Creating and Learning Something Different: Similarity, Contrast, and Representativeness in Categorization

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Abstract

The ability to generate new concepts and ideas is among the most fascinating aspects of human cognition, but we do not have a strong understanding of the cognitive processes and representations underlying concept generation. In this paper, we study the generation of new categories using the computational and behavioral toolkit of traditional artificial category learning. Previous work in this domain has focused on how the statistical structure of known categories generalizes to generated categories, overlooking the extent that the contrast between the known and generated categories is a factor. We report three experiments demonstrating that contrast between what is known and what is created is of fundamental importance for categorization. We propose two novel approaches to modeling category contrast: one focused on exemplar dissimilarity and another on the representativeness heuristic. Our experiments and computational analyses demonstrate that both models capture different aspects of contrast's role in categorization. Our work also serves as a concrete example of how well-established categorization models can be applied beyond category learning.

Keywords: categorization; concepts; category learning; generation; computational modeling; exemplar models; representativeness

1 Introduction

Creating and learning new ideas is one of the most fascinating and important human capabilities. For example, cell phones and smart phones are newly created categories of objects that young and old adults learned and have become reliant on in the last few decades. In fact, computational researchers have identified generating novel objects and objectives as one of the defining, and most difficult to formalize, characteristics of intelligent life (Lake, Ullman, Tenenbaum, & Gershman, 2017; Lehman & Stanley, 2011; Taylor et al., 2016). Yet, the cognitive mechanisms that enable people to innovate and learn new innovations are not well understood and are understudied by scientists. In part, this is due to the inherent difficulty of designing and conducting experiments that test these capabilities. How would a scientist devise an experiment that induces a participant to create and learn new categories that are as interesting as cell phones and smart phones? As a step towards these goals, in this article we investigate the expectations that people have when they learn and generate new categories using computational models and behavioral experiments.

Generating and learning new concepts are, however, not altogether different from the types of behaviors typically studied in cognitive psychology laboratories. In particular, generating a member of a novel class can be considered a 'special case' application of existing category knowledge (Kemp & Jern, 2014; Kurtz, 2015). Research in categorization typically focuses on what properties of a category affect human learning of an object's category given its features (Kurtz, Levering, Stanton, Romero, & Morris, 2013; Shepard, Hovland, & Jenkins, 1961), or the prediction of an object's unobserved features given some of its other features and/or its category (Markman & Ross, 2003). The generation of members of a new category consists of inferring *all* features for a *novel* category label. Thus, we can make progress formalizing the processes involved in category generation by extending theories of categorization to this case. Then, to ensure that these principles reflect basic principles of categorization and are not just specific to category generation, we can examine what factors of the generated categories affect the ease at which people learn the category.

Previous work in category learning and generation has established that people are highly sensitive to the structural properties of categories, such as correlations between the features of category members and the relation between items within the same category and those in different categories (Regier, Kay, & Khetarpal, 2007; Rosch & Mervis, 1975; Shepard et al., 1961; S. M. Smith, Ward, & Finke, 1995). Inspired by this work, previous research on the topic of category generation has explored a similar principle: People tend to create new categories that have similar *statistical regularities* as previously learned categories (Jern & Kemp, 2013; Ward, 1994). Although this is an important characteristic of generating new categories, it cannot be the only one. Taken to the extreme, the best "new" category in terms of having the same statistical regularities to other categories would be identical to a known category that is representative of the domain (and thus, not new at all). Contrast from other known categories should play a role. Further, scientists in other fields, such as marketing (Berger, 2016) and sociology (Rogers, 2003), highlight the critical importance of contrast in the creation of new ideas.

To successfully generate something novel, what is generated must be different from what is already known. This fundamental constraint, "being different", or contrasting from other categories in the relevant domain, is the focus of our work. Although implicitly assumed in some work, this constraint has been overlooked in previous research: To our knowledge, there has not been any systematic investigation addressing how generated categories *differ* from what is already known. Although the idea of category contrast is ubiquitous throughout the categorization literature, and extends to a variety of other fields (e.g., color; Regier et al., 2007), the idea that a new category should be "different" is vague, as there are many ways it could be different from a previously observed category.

We examine two different definitions of how categories should differ from one another: exemplar dissimilarity and representativeness of the alternative category. To formalize the first technique, we build on the largely successful exemplar modeling framework that (Medin & Schaffer, 1978; Nosofsky, 1984, 1986). In doing so, we propose a novel exemplar model of category generation, *Producing Alike and Contrasting Knowledge using Exemplar Representations* (PACKER), formalizing how new categories should differ from previous categories. It embodies the exemplar dissimilarity principle by incorporating a factor that repulses members of opposite categories from one another. To foreshadow, we find that this notion of contrast predicts human category learning performance, above and beyond other category learning models in a novel behavioral experiment. This demonstrates that contrast plays a central role in other important categorization tasks, and it is not specific to category generation.

The second hypothesis for how contrast might affect categorization is contrast as *representativeness*. The representativeness heuristic (Kahneman & Tversky, 1972) states that people make judgments regarding an outcome based on how representative it is of the evidence given in the current context. The heuristic is a powerful theoretical construct that has been used to capture a range of complex patterns of human judgments (Kahneman & Tversky, 1973; Tversky & Kahneman, 1974, 1983), especially those that deviate from normative theory (as given by a straightforward application of Bayes' rule). For example, the coinflip sequence TTHTH is perceived to be more random (due to it being representative of a coinflip sequence) than TTTTT (despite both having the same probability of having been generated from a fair coin). Although there is a healthy debate as to whether perceived randomness *really* deviates from normative theory (Griffiths, Daniels, Austerweil, & Tenenbaum, 2018; Hahn & Warren, 2009), the representativeness heuristic remains one of the main explanations of human judgments (Reimers, Donkin, & Le Pelley, 2018). To formalize the hypothesis that people expect a new category to be representative of the opposite of the current category, or contrast as *representativeness*, we use the Bayesian formulation of representativeness (Tenenbaum & Griffiths, 2001), which has been used successfully to capture human performance in color categorization (Abbott, Griffiths, & Reiger, 2016), image category learning (Abbott, Heller, Ghahramani, & Griffiths, 2011), and language grammar learning (Rafferty & Griffiths, 2010). We do so by extending the state-of-the-art category generation model (Jern & Kemp, 2013) and find that human category generation is best captured as generating representative, rather than probable, samples.

The outline of the article is as follows. First we describe previous computational formalizations of theories of category generation and empirical work investigating them. We then present two hypotheses for how contrast might affect categorization and formalize them in computational models. The first is a novel exemplar model, which is designed to generate categories that systematically differ from existing categories in the domain. The second assumes that the goal of category generation is to create representative samples of the opposite of the observed categories. We present two experiments demonstrating strong and systematic effects of category contrast on concept generation, and we qualitatively and quantitatively analyze the performance of each model in capturing human category generation. Afterwards, we find support for category contrast predicting the ease at which people learn a pair of categories in a novel empirical experiment. We conclude with a discussion of the implications of our results for categorization and directions for future work.

2 Prior work

Much of what we know about concept generation and contrast comes from the foundational literature on creative cognition. In a series of reports, Ward and colleagues (Marsh, Ward, & Landau, 1999; S. M. Smith, Ward, & Schumacher, 1993; Ward, 1994, 1995; Ward, Patterson, Sifonis, Dodds, & Saunders, 2002) established that category generation is highly constrained by prior knowledge: Generated categories tend to consist of features observed in known categories, and they tend to exhibit the distributional properties found in known categories. In a seminal study, Ward (1994) asked participants to generate new species of alien animals by drawing and describing members of the species. People tended to generate species with the same features as on Earth (e.g., eyes, legs, wings), and possessing the same feature correlations as on Earth (e.g., feathers co-occur with wings). Likewise, aliens drawn from the same species tended to share more features with one another compared to members of opposite species.

The broader set of observations made by Ward and colleagues provide a great deal of insight into the role of prior knowledge in constraining category generation. Much of the work from this area (e.g., Marsh et al., 1999; S. M. Smith et al., 1993) focuses on how information provided to participants (such as an example of a species generated by other participants) can drastically diminish the difference of a new category from pre-existing categories. Theoretical accounts of these effects have primarily been grounded within the categorization literature. For example, the predominant "Path of Least Resistance" account (see Ward, 1994, 1995; Ward et al., 2002) proposes that, when generating a new species of animal, people retrieve from memory a known subcategory of animals (e.g., *bird*, *dog*, *horse*), and simply change some of the features to make something new. People are thought to change only features that are not characteristic of the retrieved category (e.g., if *bird* was retrieved, the presence of *wings* would not change, but *color* might). This theory incorporates elements of the highly influential basic-level categories framework (Rosch, 1975; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976), as well as the exemplar view (Brooks, 1978; Medin & Schaffer, 1978). While this work has been incredibly useful in providing a conceptual sketch of generation theories, its qualitative nature and the hand-drawn responses used in the experiments paradigms precludes the development of formal approaches that can be used to test them in a fine-grained manner.

Jern and Kemp (2013) recently showed that concept generation could be studied in a more controlled manner through the well-developed methods of an artificial categorization paradigm (see Kurtz, 2015, for a review). In Experiments 3 and 4 of their article, participants were exposed to members of experimenter-defined categories of "crystals" varying in size, hue, and saturation. Following a training phase during which the experimenter-defined categories were learned, participants were asked to generate novel categories of crystals. In a finding mirroring Ward (1994), Jern and Kemp (2013) found that participants generated categories with the same distributional properties as the experimenter-defined categories. For example, after learning categories with a positive correlation between the size and saturation features (larger sized crystals were more saturated), participants generated novel categories with the same positive correlation. By replicating Ward (1994), they demonstrated that category generation can be studied in a well-known and highly controlled experimental paradigm.

