

Preserved Structure Across Vector Space Representations

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Abstract

We find evidence of preserved structure between vector space representations of words and their corresponding image embeddings. This is evidence of regularity between the representations learned using distributional statistics of words and the visual characteristics of those same items. We find that some classes of objects, namely inanimate ones, preserve their within-class structure across these two spaces more strongly than others (e.g. animate objects), and that this quality of preserving class-level relationships across representational spaces might aid in lexical acquisition, with invariance serving as an informative marker of category boundaries. Our current analysis does not show significant age-of-acquisition benefits for inanimate objects, but does exhibit a stable pattern suggesting that other partitioning schemes might be worth exploring (or something like that)

Keywords: vector space models; semantic similarity; word learning

Introduction

Infants are presented with a challenge to carve the world into distinct lexical entities in the process of learning their first language. They're provided little supervision while mapping a territory which William James (1890) dubbed a "great blooming, buzzing confusion". How they determine which aspects of the world to attend to in service of this goal, is an area of ongoing research (Mareschal & Quinn, 2001). Different features of objects and their environments are varyingly informative with regards to object segmentation and category structure. Some researchers have suggested that categorization is along fundamentally perceptual grounds and that only later in development is conceptual knowledge incorporated into these nascent perceptual categories (Quinn & Eimas, 1997, 2000; Quinn, Johnson, Mareschal, Rakison, & Younger, 2000). Others suggest that there are in fact two distinct processes, such that perceptual categories are computed automatically by the sensory systems, while conceptual categories are independently formed through conscious action (Mandler, 2000). Träuble and Pauen (2007) provide evidence of functional information (regarding the animacy of objects) influencing early category judgements. Gelman and Markman (1986) explicitly set these two sources of category cues against each other (i.e. functional vs. perceptual), in hopes of discovering which holds greater influence in infant categorization behavior.

The degree to which these two sources of information are separable is an important open question. Any model which hopes to explain the mechanics of human categorization must address how these seemingly disparate forms of information interface in mental representations, and to what degree they interact. In our current study we examine the degree of inter-

action between representations learned by two different algorithms which operate on apparently dissimilar inputs, namely images and text. These algorithms learn feature representations as an unsupervised byproduct of their particular training objectives, which are completely divorced from one another and which may themselves be supervised. The features they learn serve as the basis for their subsequent use towards practical ends (e.g. machine translation or object recognition in images).

Methods

We generate two sets of vector representations for a common set of words first learned by most infants. The first set of vectors are taken from a pretrained set of GloVe representations (Pennington, Socher, & Manning, 2014), a modern distributional semantic vector space model. The second set is taken from the final layer activations of a pretrained image recognition model, Google's Inception V3 convolutional neural network (Szegedy, Vanhoucke, Ioffe, Shlens, & Wojna, 2016). Both of these representations are what's referred to as "embeddings". They map objects from one medium (e.g. images or words) into a metric space where distances between points can be computed and function as a measure of similarity between objects.

In the case of our word vectors, the GloVe algorithm instantiates the distributional hypothesis, which proposes that words which co-occur with each other share similar meaning (Firth, 1957; Harris, 1954), and by capturing the covariance of tokens in large text corpora, you capture some aspect of their semantic structure. The image embeddings, on the other hand, are taken from the final layer of activations in a convolutional neural network, whose objective function tunes network parameters in service of object recognition, where the loss function is computed in reference to a set of labeled training images (Russakovsky et al., 2015). The final layer of this network encodes the most abstract and integrated visual features, serving as the basis for classification into 1000 different classes.

Defining a prototypical image

In the case of word vectors, each word is assigned a unique point in a common vector space. Different images containing objects of the same type, on the other hand, will have varying vector representations after passing through the layers of a neural network. This presents a problem in comparing the two forms of representation. We must first define the most prototypical (or average) image vector for any given category of object.

Given a set of images S_c containing objects belonging to a single category c (e.g. cat, dog, chair), we define our prototypical vector \hat{x}_c of S_c as the generalized median within a representational space U . This is the vector with minimal sum of distances between it and all the other members of set S_c in U . If x and y are vectors in space U , products of images in S_c being passed through a neural network, then

$$\hat{x}_c = \arg \min_{x \in U} \sum_{y \in U} d(x, y)$$

We define our $d(x, y)$ to be the cosine similarity measure:

$$d(x, y) = 1 - \frac{x \cdot y}{\|x\| \|y\|}$$

Our $d(x, y)$ is not a metric in the strict sense, but is less susceptible to differences in L^2 norm influencing our measure of similarity, as is the case with the Euclidean distance. These magnitude difference can be the product of frequency effects in the training data, and the cosine similarity corrects for this.

