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Categorical/continuous perception: A phenomenon pressed into different models

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The continuous thread through Massaro's book, as it seems to me, is the author tilting at windmills that are permanently droning: Speech is perceived categorically and by specialized phonetic modules. Unlike Don Quixote, who trusted idealism, Massaro has compiled a wealth of facts and arguments that might eventually take the wind out of these sails.

In my commentary, I will concentrate on aspects of categorical/continuous perception, which is the topic of the central two chapters and repeatedly occurs at other places throughout Massaro's book. In the classical and, as it is obvious now, limited view (Liberman et al. 1957; Studdert-Kennedy et al. 1970), speech phonemes are perceived categorically if stimuli from an acoustic continuum (e.g. voice onset time) are labeled (or identified) as belonging to different classes and discrimination of within-class stimuli is poor, whereas between-class stimuli are well discriminated. Thus labeling functions are expected to predict the outcome of discrimination tests and vice versa, with both kinds of experiments producing boundaries between categories at the same regions of the acoustic continuum. On the basis of his own work and studies of others, Massaro replaces categorical by continuous perception followed by a categorical decision stage. Experimental evidence and arguments such as within-category discrimination, integration of multiple auditory and visual properties *before* phonemes are identified, and model-fitting calculations that favour continuous evaluation of parameters are detailed in support of a model including continuous sensory analyses of stimulus properties in appropriate channels, integration of the valued information from the channels, and a classification of the integrated information by matching it against prototypes in memory (Fig. 4, Chapter 1; Fig. 1 of the précis). The decisive difference between Massaro's model of continuous speech perception plus categorical recognition and categorical perception concerns the level in the hierarchy of proposed elements of building blocks where the categorization of the speech percept (i.e. the identification of phonemes) should take place. The term categorical "perception" implies that categorization is expected to occur within the *sensory* network of the brain, whereas Massaro places categorization on a supposedly higher level of "recognition" (whatever that means in terms of neuronal processes).

An elegant way of bringing both views in harmony with each other is to shift labels, that is, to extend the term "perception" to include Massaro's recognition or decision level (the reason for doing this should become clear below). Thus speech would be perceived categorically as long as both labeling and discrimination behaviour indicate a consistent and statistically significant but not necessarily pronounced boundary in the physical continuum of a given speech (or sound) parameter. This operational definition of categorical perception stands without any implications about levels, mechanisms, or theories of signal processing and recognition. Categorical/continuous perception understood in this way would be just a *descriptive term* about the outcome of the overall operation made by the brain which could comprise any kind of handling of information (continuous and/or categorical) in any channel at any level, including that of recognition. A good example for multi-channel continuous feature evaluation, feature integration, and pattern recognition is Ewert's (1987) model of visual pattern recognition in toads. This model has no defined decision level but nevertheless can produce categorical and continuous perception of a prey stimulus depending on the visual parameter varied in perception tests. Experiments suggest that stimulus recognition is accomplished by the coordinated activity in parallel, hierarchical, and loop-organized neuronal networks in which different classes of neurons contribute to the processing of different aspects of the stimulus, of learned associations, and of arousal. I mention Ewert's work because it demonstrates nicely that sensory perception, pattern recognition, and response generation is represented by a continuum of operations in the brain that can be divided into sections only arbitrarily. Thus, the problem of the categorical versus continuous perception of speech representing patterns may be a superficial one created by attaching different labels to different levels of the continuous process of speech evaluation which is able to produce both categorical and continuous results depending on test conditions.

Several studies have demonstrated continua between categorical and continuous speech evaluation. For example, categorical perception of voice onset time can be changed to continuous perception by specific training and stimulus presentation techniques (Carney 1977; Pisoni & Lazarus 1974; Samuel 1977). In addition, third formant transitions are categorized as /ra/ and /la/ after learning to "hear" the difference by English speakers; Japanese speakers lack this experience and thus perceive the /ra/-/la/ continuum continuously (Miyawaki et al. 1975). Again, brain mechanisms in speech perception produce a variable output in that they discriminate what is biologically (or culturally) important and dismiss potentially available distinctions if they have no semantic value. A similar phenomenon is reported in a study of tone discrimination (Spiegel & Watson 1981). Training and knowledge of an important acoustic feature of a stimulus improves the discrimination ability of that feature. In Massaro's view, these examples demonstrating a continuum between categorical and continuous stimulus evaluation are clear evidence for continuous information processing which is followed by a categorical decision process in the case of category recognition.