The authors evaluated the predictions of several formal models on their data. Most notably, they showed that a hierarchical Bayesian model provided the strongest account of their results. Their model views observed examples as samples from an underlying category distribution, describing the location of the category in the space, as well as how it varies along each feature. In turn, each category is viewed as a sample from an underlying *domain* distribution, specifying distributional commonalities among the observed categories. Generated categories are thought to stem from the same domain distribution as observed categories, thus the distributional properties of observed categories will be preserved within the generated category.

Jern and Kemp (2013) additionally tested a "copy-and-tweak" model that broadly resembles the earlier "Path of Least Resistance" account. The core proposal is that participants generate new items by copying stored examples from memory and tweaking them to generate something new. The copy-and-tweak model differs from the Path of Least Resistance account in that it notably omits the hierarchical organization of categories, as well as selectivity to which features are changed (both of which are factors in the Path of Least Resistance account; Ward et al., 2002). Instead, their copy-and-tweak model corresponds to a direct exemplar-similarity approach (e.g., Nosofsky, 1984, 1986), generating new items according to their similarity to known members of the target category. The copy-and-tweak model provided a poor account of their results, as the experiments devised by Jern and Kemp were specifically designed to challenge it. Its application is notable as a first step toward understanding theories developed in the creative cognition literature using well-known formal approaches from the categorization literature.

It is worth pointing out that the early observation of regularities in distributional properties across categories is not confined to the work of Ward and colleagues. Most notably, Thomas (1998) trained participants to classify circles of different sizes, each with a radial line of varying orientation, into two categories. During a surprise prediction phase, participants were asked to generate a value for a missing feature for a certain category exemplar given a value on the other feature. Their results revealed that exemplars tended to share the same feature correlations as exemplars from previously learned categories. Interestingly, this effect was not consistently observed when the given values of a feature fell outside the range of learned values for that particular category. For instance, if the learned Category A exemplars were generally 8 cm to 10 cm in radius and negatively correlated with the angle of the radial line, participants generally produced radial line orientations that were also negatively correlated with the exemplar size when the given size was between 8 cm and 10 cm. However, when the given size fell outside that range for that category (e.g., 14 cm for a Category A exemplar), some participants consistently produced radial line orientations that were not negatively correlated with the size and that also placed the exemplars in a significantly different location in the feature space. These results suggest that when tasked to produce exemplars that fall outside what was previously learned, people show some tendency to generate exemplars that are different (both distributionally and spatially) to what was learned. We explore this idea of contrast more deeply in the following section.

3 And Now for Something (Completely) Different: The Role of Contrast

Prior work on category generation has explored only one factor: distributional correspondences between learned and generated categories. As a result, most of the computational, theoretical, and empirical efforts have been focused on explaining those effects. In this paper, we investigate another important factor: category contrast. To generate a novel concept, individuals must produce something that is in some capacity *different* from what they already know. As a consequence, we propose that contrast should be a primary constraint that underlies people's expectations about how a set of categories are organized: Categories should be different from each other.

Although it is evident that people are *capable* of creating new concepts and categories, it is not entirely clear how new concepts are systematically made different from what is already known. The hierarchical Bayesian model developed by Jern and Kemp (2013) assumes that differences between observed and generated categories are only due to random variation. The model assumes that generated categories are sampled from the same underlying domain distribution as observed categories, and will thus share a common distributional structure. The model does not make predictions about the *location* of the category within the domain (the perceptual instantiation of category members). Under a strict interpretation of their model, given knowledge of a single category within the domain, the most probable new category to be generated is located in *exactly* the same location and possesses an identical distributional structure. This is not an issue with their model specifically, but using a broader class of standard hierarchical Bayesian models without any additional features (e.g., Griffiths, Sanborn, Canini, & Navarro, 2008; Kemp, Perfors, & Tenenbaum, 2007). Many of these models assume that at some point of the latent generative process the same underlying distribution generates all of the categories and thus, any differences between categories are due to *noise* and should not be *systematic*.

If the goal of creating a new category given others in a domain is generating from the posterior predictive distribution then the best a standard hierarchical Bayesian model without a notion of contrast built into the model can do at capturing contrast is to assume that the new category is placed uniformly at random over stimulus space. But, this defeats the purpose of a hierarchy as it is ignored when determining a new category location![1] Note that this does not mean location information and contrast cannot be captured using hierarchical Bayesian models. In fact, a model instantiating contrast as representativeness is a hierarchical Bayesian model. But, it requires an additional factor, which in our case is having a different goal than predicting the next category.

The copy-and-tweak model tested by Jern and Kemp (2013) also claims little about how generated categories should contrast with what is already known. In their simulations, the model was only tested on generation after the learner had been exposed to members of the target category, and so the model's ability to generate a new category from scratch was not evaluated. However, the model's generation is based exclusively on similarity to known members of the *target* category; when there are no members of the target category, generation is presumably random.

3.1 Contrast as exemplar dissimilarity: The PACKER Model

As noted above, the constraint that new concepts should differ from what is already known has been largely overlooked in previous work. This is no doubt in part due to the vague definition of what it means for a concept to be "different": A generated category may be different from what is already known in any number of respects. Towards providing a more precise definition of the role of contrast in generation, we formalized contrast in a novel exemplar model, PACKER (*Producing Alike and Contrasting Knowledge using Exemplar Representations*). PACKER explains category generation as a balance between two

[1]It is plausible that some hierarchical Bayesian models could be created that generates categories different from each other. However, this model would not be a standard application or extension of most pre-existing hierarchical Bayesian models. The generative process would need to include a component that presumes contrast.

fundamental constraints: The category to be generated should not be similar to known categories, and exemplars within each category should be similar to one another. These ideas are implemented within the well-studied exemplar framework – the PACKER model is an extension of the influential Generalized Context Model of categorization (GCM; Nosofsky, 1984, 1986).

Although, as an exemplar model, one of PACKER's proposals is people represent categories in terms of a collection of stored exemplars, we did not pick it assuming it is the correct model of human categorization. The choice to develop PACKER within an exemplar framework reflects the facts that exemplar models have been throughly evaluated, are strongly theoretically motivated, and dominate much of the theoretical and empirical work in categorization. The focus of our work with PACKER concerns the dual constraints of within- and between-class similarity; it is not difficult to imagine how such constraints may be instantiated using alternative frameworks (e.g., Kurtz, 2007; Love, Medin, & Gureckis, 2004; D. J. Smith & Minda, 2000; for a review of categorization models, see Pothos & Wills, 2011).

Both PACKER and the GCM simulate categorization under the assumption that learners represent categories as a collection of exemplars, corresponding to the labeled stimuli they have observed. The exemplars are encoded within a k-dimensional psychological space, and model performance is based on the amount of similarity between the item to be categorized and the stored exemplars. Similarity between two examples, $s(x_i, x_j)$, is computed as an inverse exponential function of distance (following Attneave, 1950; Shepard, 1957, 1987):

$$s(x_i, x_j) = \exp\left\{ -c \left[\sum_k w_k \left| x_{ik} - x_{jk} \right|^r \right]^{1/r} \right\} \tag{1}$$

where w_k is the attention weighting of dimension k ($w_k \geq 0$ and $\sum_k w_k = 1$), accounting for the relative importance of each dimension in similarity calculations, and c ($c > 0$) is a specificity parameter controlling the spread of exemplar generalization. For simplicity, attention will be distributed uniformly in our simulations (unless otherwise noted). The value of r depends on the nature of the experimental conditions being simulated: $r = 1$ is appropriate for separable dimensions, whereas $r = 2$ is appropriate for integral dimensions (e.g., Garner, 1974; Shepard, 1964). In our simulations, we set $r = 1$ due to the separable nature of the stimulus dimensions used in our experiments (see Figure 3).

PACKER (as well as its name) was in part inspired by earlier work from the categorization literature (Hidaka & Smith, 2011; Stewart & Brown, 2005). Hidaka and Smith (2011) argued that natural categories "pack" the values of features such that different categories fill the domain space with distance between one another, while keeping items within the same category close together. Inspired by this idea, PACKER proposes that generation is constrained by both similarity to members of the target category (the category in which a stimulus is being generated) as well as similarity to members of other categories: the most desirable generation candidates are similar to members of the target category and not similar to members of contrast categories. This is achieved by aggregating similarity across known exemplars differently according to class membership. The aggregated similarity $a(y, x)$ between generation candidate y and stored exemplars x is given by:

$$a(y, x) = \sum_{j} f(x_j) s(y, x_j) \tag{2}$$

where $f(x_j)$ is a function specifying each exemplar's contribution to generation. A negative value for $f(x_j)$ produces a 'repelling' effect (items are less likely to be generated nearby x_j), and a positive value produces an 'attracting' effect (items are more likely to be generated nearby x_j). When $f(x_j) = 0$, the exemplar does not contribute to generation.