The image inputs we use are all 960x960 images of a single object on a gray background. These images were chosen by virtue of their presence in infants' early linguistic environment, aggregated as part of the SEEDLingS project, which gathered longitudinal audio and video data of infants' home environments (Bergelson, 2016a, 2016b). We arrive at a set of 27 unique words, selected on the basis of having at least 9 unique images with which to determine the most prototypical. The more images we have of any given category, the more robust our measure of category variance in image vector space, resulting in more representative category vectors. These are all words found on WordBank (Frank, Braginsky, Yurovsky, & Marchman, 2017), a compilation of the MacArthur-Bates Communicative Development Inventory, which we use as our proxy for age of acquisition. By studying the behavior of these developmentally salient objects, our analysis is able to speak to the statistical structure of those objects which infants will be most readily contending with.

Comparing spaces

After we have our two sets of vectors (i.e. those from word vector space and those from image vector space), we can compare all the pairwise distances between objects, both within a single space and across the two. When comparing across the two spaces, a correlation in pairwise distances implies that inter-object distances have been conserved. For example, if "dog" and "cat" are close together in word space and mutually far apart from "chair" and "table" in that same space, maintaining this relationship for all pairwise distances in the *other* vector space means that the global inter-object structure is preserved across this mapping, despite being in radically different spaces, both in terms of dimensionality (300 for words, and 2048 for images in our case) and by virtue of using completely different algorithms and inputs to establish the vector representations for objects. So while their absolute locations might have been radically transformed, this

correlation would be a measure of the *degree of invariance* in their positioning relative to each other.

Results

We find that pairwise cosine distances between objects in word vector space correlate with those same pairwise distances in the image vector space (see Figure 1). If we partition the set of inter-word distances into those that are either animate-animate, inanimate-inanimate, or mixed, we find that the pairs of distances between inanimate objects significantly correlate across our two spaces ($R = 0.38$, $p < 1.7e - 07$), while the other two pairings do not (see Figure 2). We expect that those classes of objects which preserve their structure between representations more strongly would result in earlier object-referent mappings. This is because inferences about object-referent mappings conditioned on both visual and semantic features would be more stable compared to those cases where the two representations vary independently. For example, an object that is both round (i.e. visual feature) and tends to roll (i.e. semantic feature) would be more salient as a distinct entity than an object whose visual features are entirely uninformative about its functional or semantic qualities.

In our current analysis the class of objects which displays stronger structure preservation (within class) are the inanimate objects. When we partition our set of 27 words into animate and inanimates and plot their relative AoA, we find a noticeable though insignificant preference for inanimates (see Figures 3 and 4). The choice to partition our set into these two categories is to a degree arbitrary, and we have no reason to believe infants would learn one class of objects earlier than the other. Our current analysis is offered purely as an exploratory exercise, suggesting that perhaps partitions along other taxonomic or associative lines may provide insight in future investigations.

Discussion

Conclusion

Acknowledgements

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(Gelman & Markman, 1986, Tversky (1977), Kemp, Bernstein, & Tenenbaum (2005), Hahn, Chater, & Richardson (2003), Pennington et al. (2014), Szegedy et al. (2016), Firth (1957), Harris (1954), Russakovsky et al. (2015))

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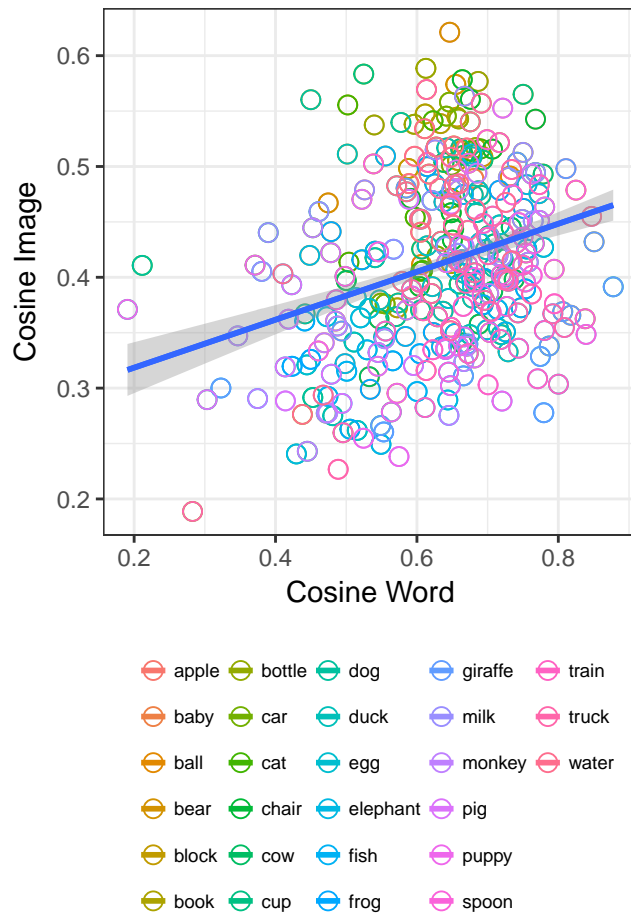


