THE PERCEPTUAL-MAGNET EFFECT: AN EMERGENT CONSEQUENCE OF EXEMPLAR-BASED PHONETIC MEMORY

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ABSTRACT

This paper uses a mathematical model of infant speech perception to examine the assumptions and consequences of Kuhl's Native Language Magnet theory (NLM). A basic assumption of the NLM theory is that perceptual space is partitioned into phonetically relevant categories that are represented by category prototypes — the category's "best exemplar". The category prototypes function as "perceptual magnets" that attract exemplars falling within their zone of influence. As a consequence, discrimination as a function of the auditory distance between a prototype and other exemplars is low in the neighborhood of the prototype and has an increasing positive derivative as the exemplar moves away from the prototype (discrimination is proportional to the square or the cube of the auditory distance between the prototype and the exemplar).

While Kuhl's description of the perceptual magnet effect in terms of prototypes is elegant, I argue that the magnet effect emerges from a simple similarity metric operating on collections of exemplars stored in memory, without the need to refer to special exemplars.

INTRODUCTION

With this paper I would like to open a debate on conceptual aspects of Kuhl's Native Language Magnet theory (NLM) that has recently become very influential in the description of categorization and discrimination phenomena.

According to Kuhl [8], the phonetic perceptual space is organized in terms of particular exemplars, prototypes, that function as references for different classes of speech sounds. Prototypes are regarded as particular good vowel-category representatives — "focal" exemplars [15;1] — against which other instances of vowel sounds are compared in the course of the perception process. Kuhl's important addition to a traditional prototype-based classification process is the assumption that each prototype has its specific neighborhood of influence. The prototype is pictured as a "perceptual-magnet" that exerts its attraction force on neighboring auditory representations [7]. Stimuli producing auditory representations in that neighborhood are attracted to the prototype. In contrast, non-prototypical sounds are not supposed to exhibit the magnetic effect. In other words, discrimination, as a function of the psychoacoustic distance, is low and increases slowly within a prototype's neighborhood. Thus, variants producing auditory representations in that region tend to be perceived as more similar to the prototype than what might be expected on the basis of the auditory distance per se. As a consequence, the perceptual space appears warped in the neighborhood of a prototype whereas in the neighborhood of a non-prototype discrimination increases proportionally to the psychoacoustic distance.

Looking at categorization processes in terms of focal prototypes clearly captures the functional aspects of classification phenomena. Kuhl's introduction of the perceptual-magnet notion extends the traditional view of prototype-based classification processes by accounting for non-linear effects. Nevertheless a prototype-based approach raises issues that are rooted in the very notion of prototype. One issue, for instance, concerns its application to language acquisition processes. To account for effects of learning, prototypes must be re-tuned as a result of the learning procedure. In this case the magnet must be re-located during the language acquisition process at the same time that it functions as a prototypical reference. Another issue concerns the general motivation of prototypes in describing perceptual phenomena. Is the concept of a prototype really needed to account for categorization processes or can a prototype-like behavior emerge from collections of exemplars?

In this paper I will focus on the latter issue and present a sketch of how the magnet-effect can be derived from exemplars stored in memory and a simple distance metric.

PROTOTYPES

One problem I see with the prototype approach is that the very nature of the language acquisition process requires prototypes that can be rearranged in the perceptual space. If prototypes are assumed to be determined by the acoustic properties of the speech sounds — like the case of "point vowels" — it is necessary to assume a loss mechanism to discards non-functional prototypes. Following Kuhl's magnetic analogy (surely in more literal sense than she claims) the prototype must have larger mass than the variants in order to be stable enough in the perceptual space. Otherwise the system cannot be described in terms of a relatively stable magnet towards which "lighter" magnets are attracted. As the disparity of masses involved diminishes, the system becomes a two-mass system in which both elements clearly interact with each other. Thus, in order to achieve stability of the perceptual-magnets it seems necessary to postulate forces that anchor the prototypes at the appropriate locations or a process by which a prototype-like structure emerges in the perceptual space. Possible acoustic-articulatory arguments for a priori locations of vowel prototypes may be found in Stevens' [16] quantal theory of speech — but why should perceptual prototypes necessarily match acoustic-articulatory constraints? An alternative perceptual account for specific vowel-prototype locations might be based on Lindblom's [14] modeling of vowel systems. However, this account would involve circularity since Lindblom starts out with a given number of vowels (matching a priori Kuhl's prototypes) and tries to determine their positions under the constraints of both maximal perceptual distance among the vowels in the system and articulatory feasibility. But prototypes cannot, at any rate, be determined solely by constraints in the perceptual and articulatory system.