PACKER sets $f(x_j)$ depending on exemplar x_j's category membership: $f(x_j) = \theta_t$ if x_j is a member of the target category, and $f(x_j) = -\theta_c$ if x_j is a member of a contrast category. θ_t and θ_c are free parameters ($0 \leq \theta_t, \theta_c$) controlling the trade-off between within-

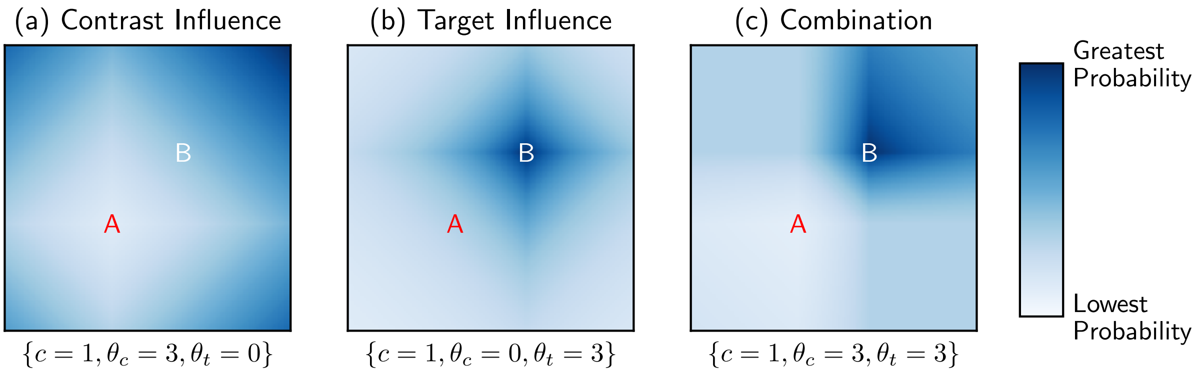

Figure 1: PACKER generation of a category 'B' example, following exposure to one member of category 'A' and one member of category 'B'. Predictions are shown for three different parameterizations (differing in values of θ_t and θ_c): *(a)* Predictions based on contrast similarity only. *(b)* Predictions based on target similarity only. *(c)* Predictions with both constraints considered.

and between-category similarity. For example, when $\theta_t = \theta_c = 0.5$, $f(x_j) = 0.5$ for members of the target category and $f(x_j) = -0.5$ for members of other categories; thus, the model is likely to generate items that are similar to members of the target category but are not similar to members of other categories. In this way, $\theta_t > 0$ with $\theta_c = 0$ produces exclusive consideration of target-category members, and $\theta_c > 0$ with $\theta_t = 0$ produces exclusive consideration of contrast-category members. The combination of θ_t and θ_c parameters thus specifies a wide breadth of possible approaches; by fitting it to a dataset, one can describe the relative roles of between-category contrast and within-category similarity in generation. See Figure 1 for an illustration of how these parameters control the relative influence of within-category similarity and contrast to other categories when generating a new exemplar.

The probability that a candidate y will be generated is evaluated using an Exponentiated Luce (1977) choice rule. Candidates with greater values of $a(y, x)$ are more likely to be generated than candidates with smaller values:

$$p(y \mid x) = \frac{\exp\{a(y, x)\}}{\sum_i \exp\{a(y_i, x)\}} \tag{3}$$

It is worth noting that PACKER is only one possible exemplar-based account of category generation within our proposed framework. That is, PACKER places specific constraints on the possible values of $f(x_j)$, but other exemplar-based category generation models with drastically different behavior can be formalized in this framework by imposing alternative constraints. For example, as will be discussed in more detail below, PACKER is formally equivalent to the copy-and-tweak model proposed by Jern and Kemp (2013) when $\theta_c = 0$ and $\theta_t > 0$. Likewise, when $\theta_t = 0$ and $\theta_c > 0$, PACKER can represent a contrast-only generation mode, relying exclusively on contrast when generating new categories. When $f(x_j) < 0$ for all x_j (regardless of class membership), a "pure-packing" approach is yielded, generating items in unoccupied areas of the domain. Thus, the proposed framework may be used to describe a wide variety of qualitatively distinct generation strategies.

3.1.1 Relation Between PACKER and Copy-And-Tweak

The PACKER model is similar to the copy-and-tweak model reported by Jern and Kemp (2013): Both models are exemplar-based, and both models generate new items according to their similarity to known members of the target class. However, PACKER diverges from the copy-and-tweak model by including a contrast mechanism, enabling generation according to dissimilarity to members of opposing categories. As a consequence, copy-and-tweak can be realized as a parameterization of the PACKER model that is insensitive to category contrast. Specifically, when $\theta_c = 0$ and $\theta_t > 0$ (see Figure 1, panel B), $f(x_j) = 0$ for x_j belonging to contrast categories; thus, PACKER is not influenced by these items, and is mathematically equivalent to a copy-and-tweak approach.

In this paper, we report simulations using this copy-and-tweak model. This model fits within the exemplar-based category generation framework defined above, and is a continuous-dimension adaptation of the model tested by Jern and Kemp (2013). By formalizing a model family where PACKER and copy-and-tweak are different parameterizations of models within the same framework, the comparison between

PACKER and copy-and-tweak provides a test of the explanatory value of the contrast mechanism based on exemplar dissimilarity: The account provided by copy-and-tweak will only equal that of PACKER if the contrast mechanism does not offer an advantage (i.e., if $\theta_c > 0$ significantly improves model fits). Note that the purpose of the article is to explore and formally analyze the role of contrast in categorization and thus, we leave extending PACKER to incorporate distributional factors for future work.

3.2 Contrast as representativeness: An extension to Jern and Kemp (2013)

An alternate conceptualization of category contrast is the idea of representativeness – exemplars are generated such that they resemble the target category and thus more distinct from and less similar to other categories. We adopt the formalization given by Tenenbaum and Griffiths (2001), where the representativeness $R(y, h)$ of an item y (or in our case, an exemplar) is the relative amount of evidence that is provided by y for a given hypothesis h in a space of hypotheses $\mathcal{H}$ in contrast to all other hypotheses $\mathcal{H}^c = \mathcal{H} \setminus \{h\}$:

$$R(x, h) = \log \frac{p(x|h)}{1 - p(x|\mathcal{H}^c)} = \log \frac{p(x|h)}{\sum_{h' \in H'} p(x|h')p(h')}. \tag{4}$$

In Equation 4, $p(h')$ is the prior probability distribution on the hypothesis space that excludes h. Note that when there are only two hypotheses (e.g. two categories) involved in the domain, this prior takes the value of 1 since there is ever only one alternative hypothesis.

The Bayesian formalization of representativeness makes it straightforward to extend the existing hierarchical Bayesian model of category generation developed by Jern and Kemp (2013).[2] Specifically, both models assume that exemplars are sampled from a given category distribution (h in Equation 4). Each category distribution is a multivariate

[2]We thank Charles Kemp for the suggestion.

normal parameterized by a location vector μ_k and covariance matrix Σ_k (i.e., $h = \mathcal{N}(\mu_k, \Sigma_k)$). The parameters μ_k and Σ_k are assumed to be samples from a prior normal-inverse-Wishart (NIW) distribution parameterized by $\mu_0, \Sigma_0, \kappa, \nu$. Mathematically,

$$\mu_k, \Sigma_k | \mu_0, \Sigma_0, \kappa, \nu \sim \text{NIW}(\mu_0, \Sigma_0, \kappa, \nu) \tag{5}$$

$$y|C \sim \mathcal{N}(\mu_k, \Sigma_k) \tag{6}$$

In our simulations, we set the prior mean μ_0 to the center of the stimulus space the prior variance to be isotropic ($\Sigma_0 = \lambda\mathbf{I}$ where λ is a free parameter and $\mathbf{I}$ is a d-by-d identity matrix with d representing the number of dimensions or features in the domain). The κ and ν parameters are freely estimated within the constraints $\kappa > d - 1$ and $\nu > 0$.

With the assumption of the NIW prior, the expected location vector μ_k given exemplars observed from category k is:

$$\mu_k = \frac{\kappa\mu_0 + n_k\bar{x}_k}{\kappa + n_k} \tag{7}$$

where n_k is the number of observed exemplars in category k and $\bar{x}_k$ is the observed category mean. Note that if there are no observed exemplars in the target category (i.e., if the model is generating a completely novel category), Equation 7 simplifies to $\mu_k = \mu_0$.

The NIW prior also allows us to infer the category covariance matrix Σ_k by computing the following:

$$\Sigma_k = [\nu\Sigma_D + C_k + \frac{\kappa n_k}{\kappa + n_k}(\bar{x_k} - \mu_k)(\bar{x_k} - \mu_k)^T](\nu + n_k)^{-1} \tag{8}$$

where C_k is the observed category covariance and Σ_D is the domain covariance matrix from which Σ_k samples are obtained. We can infer Σ_D from the observed category covariances C

and the prior covariance Σ_0. Specifically,

$$\Sigma_D = \Sigma_0 + \sum_k C_k \tag{9}$$

At this point, both the representativeness model and the hierarchical Bayesian model from Jern and Kemp (2013) are largely identical. However, both models diverge in their computation of exemplar generation probabilities. While the original hierarchical Bayesian model produces novel exemplars with probabilities proportional to the multivariate normal likelihood $p(y|h)$, the representativeness model generates new exemplars according to their representativeness $R(y, h)$. In practice, the probability of generating a particular candidate y is obtained using an Exponentiated Luce (1977) choice rule:

$$p(y) = \frac{\exp(\theta \cdot R(y, h))}{\sum_k \exp(\theta \cdot R(y_k, h_k))}. \tag{10}$$

where θ is a freely estimated response determinism parameter (constrained such that $\theta \geq 0$).