As I have argued before, we cannot unambiguously attribute categorization to the level of sensory processing, or to that of feature integration, or to recognition, or to processes at all levels together, until the neuronal (physiological) mechanisms underlying the categorization process are known. Thus, there seems to be little reason for changing names merely because categorical perception in the classical sense can be modeled by a theory that divides the entire process into continuous perception and categorical recognition. A theory of continuous speech perception as proposed by Massaro may easily lose sight of categorical phenomena. I am not an advocate of categorical speech or sound perception. However, lacking physiological evidence for making adequate distinctions between levels and mechanisms of continuous and categorical processing in speech, we should stay with the phenomena, which are interesting enough because they are continuous and categorical.

I find the classical concept of categorical perception a useful working hypothesis for designing experiments on stimulus perception, especially for communication sounds of animals, and a helpful framework for critically interpreting the results. There are even some cases where there exists experimental evidence for category formation within the sensory pathway leading to the categorical perception of communicative sounds, as we have demonstrated for ultrasound perception in house mice (Ehret 1987; Ehret & Haack 1981; 1982). The physiological basis for category formation in the frequency domain is the critical band phenomenon (e.g. Scharf 1970), an auditory filter mechanism established at or below the inferior colliculus of the midbrain (Ehret 1988; Ehret & Merzenich 1985; 1988). The category boundary in the temporal domain close to 25 ms may reflect absolute limits of temporal resolution in the auditory pathway because it coincides with the shortest boundary of voice onset time perception in man, monkey, and chinchilla and with thresholds of perception of temporal order in humans (compare Ehret 1987). These cases show that categorical perception in Massaro's sense is likely to exist and should not be abandoned as a possibility for human speech unless falsified by physiological evidence. Finally, one has to consider the efferent auditory system that can influence tone discrimination even at the cochlear level and may be expected to influence speech processing as well (e.g. Winslow & Sachs 1988). Thus top-down conditioning of the ascending auditory pathway is present and one might hypothesize that whenever categorical *information* in terms of speech phonemes is expected in a communicative context, peripheral processing is conditioned to accentuate these natural categories in order to preserve the semantic contents of the message optimally. If this is true, the categorization of speech information could gradually emerge in the auditory system and would hence be an inherent property of the perceptual process.

A general algorithm for pattern recognition?

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How does the brain make sense of the world? "In the same way that scientists do, and with the same tools," answer an increasing number of cognitive psychologists. The eighteenth-century mathematicians Laplace and Condorcet used their "probability of causes" to model the way scientists reason (Daston 1988); Dominic Massaro now proposes the identical formula as an algorithm for pattern recognition in general and speech perception in particular. To show the generality of the algorithm (the "fuzzy logical model of perception [FLMP]") is the ambitious goal of Massaro's book: "well-learned patterns are recognized in accordance with a general algorithm, regardless of the modality or particular nature of the patterns" (p. 16). The project of reducing pattern recognition to any algorithm, much less a single one, may strike many as overly ambitious. For the purposes of this commentary, however, I will accept Massaro's goal as in principle attainable and will try to invite him to clarify one of his major arguments by revealing its conceptual difficulties.

This argument is central to the issue of generality, and runs like this: (i) The FLMP is not only general but also optimal since it is mathematically equivalent to Bayes' theorem; (ii) here Bayes' theorem is implemented as it was by Laplace, that is, with the assumption of uniform prior probabilities and independence of events (features), but (iii) this equivalence poses a dilemma for the FLMP, since previous research, in particular on intuitive probabilistic reasoning, has rejected Bayesian reasoning as a general mental algorithm. In analyzing this argument, I shall proceed from the general to the specific.