To account for the language acquisition process, prototypes will have to be moveable entities. Actually, as revealed by Kuhl and Meltzoff's [9] recent research, prototypes are highly plastic entities since 3, 4 and 5 months-old infants rearranged their prototype locations after only 3x5 minutes audio-visual exposure to model presentations. At first glance, this extreme plasticity by 5 months of age is hard to reconcile with the establishment of stable language-dependent prototypes by 6 months of age [12]. Given the normal signal variability, establishing stable prototypes within one month's period should, in principle, be a difficult task for the infant. Yet, taking into consideration that from the infant's point of view there may be only a limited number of functionally relevant audio-visual combinations, maybe the task is afterall less demanding than it first appears. At any rate, to account for this reorganization during the language acquisition process, prototypes must be seen as plastic entities, suitable to modification by adequate exposure to language but this diminishes the referential role of prototypes. If prototypes are the distal effect of external stimulation, there is no obvious conceptual reason to use prototypes instead of the very exemplars on which they are based.

EXEMPLAR-BASED MODEL

To present my argument that prototypes are implicit in exemplar-based categorization processes, I will introduce a very simple perception model in which the perceptual magnet effect emerges from an exemplar-based categorization process.

Model assumptions

Let us simplify the exemplar-based perceptual model by addressing classification and discrimination of one-dimensional elements. This one-dimensional case represents a situation in which there is a determinant main dimension that allows discrimination of the stimuli. An example would be discriminating vowels in terms of degree of opening. Although vowels can be represented by multi-dimensional points in a formant space, degree of opening can be satisfactorily discriminated by considering F_1 alone. The general case in which co-variation in several dimensions must be considered can, in principle, be treated as a combination of appropriate one-dimensional cases.

My basic assumption is that representation of exemplars are stored in memory and that an external labeling function is also available during the learning phase. The plausibility of a memory representation of specific exemplars is supported by Jusczyk's recent results indicating that infants store specific information about voices and words [3;4;5]. In addition, access to a labeling function is typical of the learning situation. During the language acquisition process, the infant is exposed to allophonic variation in its ambient language and to correlated category information that is available from other modalities. Thus, stimulus variability along a perceptual dimension for a given category is assumed to produce distributed memory representation of exemplars. This distribution represents the frequencies with which particular values of that dimension were observed for the category. In the following example I will assume that stimuli generate normal distributions with mean μ and standard deviation σ, as indicated by the function Class(x, μ, σ):

$$\mathrm{Class}(x,\mu,\sigma) := \frac{1}{\sqrt{2\cdot\pi}\cdot\sigma}\cdot e^{-\frac{(x-\mu)^2}{2\cdot\sigma^2}}$$

The function describes the relative frequency with which a **x**-values were stored in memory.

The model categorizes new stimuli using a similarity metric that is based on the labels of the memorized exemplars that are found within the immediate neighborhood of the new stimulus. The new stimulus is given the label of the category contributing with the largest number of exemplars in the stimulus' neighborhood, provided that category's dominance is above a pre-established minimum decision threshold[1]. If similarity is below the threshold, no decision is made and the new stimulus is classified as "unknown". In this paper I will assume that the decision threshold is 0. This metric behaves like a cohort model for lexical access. The number of neighbors belonging to category **A** (**μ=0**) found in the neighborhood **ε** of the stimulus is given by

$$\mathrm{NeighbA}(x0,\varepsilon) := \mathrm{TotalA}\int_{x0-\varepsilon}^{x0+\varepsilon}\mathrm{Class}(x,0,\sigma)\,dx$$

[1] If there are many competing categories, the relative similarity to any of them may be so low that no decision should be made by the model.