Despite both the original hierarchical Bayesian model and our representativeness model sharing identical hierarchical structures, their distinct response processes can yield very different exemplars. Specifically, the hierarchical Bayesian model emphasizes the generation of exemplars that maintain distributional commonalities across categories. In contrast, the representativeness model focuses on the generation of exemplars that are representative of the underlying distribution for a target category. Generally, this mechanism of representativeness results in the generation of exemplars that are less similar to exemplars from other categories. We see this illustrated in Figure 2, where the representativeness model displays a strong preference for generating exemplars from target category 'B' that are further away from the contrast category 'A'.

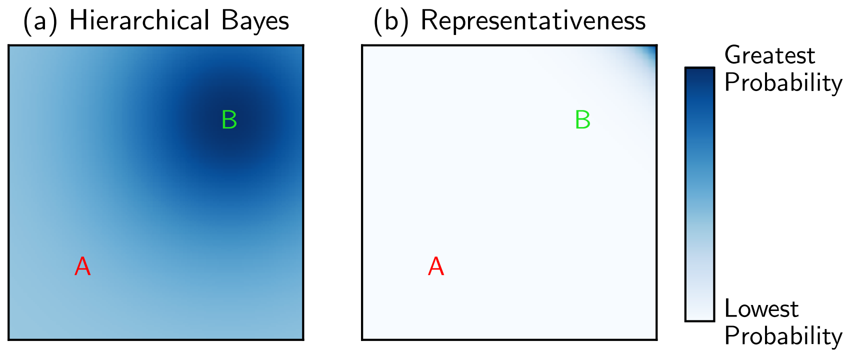

Figure 2: Generation of a category 'B' example, following exposure to one member of category 'A' and one member of category 'B'. Predictions are shown for (a) the original hierarchical Bayesian model and (b) the representativeness model.

3.3 Synopsis and Prognosis

Research on categorization and category generation has focused on the finding that generated categories tend to possess distributional commonalities with known categories. However, a fundamental task of categorization is to create something *new* (i.e., different from what is already known). The manner in which generated categories differ from known ones is, nonetheless, poorly understood: Existing theories do not make strong predictions about how generated concepts should systematically differ from existing ones. Above, we introduced two novel approaches to formalizing the roles of similarity and contrast in category generation.

In the sections below, we present two experiments demonstrating systematic effects of category contrast on category generation inspired by factors influencing how the contrast models generate new categories. Our experiments are based on Jern and Kemp (2013)'s paradigm, which is a straightforward translation of the traditional artificial classification paradigm to the task of category generation: Participants are first exposed to a single, experimenter-defined category, and are then asked to generate members of a new category. We then report quantitative analyses of our results comparing the exemplar dissimilarity and the representativeness accounts of our results to that of the hierarchical Bayesian and copy-and-tweak models developed by Jern and Kemp (2013). After analyzing the category generation studies, we present third experiment to demonstrate the effect of contrast in category learning. This ensures that our results are not idiosyncratic to category generation.

4 Experiment 1

To begin our investigation, we examined category generation in a well-understood domain using a few disparate category types. We used an artificial stimulus design: A two dimensional domain of squares, varying in color and size (see Figure 3a). These dimensions have been used in numerous classification learning studies (e.g., Conaway & Kurtz, 2016a, 2016b; Nosofsky, Gluck, Palmeri, & McKinley, 1994; Shepard et al., 1961). Unlike those used in the Jern and Kemp (2013) experiments, distance on these physical dimensions aligns more directly with perceptual similarity, allowing us to evaluate the role of contrast in categorization more precisely. It also enables more straightforward comparisons to prior work. We tested the effects of category contrast after learning one category from a set of qualitatively distinct category structures, as shown in Figure 3.

Figures 3b-d show the values of exemplar dimensions belonging to the experimenter-defined categories (‘A’, or ‘Alpha’) that participants were assigned to learn about prior to generating a new category. Each participant learned one of the category types during training. In the ‘Cluster’ type, category A is a tight cluster of examples in the space. Perceptually instantiated, the members of category A might, for example, be large and dark in color. In the ‘Row’ type, category A has a row pattern across the space, varying along one feature but not the other. Thus, its members might all be dark in color but would vary in size. Finally, in the ‘XOR’ type, the experimenter-defined category consists of two clusters separated in opposite corners of the space, conforming to the exclusive-or logical structure (e.g., members are small and dark or large and light).

It should be noted that in our experiments the assignment of the perceptual to

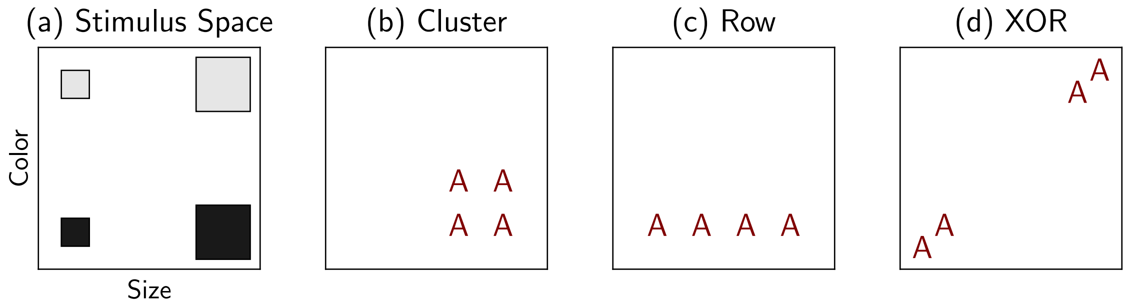

Figure 3: Stimulus domain and category types tested in Experiment 1. Stimuli are not drawn to scale. Dimension and direction assignment (e.g., large to small or small to large) for color and size were counterbalanced over participants.

conceptual dimensions (e.g., $X \rightarrow Size$, $Y \rightarrow Color$) and the direction of variation along each dimension (e.g., $dark \rightarrow light$ or $light \rightarrow dark$) were counterbalanced across participants. The category types in Figure 3 are plotted in conceptual space, rather than perceptual space. Thus, while the conceptual organization of the category types remains constant, each category type may have a different physical instantiation according to the counterbalance assignment. For example, the Cluster type may be large and dark in color, or it may be small and light in color, depending on the assignment and direction of the dimensions. For this reason, below we will discuss generation within a conceptual space, rather than a physically instantiated one.

After learning about an experimenter-defined category, participants are asked to generate examples of a new category. Within this paradigm, an effect of category contrast would be realized if participants prefer to generate items in locations that are distant (i.e., perceptually dissimilar) from members of category A. However, generation is left unconstrained. Critically, participants were not asked to generate something different in the prompt. For example, participants assigned to the Cluster condition may generate a tightly clustered category in the corner opposite of the experimenter-defined category. Alternatively, they may generate a tightly clustered category directly overlapping with the experimenter-defined category. Further, they may even generate an entirely different type of category (e.g., a row category).

Our experimental results also provide a converging test that generated categories tend to share distributional properties with known categories in the domain (Jern & Kemp, 2013; Ward, 1994). From these results, we can predict that, in each condition, participants should generate categories that are distributionally similar to the experimenter-defined category: In the Cluster condition, generated categories should be tightly clustered. In the Row condition, generated categories should vary more along the X-axis than the Y-axis. In XOR condition, generated categories should be widely distributed across both dimensions, and the two dimensions should be positively correlated.

Interestingly, the XOR condition also offers a dissociation between the roles of category contrast and the emulation of distributional structure: widely-distributed, positively-correlated categories would need to lie along the positive diagonal of the space (that is the only place they "fit"), which is already occupied by the experimenter-defined category. Thus, if contrast plays a role, exemplars in the generated categories of participants in the XOR condition may not be positively correlated – they may be negatively correlated instead. In this case, contrast and statistical regularities would interact, which would be inconsistent with prevailing theories of category generation (Jern & Kemp, 2013).

4.1 Participants and Materials

183 participants were recruited from Amazon Mechanical Turk. Each participant was randomly assigned to one condition: 64 participants were assigned to the Cluster condition, 61 were assigned to the Row condition, and 58 were assigned to the XOR condition (sample sizes differ due to random assignment). Stimuli were squares varying in color (grayscale 9.8%–90.2%) and side length (3.0–5.8cm), see Figure 3. The assignment of perceptual features (color, size) to axes of the conceptual space (x, y) and the direction of variation along each axis (e.g., $dark \rightarrow light$ or $light \rightarrow dark$) were counterbalanced across participants.

4.2 Procedure

As noted in the introduction of this paper, the task of generating members of a new category is well situated as a task in the categorization literature: Whereas classification consists of predicting an object's category label on the basis of its features, inference consists of predicting an observed feature, given a set of observed features and a category label. Generation thus consists of predicting *all* features of an object, given a novel category label. We designed our generation task as an extension of the traditional artificial classification learning paradigm. The task differs from traditional work in creative cognition primarily through the use of an artificial domain, which enables the application of computational models. The use of an artificial domain also requires the addition of a training phase, during which participants learn about the categories in the domain. As a result, unlike most previous studies (e.g., Ward, 1994), participants in our studies have no experience with the domain before the start of the experiment, and the experimenter-defined categories are not hierarchically structured (as are many natural categories).