1. Is the general algorithm a Bayesian one? The FLMP assumes that pattern recognition occurs in three sequential stages. I shall consider the simplest case, with only two features and two prototypes. In the feature evaluation stage, the match $t(E_1/H_1)$ between a feature E_1 and a prototype H_1 is calculated; in the feature integration stage the overall match $t(E/H_1) = t(E_1/H_1)t(E_2/H_1)$ between the two features and the prototype H_1 is calculated; and in the pattern classification stage the probability that the pattern will be identified as H_1 is given by $p(H_1/E) = t(E/H_1)/(t(E/H_1) + t(E/H_2))$. Massaro (pp. 196–98) says that this algorithm is mathematically equivalent to Bayes' theorem, assuming uniform prior probabilities and independent events, and replaces the above t (i.e. truth) values by p (i.e. probability) values. However, Massaro repeatedly (e.g. pp. 21, 166, 202) asserts that $t(E_1/H_1) + t(E_1/H_2) = 1$, which is not true for the corresponding probabilities $p(E_1/H_1)$ and $p(E_1/H_2)$ in Bayes' theorem. According to standard probability theory, which mathematically implies Bayes' theorem, the sum of these probabilities can be either less or more than 1. Thus, I doubt that the proposed general algorithm is in fact mathematically equivalent to Bayesian probabilities, and I therefore also doubt the claim that "either of these two models is adequate to account for the results" (p. 198).

2. A general pattern recognition algorithm with uniform priors? To keep the next points separate from the first, let me assume that I have overlooked something and that Massaro is right in pointing to the equivalence of the FLMP and Bayes' theorem. Laplace's urn analogy and Bayes' billiard table suggested uniform prior probabilities on the grounds that our ignorance gives us no reason to expect one urn or one area on the table to be a priori more likely than any other. But should we assume that a general pattern recognition algorithm also works on the principle of ignorance and uses uniform priors? An algorithm with uniform priors may be sufficient for the experimental designs reported in the book, in which the prototypes to be identified, such as /ba/ and /da/, are equally likely in the laboratory. But in everyday speech, just as in many other domains, different patterns have different prior probabilities depending on context. Where expectation plays a role, nonuniform priors seem to be indispensable for improving the perceptual "bet" in situations with uncertain information.[1]

3. Does intuitive probabilistic reasoning challenge the generality of the algorithm? Massaro argues that the mathematical equivalence of the FLMP and Bayes' theorem "poses a new dilemma" for the generality claim, since previous research has rejected Bayes' theorem as a model of intuitive probabilistic reasoning. His major defense is that most previous researchers used "objective" rather than "subjective" probabilities to calculate the so-called normative Bayesian outcome. Massaro's reply is correct: There are many ways to be a Bayesian, and such experiments do not rule out that intuitive reasoning is Bayesian by using subjective probabilities. But there are designs, such as in Kahneman and Tversky's (1973) Engineer-Lawyer study, which allow for subjective likelihoods and which still lead the authors to conclude that reasoning is not Bayesian, since base rates are ignored due to a representativeness heuristic. Massaro has to deal with these kinds of experiments. Moreover, even in the Engineer-Lawyer Problem, the neglect of base rates can easily be eliminated if one crucial structural assumption (random sampling of description) is made vivid to subjects, although the feature values remain constant (Gigerenzer et al. 1988). Such systematic changes in reasoning indicate that neither representativeness (i.e. uniform-prior Bayesianism, see below) nor Bayes' theorem is a general algorithm of the mind. Massaro's "dilemma," in my opinion, is not that intuitive reasoning ignores base rates (as does the FLMP in the book under review), but rather that intuition seems to have a whole toolbox of algorithms available.

Two things puzzle me concerning the relation between reasoning and the FLMP. First, as noted above, Massaro says that the pattern recognition algorithm is a Laplacean uniform-prior variant of Bayes' theorem. Why then does he believe it is a "dilemma" that intuitive reasoning seems to violate Bayesian reasoning by neglecting base rates and using uniform priors? Base rate neglect is exactly what his algorithm predicts – just as Baconian probability would (Cohen 1986). [See also Cohen: "Can Human Irrationality Be Experimentally Demonstrated?" *BBS* 4(3) 1981 and Kyburg: "Rational Belief" *BBS* 6(2) 1983.]