In this expression **x0** represents the actual value of the stimulus along the relevant dimension and **TotalA** the total number of exemplars in the category.

If the alternative category is **B**, with **μ=3**, then the similarity of stimulus **x0** to category **A** and to category **B** is defined as

$$\mathrm{sA}(x0) := \frac{\mathrm{NeighbA}(x0,\varepsilon)}{\mathrm{NeighbA}(x0,\varepsilon)+\mathrm{NeighbB}(x0,\varepsilon)}$$

The similarity of elements **x0** to each of the categories **A** and **B** is depicted in figure 1 for the case in which categories **A** and **B** are described in table 1.

Table 1. Specifications of two categories, A and B, with normally distributed exemplars (mean μ and standard deviation σ). The categories have different numbers of exemplars.

Category	μ	σ	Exemplars in the category
A	0	1	1000
B	3	1	100

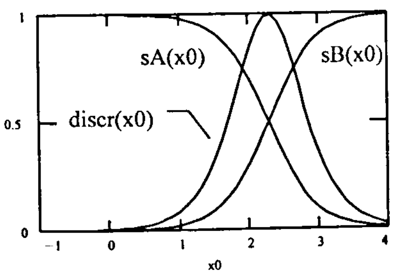

Figure 1. Similarity functions to classes A and B and discrimination function. Note that the category boundary is shifted towards category B because A contains a larger number of exemplars.

If similarity to a category is 1 all the neighbors come from that category. The figure also displays a discrimination measure, **discr(x0)**, that is based on the local variation in the number of exemplars coming from different categories. For the two categories case, the measure is defined as

$$\mathrm{discr}(x0) := \frac{\left|\frac{d}{dx0}\mathrm{sA}(x0)\right| + \left|\frac{d}{dx0}\mathrm{sB}(x0)\right|}{2\cdot\mathrm{Const}}$$

where the constant, **Const**, is arbitrary and represents here the maximum slope of the similarity functions and is used to make the discrimination function to fit the interval [0;1].

An interesting property of this exemplar model is that it can simulate Kuhl's perceptual magnet effect without reporting to a specific prototype. In fact, assuming that a prototype, in Kuhl's terms, is the center of the category distribution, the discrimination curve, **discr(x0)**, suggests that discriminability will be lower in the neighborhood of the prototype than for stimuli falling on the outer skirts of the prototype's category. The category limits are dependent on both on the spreading and on the number of exemplars defining the category.

According to the present model, the perceptual-magnet effect occurs as a consequence of the distance metric that is applied to the perceptual space in which representations of stimuli are stored. Under the plausible assumption that the perceptual representations of exemplars belonging to two different categories are only partially overlapping along a relevant perceptual dimension[2], the above described similarity measure will generate the perceptual-magnet effect when assigning novel stimuli to those categories. Thus, the warping of the perceptual space invoked to describe

[2] This condition is always met. Stimuli belonging to different categories must be distinguishable in some way. There may not be necessarily a single dimension that distinguishes them but at some level of complexity, including contextual dependencies, there will always be a difference between stimuli that signal different categories.

the magnet effect emerges as a corollary of the application of the present similarity metric the entire perceptual domain.

In conclusion, it seems that the observation of a perceptual magnet effect is not necessarily linked to the existence of language-specific prototypes for the different classes of speech sounds. The focal prototypes used in Kuhl's NLM theory are elegant functional higher level entities but they demand a specific non-linear metric. In my opinion, the exemplar-based account that I sketch here is a preferable approach to account for the perceptual magnet effect, since it is based on "simple" memory representations and uses a more "straight forward", cohort-based, perceptual distance.