Participants began the experiment with a short training phase (3 blocks of 4 trials), where they observed exemplars belonging to the 'Alpha' category. Participants were instructed to learn as much as they can about the 'Alpha' category, and that they would answer a series of test questions afterwards. On each trial, a single 'Alpha' category exemplar was presented, and participants were given as much time as they desired to observe it before moving on to the next trial. Each block consisted of a single presentation of each of the members of the 'Alpha' category, in a random order. Participants were shown the range of possible colors and sizes prior to training.

Following the training phase, participants were asked to generate four examples belonging to another category called 'Beta'. As in Jern and Kemp (2013), generation was completed using a sliding-scale interface. Two scales controlled the values of the two dimensions (color, size) for the generated example. An on-screen preview of the example updated whenever one of the features was changed. Participants could generate any example along an evenly-spaced 9x9 grid (including members of the ‘Alpha’ category), except for any previously generated ‘Beta’ exemplars. Neither the members of the ‘Alpha’ category nor the previously generated ‘Beta’ examples were visible during generation. Prior to beginning the generation phase, participants read the following instructions:

> As it turns out, there is another category of geometric figures called “Beta”. Instead of showing you examples of the Beta category, we would like to know what you think is likely to be in the Beta category.
>
> You will now be given the chance to create examples of any size or color in order to show what you expect about the Beta category. You will be asked to produce 4 Beta examples - they can be quite similar or quite different to each other, depending on what you think makes the most sense for the category.
>
> Each example needs to be unique, but the computer will let you know if you accidentally create a repeat.

4.3 Results

We observed a substantial degree of individual differences in our data. In Figure 4 we have plotted sample data from several participants, from which it is evident that different participants generated qualitatively different category structures. In this section we will focus on analyzing the data in aggregate, but in later sections we will explore how these individual differences can be explained.

To evaluate the role of contrast, we computed the number of times each stimulus was generated, as a function of its average city-block distance from members of the experimenter-defined “Alpha” category. These data, shown in Figure 5, reveal a clear pattern: Examples that are more distant from members of the experimenter-defined categories are more likely to be generated into a new category. This supports the notion

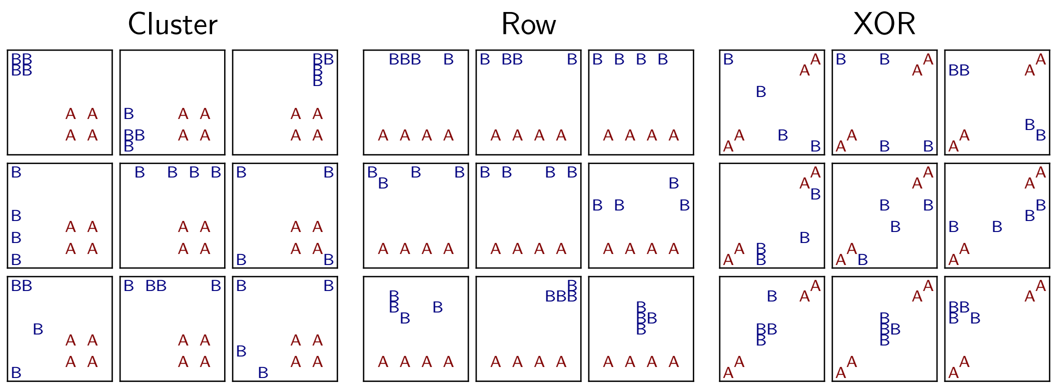

Figure 4: Sample categories generated by participants in Experiment 1. Representative samples from common generation profiles are shown.

that contrast is a fundamental constraint on how categories are related to one another and that statistical regularity alone is insufficient.

Figure 5 also depicts, for each participant, the average distance of members within the generated category (*within-category* distance) against the average distance between members of the generated and experimenter-defined category (*between-category* distance). The narrow distribution of between-category distances in the XOR condition reflects the widely distributed nature of the experimenter-defined category, reducing the possible distances to members of the participant-generated category. These data reveal a systematic pattern: The majority of participants generated categories with greater between-category distance than within-category distance. That is, members of the generated category tended to be more similar to one another than to members of the experimenter-defined category. To evaluate this claim quantitatively, we conducted t-tests comparing the amount of within- and between- class distance in each condition. All conditions possessed greater between-category distance: Cluster, $t(63) = 11.43$, $p < .001$; Row, $t(60) = 13.16$, $p < .001$; and XOR, $t(57) = 3.64$, $p < .001$. These results provide further evidence of an effect of category contrast: Participants prefer to generate categories that are dissimilar to the learned category but maintain some level of internal cohesion.

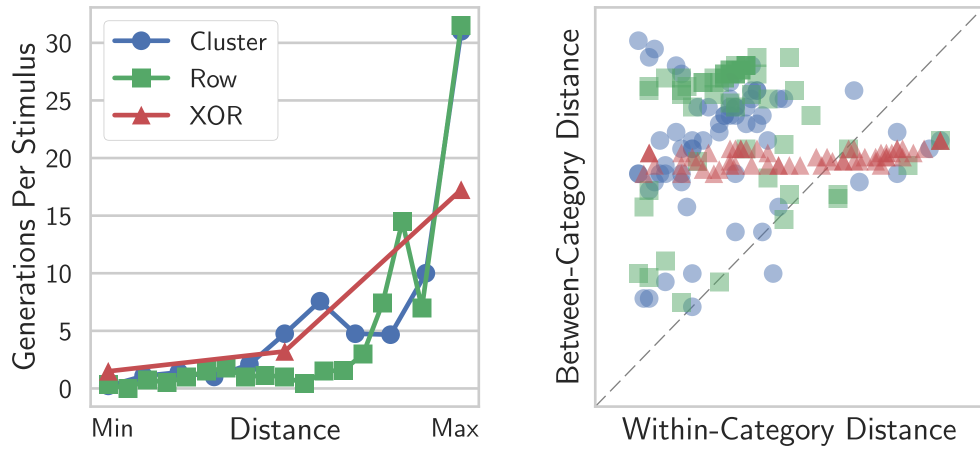

Figure 5: Experiment 1 results. *Left*: Frequency of generation as a function of distance from members of the experimenter-defined category. *Right*: Scatter plot of within-category versus between-category distance in each of the participant-generated categories.

A secondary goal of this experiment was to examine whether we replicate the classic result that generated categories often possess the same distributional properties as previously-known categories. Given the increased emphasis of replication within psychology (Zwaan, Etz, Lucas, & Donnellan, 2018), it is important as it serves as a conceptual replication of Jern and Kemp (2013). For each generated category, we computed the category range along each axis (X, Y), as well as the correlation between features. These data, shown in Figure 6, reveal broad individual differences: Within each condition, participants generated categories spanning the entire X- and Y- axis as well as categories that spanned very little along each. Likewise, in each condition participants generated categories possessing strongly positive, neutral, and strongly negative correlations between the dimensions. Comparing the distributional statistics between conditions yields a broad yet, as we will see, misleading replication of the classic effect.

With respect to ranges along each axis (X, Y), the generated categories from each condition tend to reflect the ranges of the experimenter-defined categories. The categories generated in the Cluster condition were less widely distributed along the X-axis compared to Row, $t(123) = 5.61$, $p < .001$, and XOR, $t(120) = 2.68$, $p < .01$. Categories generated in

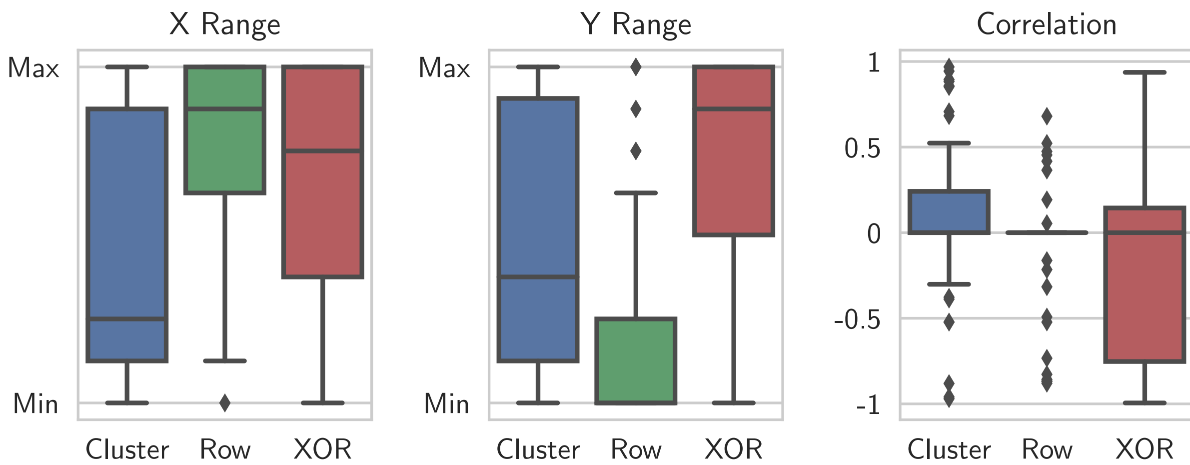

Figure 6: Box-plots of the distributional statistics from the categories generated in Experiment 1. Boxes depict the median and quartiles of each condition, with whiskers placed at 1.5 IQR. All points outside this region are marked individually.

the XOR condition were also less widely distributed along the X-axis compared to Row, $t(117) = 2.56$, $p = .046$. This latter effect was not expected because the experimenter-defined categories for XOR and Row had similar X-ranges. However, the key finding is that categories from the Cluster condition tended to be more tightly distributed along the X-axis.

