward to show that the relation between stimulus luminances at threshold is quadratic[13]. Hence, the plot of first flash luminance versus second flash luminance at threshold would be predicted to be a circle, not two parallel lines inclined at -45DEG. This model comes closer to matching the data, which tends to fall on an ellipse, but still does not quite suffice.

While it is beyond the intended scope of this document to elaborate, it suffices to say that elliptical threshold contours arise from a model in which two central neural mechanisms, one that calculates a difference and the other a sum, process the received signals from two flashes[14]. The reader will appreciate that such a model moves quite far afield from the idea of simple integration which underlies the Blondel-Rey formulation. Its most important attribute, which has a good deal of physiological corroboration, is the idea that two (or more) independent pathways in the nervous system subserve the processing of information from the two flash stimulus.

7. PHYSIOLOGY

If one fixed one’s attention on the properties of the photoreceptors that underlie the detection of warning signals, even then simple integration would not fare well. The impulse response of cones appears to be bipolar, a first depolarizing phase followed by a hyperpolarizing later phase[15]. Photoreceptors do appear to integrate across space, the surprise is that due to interreceptor coupling they have been observed to respond to their own quantal catch and that of as many as 10 neighbors[16].

If one examines current understanding of the properties of retinal ganglion cells, which are two or more synapses removed from the photoreceptors, and which initiate the optic nerve signals, one finds consensus for two separate parallel systems, the M system and the P system[17]. The M (for Magnocellular destination cells in the lateral geniculate nucleus) system is specialized to see motion, has high contrast sensitivity, poor acuity and fast responses, while the P (for Parvocellular LGN destination cells) system is high acuity, sees color, and is slow. Spatial integration in these neurons is hard-limited by the receptive field structure. A central region may sum responses over a small area, but this is accompanied by a surround region whose responses subtract from those of the center. Too, the summation in both of these areas indicates nonlinear subunits for at least the M type neurons.

Moving another two synapses up the visual pathway to the cortical cells one finds a continued expression of the M/P dichotomy[18], and here receptive field properties are elaborate. Receptive fields are spatially complex with multiple parallel-lying elongated excitatory and inhibitory zones. Cortical neurons are demonstrably disinterested in the type of light stimuli that designers build into warning signals. This, and the added noise results described above, raise an obvious question. What does the eye see best?

8. WHAT SOME THINK THE EYE SEES BEST

The answer to this question is not easily found with theory. If one could know which of the neurons in the visual chain limited sensitivity, one could then take a guess. The guess would be to pick the stimulus that most readily excites the most sensitive element. The problem is that each neuron has its own noise processes and complex interconnections render the job of unraveling the neural chain quite difficult. We can approach the problem by assuming away some of our lack of knowledge. Suppose, for example, that the most central element in the chain is limiting. One factor that could cause this to be true is that each neural element has a gain control which turns down signals from prior elements so as to keep incoming signals within the sensitive range for neural signaling. Thus at the higher light levels, the gain reductions are maximal and so the *noise of the last element should dominate*. If so, the receptive field properties of that element should be mirrored in performance.

Watson, Barlow and Robson[19] performed a test whose results fell this way. They found that the best seen stimuli were local circular patches of moving sinusoidal grating. This news will not please equipment designers, but a more recent study should be encouraging. Chaparro et al[20] re-examined this issue and concluded that a color change (e.g., yellow to red) of a spot of light, was seen far more efficiently than either Watson et al's achromatic gratings or their own luminance change stimuli (e.g., yellow to bright yellow). Their rationale was that P cortical cells are far more numerous than M cortical cells and that this numerosity would give a signal-to-noise advantage.

Further research along these lines is of course needed, and warning signal designers will be especially interested in what the eye sees best at the low luminance levels which were not examined in the above-cited studies.

9. IMPLICATIONS FOR STANDARDS

Whether in the automotive, aerospace or marine arenas, warning signals are assuming a larger and more important role. Standards that specify appropriate physical properties of warning signals have, to now been based upon a simple, though outmoded, view of how the eye behaves. That view, that the eye is essentially an integrator, is not quite accurate. One response to this situation might be to begin again. One could abandon the earlier work, the existing signal designs, and the related standards, and begin again with a newer more accurate model of the human eye as the basis. In my view such an approach is not yet warranted, particularly because we have not yet demonstrated large effects. There is another approach by which one can evolve gradually to new designs which take account of the subtleties outlined above.

Nested Standards Consider this approach. Suppose one accepts extant standards, including such improvements and elaborations as standards setting bodies already have underway. Then all existing hardware that is approvable within the current standard remains so. Suppose, then one nests within the extant standard an advisory guideline that allows designers to distinguish alternative designs as to visibility. For example, the advisory could counsel against flashes spaced in time at just the wrong temporal spacing. The advisory could also advocate such alterations as can improve detectability. A model of human vision could be developed that allowed designers to predict which alterations might be favorable and which not.

10. CONCLUSION

Vision research in both psychophysics and physiology during the past quarter century has called into serious question the elegant single channel integrator model of human vision that present day warning signal standards are based upon. Designers can, while adhering to this model, build within standard designs with greatly compromised efficiency, as the double flash example showed. This leaves open the possible existence of a design that benefits detectability; such advances may be possible and should be researched. The author has advanced the view that this situation does not, however, warrant the disposal of extant standards.

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Figure 1. Plots of luminance of first flash versus that of second flash at threshold. Inset shows separation in MSEC. Origin is the background intensity for each stimulus. Negative values are decrements from the background intensity. The upper left panel show the theoretical expectation for an ideal integrator that simply summed the energy in the two flashes. Targets are 17DEG diameter. Duration of flashes is 1MSEC (after Rashbass, 1970).