Accounting for native language tuning

One of the problems faced by the prototype approach is the need to redefine the prototype to account for the infant's tuning towards its ambient language [12]. Prototypes must be relocatable in the perceptual space to enable the infant and the young child to learn the ambient language and also to enable re-tuning in the event of change of ambient language during the early stages of the language acquisition process. Since the prototypes' relocation process is contingent on language exposure, it should be possible to account for it on the basis of the exemplars that underlie the process, without the need to invoke the prototype notion. Within the current exemplar-based model, re-tuning is a consequence of memory decay affecting "old" exemplars. Thus, the influence of the ambient language can be modeled by including a memory decay term in the exemplar distribution, a term that fades out the representations of non-activated exemplars. Computations including this term are in principle analogous to the timeless model and will be discussed elsewhere [13].

Accounting for the species-specific perceptual magnet effect

In Kuhl's original article introducing the perceptual-magnet effect [7] it was demonstrated that the effect could not be observed for non-human species (monkeys). In my opinion, the fact that "human adults and infants show perceptual-magnet effect while monkeys do not" can be accounted for within an exemplar-based framework. One of the implications of the exemplar model is that the perceptual-magnet effect arises as a consequence of the exemplar labeling and in conjunction with the memorization process. The extent of the perceptual-magnet effect, as predicted by the exemplar model is dependent on the relation between the number of stimuli in the category and the number of stimuli in the competing categories (everything else being equal). Thus, the exemplar model predicts that the perceptual-magnet effect should be observed for monkeys if the stimuli used are made meaningful for the animals. Otherwise, a discrimination test of the type described by Kuhl [7] cannot be expected to reveal any perceptual-magnet effect for monkeys because the effect is a consequence of an underlying labeling process which, in this case, may have been irrelevant for the monkeys. Hence, within the framework of the present exemplar-based model, the behavioral differences observed between the monkeys in Kuhl's [7] experiment and the monkeys in Kuhl and Padden's [10;11] earlier experiments or the quails in Kluender, Dihel and Killeen's [6] may be due to different amounts or different types of training.

TESTING THE MODEL ON EXPERIMENTAL DATA

This section is a simple numerical exercise to illustrate how the current

model may account for some of Kuhl's experimental data. I used the data in Kuhl's (1991, fig. 3) [7] category goodness ratings for the American /i/ vowel, along the vector extending from the prototypical /i/ to the non-prototype /i/, to define the parameters of the exemplar model sketched above.

According to the assumptions of the exemplar model, goodness ratings are a rough estimate of the number of category exemplars at the stimulus location and can therefore be used to estimate the frequency distribution of the exemplars in the perceptual space. I used the variation in the category goodness, provided by Kuhl's subjects, to derive a discrimination function between the elements falling along that vector and the reference element (prototype). The results of this computation are shown in figure 2. The scale of the modeled discrimination function is arbitrary and was adjusted to force the maximum of the modeled discrimination function to be close to 1.

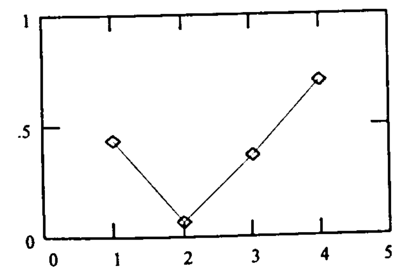

Figure 2. Discrimination sensitivity (arbitrary units) as a function of the distance (30 mel rings) to the prototype

To derive a generalization function comparable to Kuhl's experimental generalization scores, the discrimination sensitivity function in figure 2 must be integrated across rings, according to

$$AccD_{ring} := \sum_{i=1}^{ring} discr_i$$

and transformed into a generalization function, (1-AccD). The computed generalization curve is shown in figure 3.

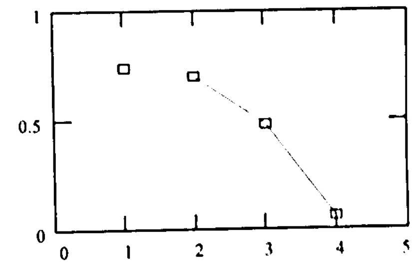

Figure 3. Computed generalization (arbitrary scale) as a function of the distance to the prototype.

