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Guest Editorial

Theoretical psychophysics?

It is worthwhile periodically to take stock in one's field and assess its achievements and shortcomings. For perception, the scientific approach is psychophysics, the study of the relationship between sensory stimuli and their perceptual effects, as determined from behavioural techniques. From its origination by a physicist in 1860, psychophysics has aspired to be a science of the quantitative rigour of material physics. How does it measure up to this standard?

From one viewpoint, it could be argued that psychophysics has done very well. It has tamed the demon of subjectivity to provide quantitative measurements of almost every aspect of human perceptual experience. Just when it seems there is nothing left to measure, someone comes up with a new type of perceptual interaction to be evaluated, such as the current interest in texture segregation rules. The perceptual variables may be measured to surprising accuracy over ranges of many log units in some cases (the spectral sensitivities of the colour mechanisms being a prime example). The data are often fitted by sophisticated mathematical models, again with surprising accuracy in some cases.

And yet, can it be said that there is a mature field of theoretical psychophysics analogous to the impressive successes of theoretical physics? There is a big difference between mathematical modelling as such and a successful scientific theory. Both have a structure of intervening variables and an output function that provides an accurate fit to a measured data set. A theory has the extra strength of having empirical validation of some of its intervening variables and of predicting data beyond the range of those for which it was originally formulated. In other words, a scientific theory allows projection of analytic properties across levels of explanation to predict previously unobserved phenomena. Judging by the hard sciences, a mature discipline is also characterised by an overarching theory that accounts for most of the phenomena throughout the field.

Now, psychophysics has models galore. Almost every paper has either a conceptual or mathematical model to account for the data, but there is a problem with validating the intervening variables because of the ethical inviolability of the human brain, on which most psychophysics is performed. Moreover, there have been few attempts to make predictions from the theoretical analysis of a nonoverlapping domain of operation. I am sure that there are many more examples than I am aware of, but it seems a fair generality that cases of explicit quantitative predictions are hard to identify. An isolated example from spatial vision was that of Wilson and Regan (1984), in which Wilson used his discrete-channel model to predict the results of adaptation on spatial-frequency discrimination that Regan would measure in his independent laboratory.

Do we in the field of psychophysics have the sense of operating within a comprehensive analytic framework? Or does the diversity of brain function seem too elaborate to allow the simplification of a single theory to hold sway? Certainly there are limited domains that seem to adhere to simple principles, many of which are classics honoured with the names of their progenitors: Weber's law of increment threshold, Piper's law of spatial summation, the Ferry--Porter law of temporal resolution, Grassman's laws of colour mixture, and so on. A fine contemporary example is Legge's (1975) power law for contrast discrimination and its threshold extension, popularly known as the `dipper function', which accurately holds over an extensive range of masking and adaptation conditions. But each such `law' seems to derive from a different theoretical philosophy and there seems to have been no notable attempt to integrate them into a coherent theory of psychophysics. Even in colour vision, where the strongest integrative tradition has been maintained, it could be argued that the consensus structure does not extend much beyond the spectral sensitivities of the colour mechanisms and their additive mixture to form the gamut of colours (although recent work in colour constancy is beginning to gel into a broader theory).

One way of viewing the issue is to consider whether there is a dearth of practitioners of `theoretical psychophysics'. A major component of modern physics is the existence of a large body of theoretical physicists who work solely at devising analytic structures within which to manipulate and predict empirical results throughout the field of physics. Certainly, there are a number of fairly wide-ranging models in psychophysics. Those of Marr and Poggio, Wilson, Virsu and Rovamo; Smith and Pokorny and their respective colleagues spring to mind as models that have been developed in close coordination with psychophysical (and physiological) data. But are there theorists working to encompass the full scope of the field within an accurate theoretical analysis? I must admit that I find myself dissatisfied on this score.

One place one might hope to locate a body of theoretical psychophysicists is in the burgeoning field of computer vision. Literally thousands of individuals are devoting intense effort to developing computational systems that address the gamut of tasks of visual processing. Do these people qualify to be considered as theoretical psychophysicists? To do so, I would argue, they have to go beyond generating an algorithm that works for a particular task, or even for a range of tasks, on the basis of a simple approximation to neurophysiological properties. They would need to subject their models to the quantitative rigour of predicting psychophysical results to the accuracy to which they are measured. They would need to make statistical comparisons to competing models, to see which stood up to this hard-nosed evaluation. And they would need to find neighbourhoods of counterintuitive or strongly discriminative predictions, which provide a stringent test of the intervening variables of the theory. These are the exacting criteria of predictive science; computational modelling that does not meet such criteria may justly be regarded as prescientific.

Within psychophysics, many would regard the theory of signal detection (TSD) as the backbone of psychophysical analysis. Implemented through a filter processing structure, it provides a broad-based framework for analysing perceptual detection tasks. To be specific, one reason for my dissatisfaction with visual theorising is that there is no complete account of TSD, despite the progress that was made at MIT in the 1960s. The basic properties of response bias (= detection criterion), neural summation (= receptive field structure) and probability summation (= attentional integration) were characterised at this time, but the emphasis was mainly on control of response bias. No resolution was provided as to how to analyse these effects once bias was controlled by use of the two-alternative forced-choice task. Subsequent theoretical analysis has been content with approximating the TSD effects rather than providing an accurate analysis. In the view of many, such approximation is adequate because the variations are within the threshold region, and therefore will not unduly affect the qualitative outcome. It has become apparent, however, that the precise theoretical assumptions may affect the outcome by up to 1 to 2 log units, the entire range of measurement in many psychophysical experiments! Thus, an accurate specification of the properties of TSD seems essential if threshold psychophysics is to be put on a firm footing.

To return to the comparison with physics, small changes in a critical variable may have profound consequences for theoretical interpretations of the data. A recent example is the homogeneity of the 3 K background radiation, our principal evidence for the Big Bang theory of the origin of the Universe. The distribution of this radiation across the sky is uniform to 10^(-4), but the fine structure below that level shows how the initial `fireball' eventually broke up to form the distribution of galaxies in space. Similarly, in vision, subtle differences in the images to the two eyes that are 10^(-5) of the width of the visual field or less may be interpreted as stereoscopic depth variations. So it is crucial to approach psychophysical measurement with appropriate respect for both the accuracy with which measurements can be made and the accuracy that may be required for appropriate theoretical interpretation.

The key approach represented by psychophysics may be described as macroanalysis of the system properties of the brain. The macroanalytic view does not imply that the psychophysical paradigm should not be as specific as possible. Careful design can target the studies to particular local mechanisms with a precision that may approach that of neurophysiological studies. For example, stimuli sufficiently local to stimulate predominantly a single cortical receptive field or even a single (peripheral) photoreceptor are feasible. Curiously, there have been few efforts to capitalise on this degree of spatial localisability. At further processing levels, stimuli may be designed to be highly specific with respect to some stimulus property such as motion velocity, depth curvature, or facial expression, for example. The results of a wide variety of experimental paradigms in such domains, which have provided many insights into the visual mechanisms that control their perception, form the basis of our current canon of visual science.

Nevertheless, it is time to rise to the challenge of developing a comprehensive theoretical framework for psychophysics. Ideally, it should encompass all relevant variables and specify accurate procedures to measure their contributions. Much of our work is involved with such efforts on an informal level, but much is to be gained by providing a coherent analysis for psychophysical hypotheses. I am not talking about the clairvoyant development of a new metatheory in the field, but the systematisation of the current hodge-podge of models into a broad theoretical infrastructure within which results can be evaluated. Only then can theoretical psychophysics become more than an aspiration for our discipline.

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