Likewise, categories generated in the Row condition had less Y-axis range compared to Cluster, $t(123) = 4.57$, $p < .001$ and XOR, $t(117) = 9.26$, $p < .001$, and categories from the Cluster condition had less Y-axis range compared to XOR, $t(120) = 3.95$, $p < .001$. As expected, the correlations in the Cluster and Row conditions were not systematically positive or negative ($ps > .1$). However, the generated categories in the XOR condition tended to possess *negatively* correlated dimensions, $t(57) = 2.04$, $p = .046$. This finding is notable, as it is the opposite of what would be expected based on previous literature (Jern & Kemp, 2013), assuming learners are emulating the distributional structure of the experimenter-defined class (which possesses perfectly positively correlated features).

We believe that the failure to replicate dimension correlation emulation is because participants in Jern and Kemp (2013) could differentiate the generated category on a third dimension (hue) to maintain the statistical regularities on the other two dimensions. In addition, in our XOR condition the stimuli were constrained to the corners of the feature space, whereas in the positive diagonal condition of Jern and Kemp (2013) the stimuli had no such constraint. Although the correlation in the XOR condition is significantly negative, it is clear from the box-plot in Figure 6 that it would be inappropriate to make a strong conclusion (e.g., the median is close to zero). However, we can conclude with confidence that there are situations where people do not emulate the distributional structure of the given category. This indicates that there is more to category generation than the emulation of distributional structure of other categories in the domain. Further, as we will discuss in more detail in the model-based analysis section, this is expected by our proposal that contrast is a fundamental principle in categorization.

4.4 Discussion

In Experiment 1 we sought to extend our analysis of the Jern and Kemp (2013) data by evaluating the influence of category contrast on category generation, given qualitatively different types of categories. We found strong evidence for effects of category contrast in each condition: Participants were more likely to generate stimuli that are more distant from (i.e., less similar to) members of a previously-learned category, and members of participant-generated categories tended to be more similar to one another than to members of previously-learned categories. We also partially replicated the classic finding that the distributional structure of generated categories reflects that of previously learned categories (Jern & Kemp, 2013; Ward, 1994): Members of generated categories were more widely distributed along dimensions which were widely distributed in the experimenter-defined category.

Notably, however, we also found that participants who learned an XOR category (composed of exemplars following a positive diagonal, see Figure 3) tended to generate items according to a *negative* feature correlation – the opposite of what was present in the

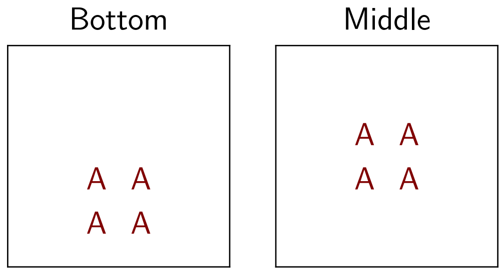

Figure 7: Category types tested in Experiment 2.

previously learned category. While this may be difficult to account for under existing theoretical approaches (which assume generated categories follow the same distributional structure as known categories), it can be concisely explained from a category contrast perspective. Specifically, within the XOR condition, individuals who seek to generate a category that is perceptually distinct from what is already known are left with only the upper-left and bottom-right quadrants of the space, as members of the previously-learned XOR category lie in the bottom-left and top-right. If examples are generated into both of the available quadrants, the generated category will possess a strongly negative correlation, opposing that of the experimenter-defined class.

Thus, the core results of Experiment 1 indicate that generated categories can systematically differ from what we would expect based on prior work. The negative (or null) correlations observed in the XOR condition suggests an interesting interaction between contrast with a given category and emulation of statistical properties. That is, the constraints on generation imposed by category contrast may not simply influence the *location* of generated categories, but also their distributional structure. In Experiment 2, we test this claim more systematically.

5 Experiment 2

To test whether category contrast influences the distributional structure of generated categories, we sought to identify conditions in which differences in the distributional structure of generated categories cannot be explained by the distributional structure of the experimenter-defined category. We created two new category types (depicted in Figure 7) that possess identical distributional structures (both are tight clusters of examples with no correlation between features), as they only differ in their Y-axis position: the 'Bottom' category lies near the bottom of the space, and the 'Middle' category lies in the center. The distributional equality of these conditions is key to the design of the experiment: If the distributional structure of previously learned categories were the only influence on the generated categories, we should observe no difference in the categories participants generate between these two conditions. Will participants distribute their generated category differently between conditions due to the differences in the available empty stimulus space for generating a new category?

If category contrast influences the distributional structure of the categories people generate, then we should observe different types of categories according to the shape of the space that is *unoccupied* by members of previously learned categories. The difference in the Y-axis position between the Bottom and Middle conditions produces a considerable change to the shape of the unoccupied space. Participants assigned to learn the Bottom category should be less likely to generate exemplars into the lower regions of the stimulus space (as these areas possess greater similarity to members of the Bottom category), preferring instead to distribute exemplars across the upper region of the space. This constraint is lifted in the Middle condition, as the Middle category exemplars are equidistant to the upper and lower regions of the space. Accordingly, participants should be more likely to utilize both of these areas. Thus, if category contrast influences the distributional structure of generated categories, we should observe more participants in the Middle condition that generate examples above *and* below the experimenter-defined category.

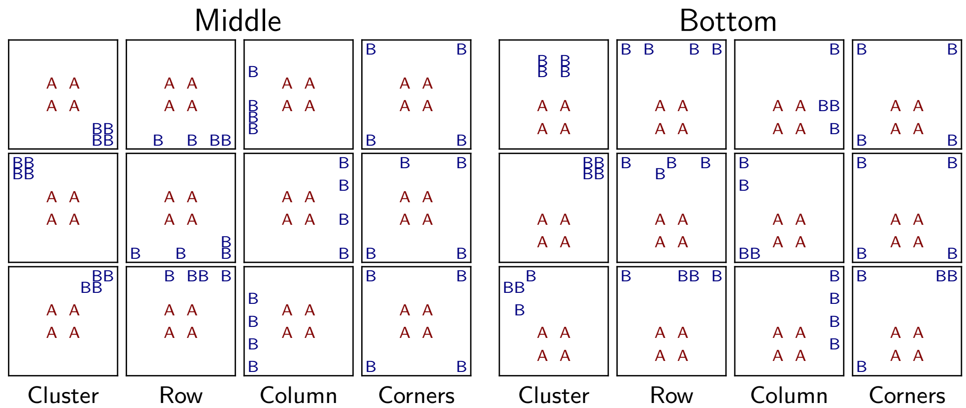

Figure 8: Sample categories generated in Experiment 2.

5.1 Participants, Materials, and Procedure

122 participants were recruited from Amazon Mechanical Turk. 61 participants were randomly assigned to the Middle and Bottom conditions each. The stimulus space and procedure were exactly as in Experiment 1. Participants first completed a short training phase, followed by the generation phase. The only difference from Experiment 1 was the category types given to participants.

5.2 Results

As in Experiment 1, we observed broad differences in the generation approach taken by different participants. To characterize the nature of these differences, Figure 8 depicts sample categories generated by participants. The data from each condition are organized into four columns based on commonly observed patterns of generation: a 'Cluster' type of tightly-clustered examples, 'Row' and 'Column' types of exemplars widely distributed along the one axis but narrowly along the other, and a 'Corners' type, wherein participants placed exemplars in disparate corners of the space. As before, in this section we focus on analyzing the data in aggregate, but in later sections we will focus more specifically on explaining the individual differences.

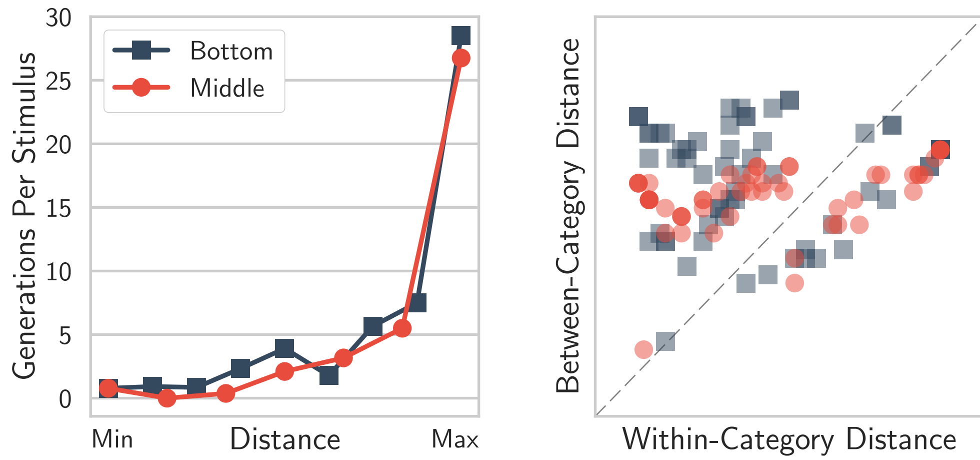

Figure 9: Experiment 2 results. *Left*: Frequency of generation as a function of distance from members of the experimenter-defined category. *Right*: Scatter plot of within-category versus between-category distance in each of the participant-generated categories.

