ON THE PHYSICAL BASIS OF PERCEPTUAL INFORMATION

Willy Wong
Edward S. Sr. Dept. of Electrical and Computer Engineering
University of Toronto, 10 King's College Rd., Toronto, ON, Canada, M5S3G4
willy@eecg.utoronto.ca

ABSTRACT

The study of psychophysics in the 19th century was founded on the principle that a single theoretical approach would permit a unified, scientific study of the senses. In the 21st century, this dream has largely remained unfulfilled. Most of current research in sensory processing lies with elucidating individual mechanisms in different sensory modalities. We describe here a different approach – one that seeks to tackle the problem at a physics-based level. The hypothesis is that the basic process underlying sensory processing lies with the exchange of information or entropy. That is, information or entropy forms the currency of perception. While our work is reminiscent of the classic work of information theory as applied to psychology in the 1950's and 60's, our approach is markedly different. Beginning with the idea that perception is a process of selecting a single alternative out of a number of possible choices, a number of important results can be derived theoretically. Some discussion is provided to link this approach to that of traditional physics.

Keywords: perception, psychophysics, physics, information theory

INTRODUCTION

The study of fundamental physics is about the unification of disparate phenomena using a single theoretical approach. While this approach may not capture all the nuances found in the experimental data, it does however teach us some very fundamental concepts about nature. Physical theories also strive to be universal. A good example of this is Newtonian mechanics which is applicable (to a good approximation) from atomistic to celestial scales.

The scientific study of sensory perception began with a similar aim of uncovering a single theory or set of principles that would govern all of perceptual phenomena. Psychophysics as pioneered by the 19th century physicist Gustav Fechner involved uncovering a single equation that would govern the transformation from physical stimuli to inner sensation. However much of modern sensory research centres upon the use of fragmented and/or reductionistic approaches. Fragmentation implies the study of the senses in isolation of the other sensory modalities. Reductionistic approaches are those that try to uncover the precise neural mechanisms underlying the sensory transduction. While they provide an incredibly detailed picture of the inner workings of the sensory system, it can be argued that this knowledge does not necessarily bring us to closer to the fundamental nature of the perceptual process.

It cannot be debated that the sense of smell is governed by a very different mechanism from, say, the sense of hearing. Yet at some level many of the senses do share common features both physiologically and psychologically. Adaptation is one example where it has been observed universally that the sensory response diminishes with prolonged exposure to sensory stimuli. The common features shared amongst the senses would appear to indicate that there exists underlying principles that govern how the sensory system functions.

ENTROPY THEORY OF PERCEPTION

Norwich (1977, 1993) provided one such principle: that all sensory organs have the ability to receive and transmit information. Information becomes the currency by which the sensory system functions. From this, Norwich derived a single master equation governing the flow of information from physical stimuli to peripheral nerve activity which could then be tested against experimental data. Note that since no consideration is provided for specific mechanisms of the individual senses, this master equation should govern the operation of any sensory organs in any living organisms.

Such a claim could be tested by comparing the predictions of the theory with experimental results (e.g. see comprehensive review in Norwich 1993). While the derivation of the master equation will not be detailed here (it can be found in a number of publications elsewhere) our interest here is to demonstrate as simply as possible the power of the equation in unifying disparate, empirical perceptual and psychophysical results.

The master equation relates subjective response *F* to a single input stimuli *I*. The other variable is the duration *t* for which the stimuli has been applied. These three main variables are connected via the single equation

$$F = \frac{1}{2}\ln\left(1 + \frac{\beta I^n}{t}\right). \tag{1}$$

All other variables in this equation are constants of the system. The derivation of this equation follows that of Shannon's derivation of the channel capacity for a binary symmetric channel with Gaussian noise and hence takes a similar mathematical form (e.g. Shannon 1948).

From here a number of fundamental results can be derived. If we fix the duration for which the signal is perceived and study the relationship between signal strength and subjective response, we can derive (in the limits of large and small intensities) both the logarithmic Fechner law and the power law of Stevens.

Conversely if we instead fix *I* and look at the relationship between *F* and *t*, we see that prolonged exposure to a stimulus will result in progressive diminuation of subjective response in accordance with sensory adaptation.