The shapes of the modeled and Kuhl's experimental generalization curves resemble each other. The discrepancies between the model prediction and the experimental data may be due to the fact that goodness ratings distribute along a rank scale, but do not necessarily fulfill the interval scale requirement that underlies my model computations. To overcome this difficulty, I generated new curves based on data recently published by Sussman and Lauckner-Morano [17]. These authors reassessed Kuhl's [7] work and provide mean percent /i/-responses based on subjects' responses in a dichotomic /i/ *vs.* not-/i/ task. These percentages are more likely to meet the requirements of an interval scale. Under this assumption, the model-based discrimination function takes the form of that is displayed in figure 4.

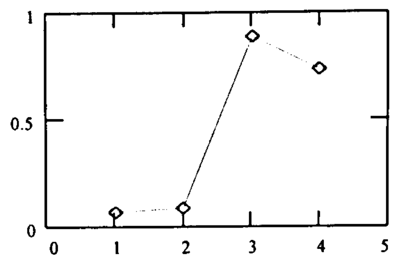

Figure 4a. Discrimination sensitivity vs. ring location predicted from Sussman and Lauckner-Morano's (1995) data.

The corresponding generalization function predicted by the model is shown in figure 4b.

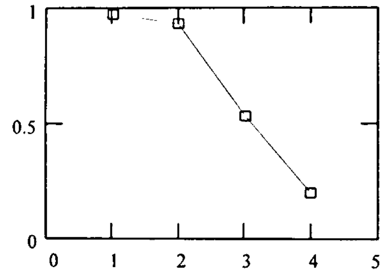

Figure 4b. Generalization associated with the discrimination sensitivity shown in fig. 4a.

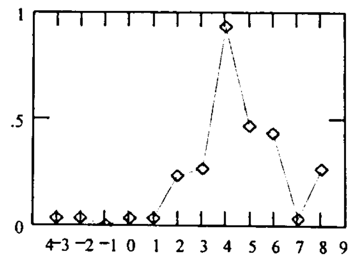

Figure 5a. Discrimination sensitivity (arbitrary units) vs. ring location. X-origin: Kuhl's (1991) prototype

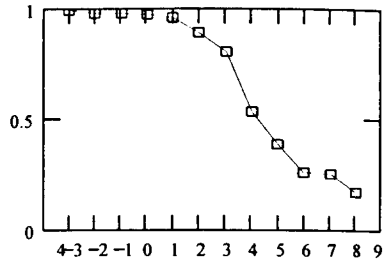

Figure 5b. Generalization computed from the discrimination function displayed in fig. 5a.

Figures 5a and 5b show the discrimination sensitivity and the generalization functions computed from Iverson and Kuhl's [2] data. The origin of the X-axis is the location of Kuhl's [7] prototype. The scale of the Y-axis is arbitrary. As illustrated by figures 4 and 5, when the model predictions are based on a more plausible interval scale, the general agreement between the predicted discrimination and the experimental is clearly improved.

CONCLUSIONS

The exemplar-based perception model that was sketched here is likely to provide a more parsimonious account of the perceptual magnet effect than Kuhl's original prototype-based account. What I tried to present here was the outline of an exemplar-based perception model that has some interesting theoretical properties but that is not, at this stage, calibrated in meaningful numerical simulations.

One important feature of the exemplar model is that it allows a rather straightforward reorganization of the listener's perceptual space as a consequence of the amount of experience with exemplars defining the relevant linguistic categories. While it should be kept in mind that a model description is obviously not an attempt to mimic neurophysiological reality, the type of

computations required by this exemplar-based model are likely to be less alien to neurophysiology than the operations associated with the prototype model. Another important consequence is that an exemplar-based metric implicitly accounts for the warping of the perceptual space in the neighborhood of the prototypes.

The potential use of the present model as a unified description of other perceptual phenomena is currently under investigation [12].

In summary, while prototypes are adequate entities to describe the functional features of the perceptual magnet effect they are not necessary to explain it.

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