We began our analysis by testing for the broad influence of category contrast on generation. As in Experiment 1, we computed the frequency each stimulus was generated as a function of its average distance from members of the experimenter-defined category, as well as each participant's average within- and between- category distance. These data, shown in Figure 9, yield very similar results. Participants generated stimuli that are distant from members of the experimenter-defined category, and the categories in each condition tended to possess more between-category than within-category distance: Bottom, $t(60) = 5.5$, $p < .001$; Middle, $t(60) = 2.71$, $p < .01$. We did, however, observe a notable subgroup of participants in each condition who generated categories with more within-category than between-category distance. Upon manual inspection, many of these individuals appear to have assumed a 'Corners' strategy, placing exemplars in disparate corners of the space, thus producing much more within-category distance, see Figure 8 for examples.

To explore the distributional structure of the generated categories, we computed the range of exemplars along each axis (X, Y), as well as the correlation between features. These data, shown in Figure 10, again demonstrate the degree of individual differences

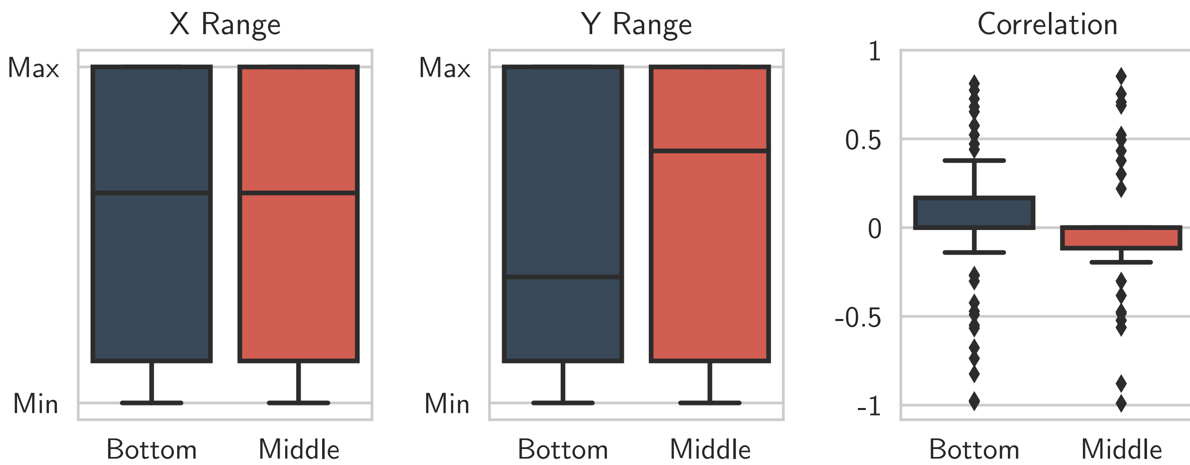

Figure 10: Box-plots of the distributional statistics from the categories generated in Experiment 2. Boxes depict the median and quartiles of each condition, with whiskers placed at 1.5 IQR. All points outside this region are marked individually.

observed in our study. In each condition, we observed tightly clustered and widely distributed categories along each dimension. Although most participants generated uncorrelated categories in both conditions, many still produced positively and negatively correlated categories.

As noted above, if the distributional structure of generated categories is influenced by the shape of the space not occupied by members of known categories, then participants in the Middle condition would be more likely to place exemplars in the upper *and* lower regions of the space, as members of the experimenter-defined category are equidistant from these regions. Participants in the Bottom condition should be less likely to generate category members in the bottom regions because members of the experimenter-defined category are located there. One way to test these predictions is to analyze the Y-axis ranges of the generated categories: If Middle participants utilize the upper and lower regions of the space, their categories should vary more along the Y-axis. T-Tests comparing the conditions on the distributional statistics, however, reveal few between-group differences: the conditions do not differ with respect to X-axis range, Y-axis range, or feature correlations ($ps > 0.17$).

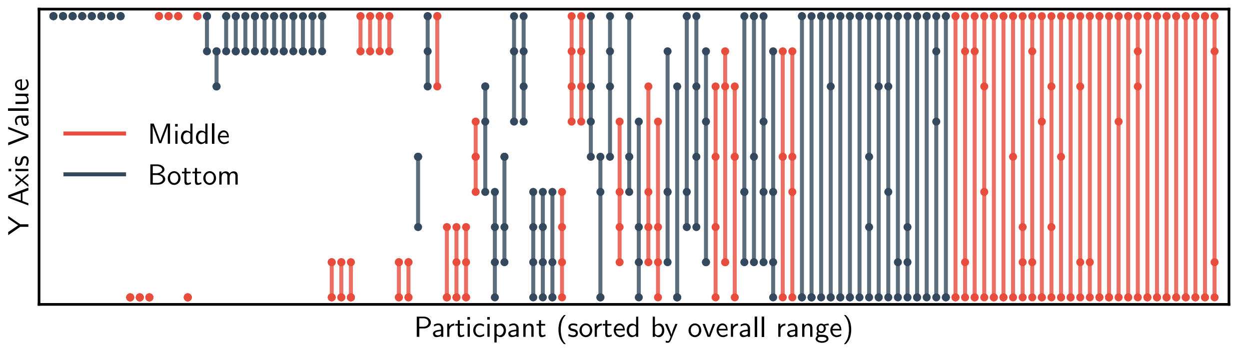

Figure 11: Y-Axis range and position of the participant-generated categories from Experiment 2. Each line corresponds to a participant's category, with notches corresponding to the Y-axis position of exemplars within the category (notches may overlap). Participants are sorted by overall range, and then by condition.

However, our ability to detect differences in Y-Axis range using a standard t-test between the conditions is, in this case, diminished due to the non-normality of the data (Shapiro-Wilk normality test $W = 0.77, p < .001$ for the Middle condition and $W = 0.85, p < .001$ for the Bottom condition). Figure 11 depicts the Y-axis position of the exemplars generated within each participant's category. Further, the median produced Y-Axis range is much smaller in the Bottom than Middle condition, whereas they are essentially identical in X-Axis range. The categories are sorted by overall range, then by condition assignment. These data reveal that there were nearly as many participants who generated categories spanning the entire Y-axis as those who generated categories spanning almost none of the Y-axis. The non-normality of the Y-axis range distributions thus requires that we use a different approach to addressing the experiment's main question.

Because our main prediction concerns the generation of exemplars within the upper and lower regions of the domain, we compared the conditions in terms of the frequency with which participants generated examples above and below the categories. Specifically, we counted the number of participants in each condition who placed at least one 'Beta' exemplar on the top and bottom 'rows' of the space (the maximum and minimum possible Y-axis value, respectively). The resulting contingencies data are shown in Table 1.

Table 1: Experiment 2 results.

Middle	Used top row	No top row
Used bottom row	28	18
No bottom row	11	4

Bottom	Used top row	No top row
Used bottom row	16	8
No bottom row	31	6

Firstly, it should be noted that nearly every participant utilized the top and/or bottom rows: only 10/122 participants generated their category entirely within the interior region. Fisher's Exact Tests comparing the conditions reveal that more Middle participants generated an exemplar in the bottom row, $p < .001$, again demonstrating the role of contrast in guiding where exemplars are generated. The conditions did not differ in use of the top of the space, $p = .16$, however, more Middle participants placed exemplars in the top *and* bottom rows, $p = .04$. The latter effect is of particular interest here, as it indicates that the shape of the unoccupied space exerts some influence on the distributional structure of generated categories: Participants in the Middle condition were more likely to generate a category spanning the entire Y-axis. Thus, the distributional structure of the generated categories can be influenced without any change to the distributional structure of the given category. Rather, it can be affected by category contrast alone.

5.3 Discussion

In Experiment 2, we replicated the core findings from Experiment 1. Stimuli are more likely to be generated if they are distant from exemplars in other categories, and most participants generate categories with more between-category than within-category distance. However, we additionally found that the *position* of a previously learned category (rather than its distributional structure) influences the types of categories people generate: Participants who learned the 'Middle' type were more likely to generate categories spanning the entire Y-axis of the space. Participants who learned the 'Bottom' type were less likely to do so as a result of the presence of opposite category exemplars in the lower regions of the space.

This finding cannot be explained from the perspective that the distributional structure of previously learned categories is the sole determinant of the distributional structure of generated categories. However, the observed behavior is expected from a category contrast perspective: Participants seeking to generate a perceptually distinct category will be more likely to use areas of space that are unoccupied by exemplars belonging to previously learned categories. In the Middle condition, the upper and lower regions of space are equidistant from members of the experimenter-defined category, whereas in the Bottom condition, the lower region of the space is closer to members of the experimenter-defined category. Thus, while Middle participants may form categories around the use of the equally unoccupied areas, the same is not true for the Bottom condition.

6 Model-based Analyses of Experiments 1 and 2

Experiments 1 and 2 revealed systematic and strong effects of category contrast on category generation. In this section, we analyze the performance of the different formal models at explaining the experimental results. Specifically, we present simulations from the two novel contrast models: PACKER and the representativeness model, and compare them to two models that do not incorporate contrast: the copy-and-tweak model (discussed in Section 3.1.1) and an implementation of the hierarchical Bayesian model proposed by Jern and Kemp (2013), described in-depth in Appendix A. For our simulations here, the copy-and-tweak model is defined as a variant of PACKER with the θ_c parameter constrained to be zero. The comparison of this set of models serves to highlight the explanatory role of contrast in categorization: If contrast affords little explanatory advantage, then there should be few differences in performance between PACKER and copy-and-tweak, or between the representativeness and hierarchical Bayesian model. The comparison between these models can also emphasize the necessity of contrast and demonstrate that generation cannot be explained entirely through the emulation of distributional structure. Each model has complementary strengths and weaknesses: Whereas PACKER and copy-and-tweak are relatively insensitive to the distributional structure of learned categories (relying only on exemplar similarities), the representativeness and hierarchical Bayesian model generates categories exclusively on the basis of knowledge of how existing classes are distributed.