Figure 1: Relative cosine distance between points in word embedding space correlates with relative distance in image embedding space ($R = 0.30$, $p < 9.9e - 16$). Graph contains all pairwise distances for every word.

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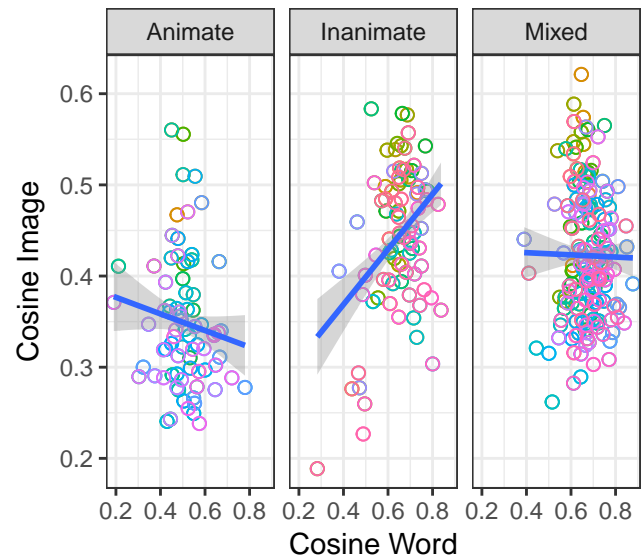


Figure 2: Inanimate objects display a significantly stronger correlation when mapping across vector spaces, meaning that they preserve their within-class structural relationships more reliably across these two spaces. Animate and mixed distances do not correlate. Each graph contains all pairwise distances between objects that are either a) both animate ($R = -0.13$, $p < 0.12$), b) both inanimate ($R = 0.38$, $p < 1.7e - 07$), or c) mixed animate-to-inanimate ($R = -0.01$, $p < 0.8$)

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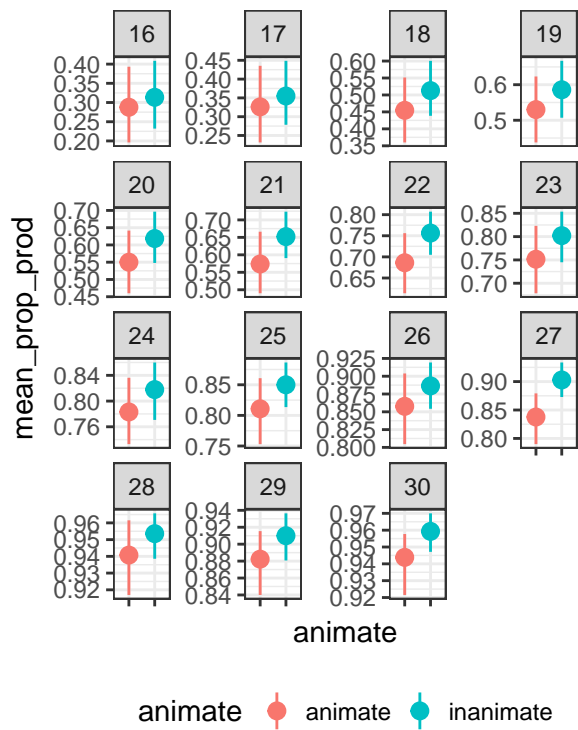


