Semantic categories of artifacts and animals reflect efficient coding

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It has been argued that cross-language variation in semantic categories reflects pressure for efficient communication (e.g. Kemp et al. 2018). On this view, the lexicons of different languages represent a variety of means to the same functional end: transmitting ideas accurately, with minimal cognitive complexity. Recently, Zaslavsky et al. (2018) cast this idea in terms of an independent information-theoretic principle of efficiency, the Information Bottleneck (IB) principle (Tishby et al., 1999), which is closely related to Shannon's rate distortion theory. In this context, IB is given an underlying cognitive representation of a semantic domain, and a prior over objects in the domain, and it produces a set of optimal category systems for that domain, for different trade-offs between system complexity and accuracy. These optimal systems define the theoretical limit of efficiency. Zaslavsky et al. (2018) showed that IB explains much of the variation in color naming across languages, and also accounts for the emergence and evolution of named color categories, including soft structure and patterns of inconsistent naming. However, it has remained unclear to what extent this account generalizes to semantic domains other than color. Here we show that it generalizes to two qualitatively different semantic domains: names for containers, and for animals.

Containers. We considered container naming and pile-sorting data collected by White et al. (2017), relative to a stimulus set of 192 images of household containers (see Figure 2A for examples), produced by Dutch and French monolingual speakers, and by bilinguals in each of the two languages, yielding four conditions: language (Dutch, French) $\times$ linguistic status (monolingual, bilingual). We took the sorting data to provide domain structure, against which we assessed the efficiency of the naming data by applying the IB method. The results are shown in Figure 1. It can be seen that the efficiency of container naming in Dutch and French lies near the theoretical limit, for both monolinguals and bilinguals. These systems were also found to be more efficient than a set of hypothetical variants of these systems.

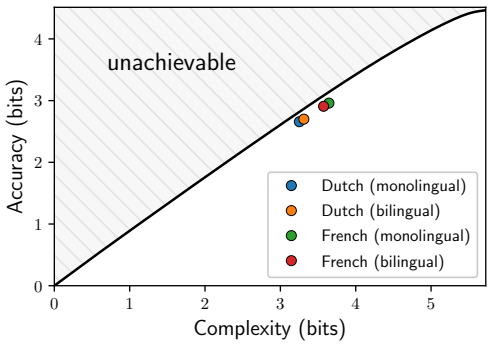

Figure 1: The black curve is the IB theoretical limit of efficiency for container naming, identifying the maximum achievable level of accuracy at each level of complexity. Points above this curve are unachievable. The four conditions considered exhibit near-optimal trade-offs between accuracy and complexity in container naming.

For visualization purposes, we embedded the 192 containers in a 2-dimensional space by applying non-metric multidimensional scaling (nMDS) with respect to the similarity data, similar to Ameel et al. (2009). We assigned a unique color to each container. The resulting 2D embedding and color coding of the containers stimulus set are shown in Figure 2A. The monolingual systems in Dutch and French are shown in Figure 2B, together with the corresponding optimal systems on the IB curve. It can be seen that the IB systems capture qualitative aspects of the actual systems, including soft categories and inconsistent naming

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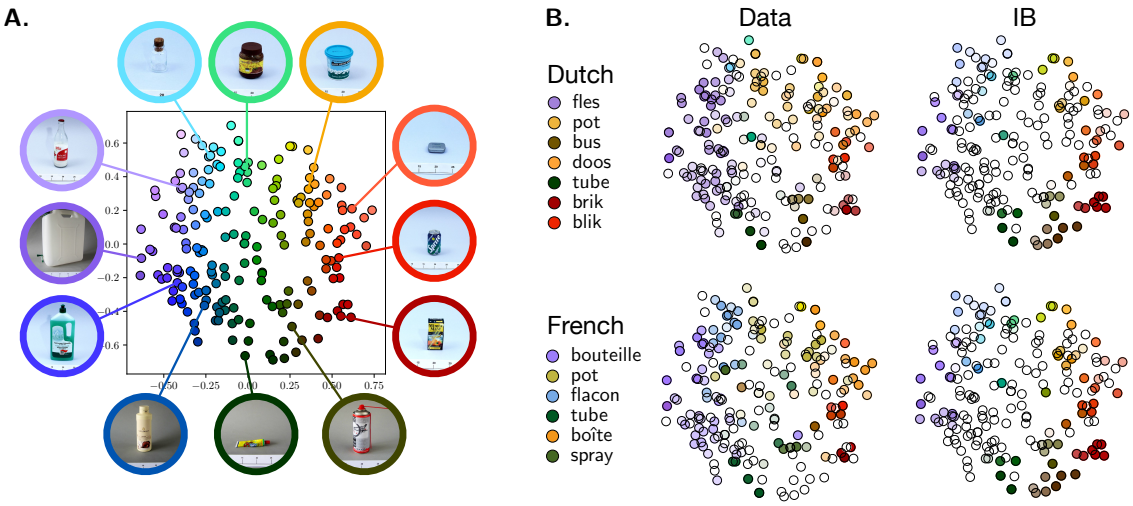

Figure 2: **A**. Two dimensional nMDS embedding and color coding of the containers stimulus set used by White et al. (2017). Images show a few examples. **B**. Monolingual naming distributions for Dutch (upper left) and French (lower left), together with their corresponding IB systems (right column), are visualized over the 2D embedding shown in (A). Each color corresponds to the color centroid of a container category, based on the color map in (A). Colors show category probabilities above 0.4, and color intensities reflect the values between 0.4 and 1. White dots correspond to containers for which no category is used with probability above 0.4. Legend for each language shows only major terms.

for some objects, showing that these phenomena can be explained by a drive for efficiency.

Animals. Brown (1984) proposed an implicational hierarchy of animal categories across languages, based on data from 144 languages. We conducted an analysis of animal naming broadly analogous to the container analysis described above, based on human-generated features and familiarity ratings drawn from the Leuven Natural Concept Database (De Deyne et al., 2008). That analysis (not illustrated or elaborated here for reasons of space) revealed that the IB theoretical limit of efficiency in this domain correctly predicts several aspects of Brown's hierarchy.

Conclusion. These findings suggest that fundamental information-theoretic principles of efficient coding may shape semantic categories across languages and across domains.

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