Other results can be obtained as well although the derivations are more involved. If we examine just noticeable differences or thresholds, one can easily derive a Weber fraction type law from Eq. (1). Similarly, an equation (like Pieron's law) governing the speed of reaction time as a function of stimulus intensity can be derived which accords well with data obtained experimentally.

As a sensory 'calculator', the entropy theory works very well. However little justification (beyond the simple analogy of the senses as a communications system) was provided for why information underlies the process of perception and why this result is universal. In the next sections, we provide two arguments which seek to remedy this situation.

INTELLEGO PERCEPTION

Norwich (1990) explored the fundamental act of perception. By studying the etymology of the word to perceive, he argued that in antiquity the word *intellego* was used as a modern day equivalent to the verb "to perceive". Intellego itself means "to choose from a number of different alternatives", an unlikely source for better understanding the act of perception. However, if we instead examine a statement like " I perceive that your hat is brown," this would suggest indeed that the act of perception is one where the perception of a brown hat involves the process of selecting a single colour from a number of other possible alternatives like black or green or white.

Intellego perception captures some critical aspects of the perceptual process. Furthermore, it illustrates why the information approach seems to work well. Information theory concerns itself with changes in entropy: as the number of alternatives changes so does the entropy or information embodied in the system.

By itself, this explanation is compelling, but requires faith that intellego perception indeed captures the crucial act of perceiving. In the next section we provide yet another reason, one that will also explain the universality of Eq. (1) in terms of sensory systems both biological and (yet to be discovered) exobiological origin.

PHYSICS OF INFORMATION

In more recent years, we have argued for a physical basis to perception (Norwich 2005; Wong 2005). This basis is not simply a direct one – in that on a microscopic level, photons or odourant molecules must obey the laws of thermodynamics, quantum mechanics, etc. – but one that has a broader, more philosophical implication. Why should such a physical basis to perception be important? Since it is generally believed that the laws of physics are universal, if we can establish that the rules of perception are governed in fact by the laws of physics, this would illustrate that sensory organs are bound by certain laws that cannot be circumvented regardless of its design.

While not commonly referred to as such, the theory of information took its origin not in the work of Claude Shannon (Shannon 1948), but earlier through the study of thermodynamics, statistical physics and quantum mechanics. Similarly, it is to the Austrian physicist Ludwig Boltzmann that we attribute the mathematical expression of entropy or information later used in telecommunications by Shannon.

For those doubtful that a classical field like thermodynamics has implications for sensory perception, we need only to quote Werner Heisenberg who once stated (Buckley and Peat 1996):

"Thermodynamics leaves classical physics and goes into the region of quantum theory, for it speaks about situations of observation; it does not speak about the system as it is, but about the system in a certain state of being observed…"

This language is strongly reminiscent of the concept of intellego perception. In statistical physics, for example, the entropy is a measure of the uncertainty in outcome or observation. The greater the possible number of unresolved possible microscopic configurations of the system, the greater the entropy.

But perhaps an even more striking argument for the connection between physics, observation and perception lies with an old paradox from the turn of the 20th century. James Clerk Maxwell offered the following thought experiment as a counter-example to Boltzmann's microscopic interpretation of the second law (see Leff and Rex 1990). A small demon is located in a chamber where a well-mixed two-component gas is present. By judicious operation of a trap door, the demon is able separate the gas into two parts of the chamber thereby lowering the entropy without energy and violating the second law of thermodynamics.

While Maxwell saw this as a problem for the statistical interpretation of matter, others like Szilard (1929) and Brillouin (1962), took it as the dawning of a new way of thinking with the physics of information. Their belief was that information works concurrently with two other variables, one of which is physical entropy and the other energy. A loss of physical entropy implies a gain in information; the acquisition of information requires the consumption of energy.

Currently we are studying ways to show that changes in physical entropy can be directly related to changes in sensory information. For example, Norwich (2005) demonstrated how a physical constant (the gas constant) can be estimated from purely psychophysical taste data. In Wong (2005), an attempt was made to show that during the process of adaptation, the sensory response follows a one-to-one correspondence to changes in physical entropy albeit with a different time scale. If sensory response can truly be shown to be a direct consequence of changes in physical information or entropy then it stands to hold that all sensory systems (regardless of modality or animal species) must be bounded by the same laws that govern the physics of information.

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