Figure 3: By-month AoA of animates vs. inanimates using child production data

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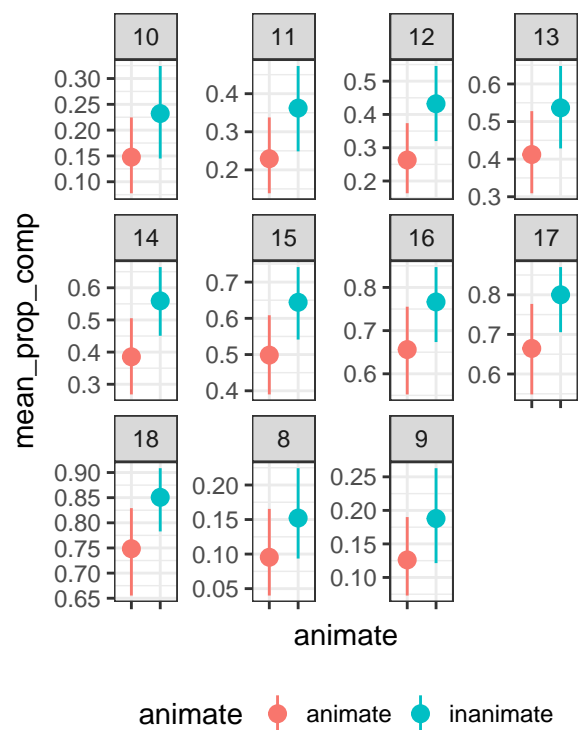


Figure 4: By-month AoA of animates vs. inanimates using child comprehension data

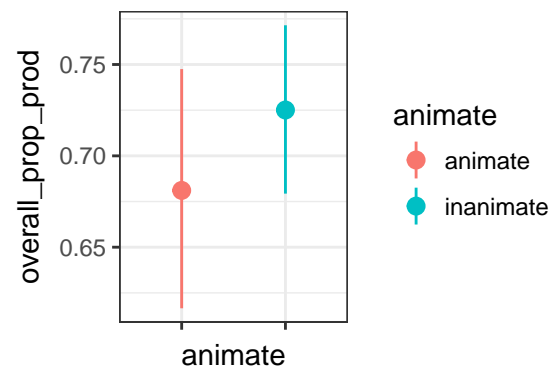


Figure 5: AoA for animates vs inanimates collapsed over month

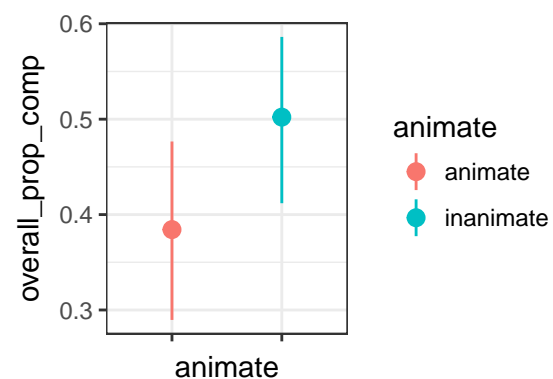


Figure 6: AoA for animates vs inanimates collapsed over month

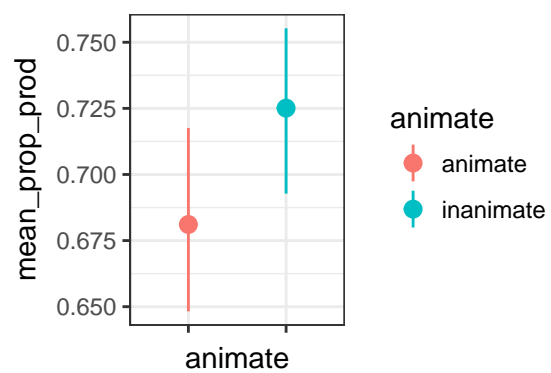


Figure 7: AoA for animates vs inanimates collapsed over month

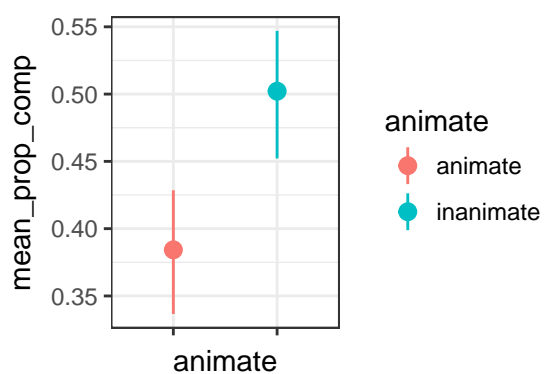


Figure 8: AoA for animates vs inanimates collapsed over month