Our approach in this section is to first broadly evaluate and compare the quality of each model's account to our entire dataset (Experiments 1 and 2 combined), then analyze the ability for each model to explain individual differences in each experiment, and lastly we describe the strengths and weakness of each model's account of category generation.

6.1 Parameter-Fitting

To obtain a global measure of the quality of each model's account, we fitted the parameters of each model to our entire dataset (Experiments 1 and 2 combined), using a hill-climbing algorithm which maximized the log-likelihood of the model's predictions of the observed responses (1220 responses from 305 total participants). We fitted three parameters in the PACKER model (c, θ_t, and θ_c; see Section 3.1), as well as four in the representativeness model and the hierarchical Bayesian model (κ, λ, ν, and θ; see Section 3.2 and Appendix A respectively). We fitted only two parameters for the copy-and-tweak model (c, and θ_t), as θ_c is held constant ($\theta_c = 0$). Attention (w, see Equation 1) in PACKER and copy-and-tweak was set uniformly. Parameters were not allowed to vary between participants or conditions – the goal was to obtain the best-fitting values to our entire dataset.

Table 2 contains the model fits. Due to the uneven number of fitted parameters among the models, we compare the model fits using the Akaike Information Criterion

Table 2: Results of model-fitting to the combined datasets from Experiments 1 and 2. Note that smaller AIC values correspond to better model fits (adjusted for number of parameters)

PACKER	**Copy & Tweak**	**Representativeness**	**Hierarchical Bayesian**
$AIC = 9069$	$AIC = 9813$	$AIC = 8783$	$AIC = 9881$
$L = -4531$	$L = -4905$	$L = -4388$	$L = -4937$
$c = 0.51$	$c = 3.22$	$\kappa = 12.23$	$\kappa < 0.001$
$\theta_c = 3.09$	$\theta_c = 0$ (fixed)	$\nu = 1.00$	$\nu = 5.44$
$\theta_t = 3.47$	$\theta_t = 3.00$	$\lambda = 7.04$	$\lambda = 0.06$
		$\theta = 10.21$	$\theta = 3.09$

(AIC; Akaike, 1974), where smaller values correspond to better fits (discounted by model complexity as measured by the number of parameters). The same qualitative results were obtained with alternative model comparison metrics (e.g., BIC, Schwarz, 1978; AIC_C, Hurvich & Tsai, 1989). In addition to AIC, table 2 contains the corresponding log-likelihood (L) and the best-fitting parameter values. These results reveal strong model differentiation: both contrast models (PACKER and the representativeness model) achieved far better fits compared to their non-contrast counterparts: copy-and-tweak and the hierarchical Bayesian model respectively. Interestingly between the contrast models, the hierarchical model (representativeness) outperformed the exemplar-based theory (PACKER), whereas between the non-contrast models, the reverse is observed. Specifically, here the exemplar-based model (copy-and-tweak) performed somewhat better than the hierarchical Bayesian model.

While PACKER's advantage may tentatively be attributed to the model's sensitivity to category contrast (this will be explored in detail below), the advantage shown by copy-and-tweak over the hierarchical Bayesian model may be attributed to its exemplar-based representation of category B, as opposed to forcing a prototype-based representation as assumed by the hierarchical Bayesian model. As observed in Figures 4 and 8, the generated categories we observed were often widely distributed, with no items near the category prototype. This aspect of the data is inconsistent with the multivariate normal distributions (similar to prototypes) used to represent categories in the Jern and

Kemp (2013) model, but can be easily accounted for using an exemplar-based approach. Interestingly, representativeness using a prototype approach fits better than an exemplar-based approach. Understanding these differences more thoroughly is left for future research.

A key distinction between the contrast and classical models is that only the contrast models are capable of making strong predictions about the location of new category members when the target class is entirely novel (i.e., no member of the category has been observed). Under these circumstances, there are no examples to copy, and thus the copy-and-tweak model predicts that items are generated at random. Likewise, with no observations on which to condition the category distribution, the hierarchical Bayesian model also picks an item at random.

Thus, it is possible that the failure of the classical models is simply due to their inability to explain each participant's first trial (generating the first item in the 'Beta' category). To ensure this is not driving our results, we conducted an identical set of simulations as above, excluding this trial (leaving 915 responses in the dataset): Again, the representativeness model ($L = -3286$, $AIC = 6580$) and PACKER ($L = -3377$, $AIC = 6759$) achieved better fits than the copy-and-tweak ($L = -3564$, $AIC = 7132$) and hierarchical Bayesian ($L = -3597$, $AIC = 7201$) models.

Finally, because copy-and-tweak is nested within PACKER, we can use a likelihood ratio test to compare the two models. PACKER explains the aggregate data significantly better than copy-and-tweak ($\chi^2(1) = 747, p < .001$ for all data and $\chi^2(1) = 375, p < .001$ excluding the first example), providing further evidence that category generation is better explained when contrast is considered.

Through comparison with the copy-and-tweak model, Figure 12 more clearly demonstrates the robustness of the explanatory gains yielded by PACKER's category contrast mechanism. It displays the log-likelihood of the participants' results under PACKER as a function of the θ_c parameter. The model's other parameters (c, θ_t) were set

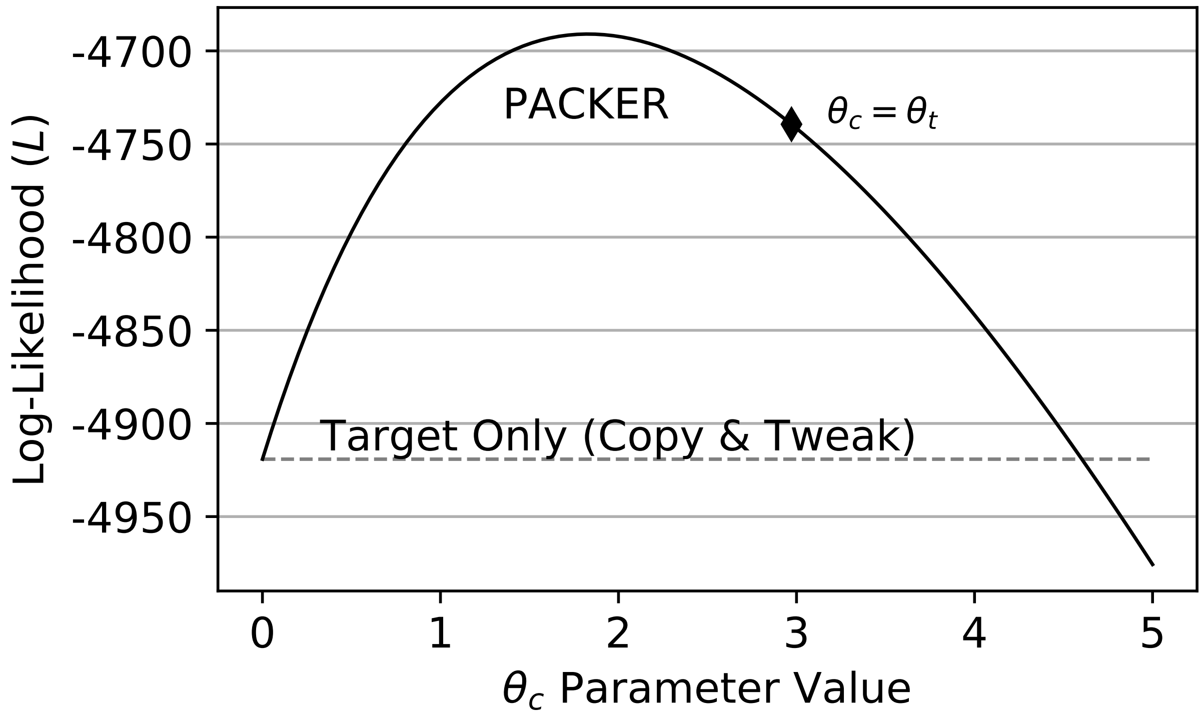

Figure 12: PACKER's fit as a function of its prioritization of within-category and between-category similarity (using the θ_c parameter) . To facilitate comparison, PACKER's other parameters (c, θ_t) were set to the best fitting values obtained for copy-and-tweak in Table 2. The black diamond marker indicates the log-likelihood for the point where $\theta_c = \theta_t$.

according to copy-and-tweak's best fits from Table 2, and thus when $\theta_c = 0$, the models are equivalent. The figure clearly shows a "sweet spot": a convex region in which PACKER achieves superior fits as a result of changes to θ_c. The best fitting values lie well above the value of 0 assumed by the copy-and-tweak model, which demonstrates the robustness of the contrast effect (though note PACKER achieves even better fits when its parameters are fitted together, as in Table 2). In sum, the data are better explained when both within-category similarity and category contrast is considered.

6.2 Individual Differences

As noted in Experiments 1 and 2, we observed a great deal of individual differences in the types of categories that participants generated. Within each condition, there were a wide variety of category types, such as row and column categories (see Figures 4 and 8). The simulations reported above serve to evaluate the models while considering the entire dataset, but a secondary goal of any formal account should be to provide some explanation of how different profiles of performance emerge. Many of the individual generation profiles we observed can be described with the models simply by tuning the model's parameters in a principled manner. In this section, we describe more specifically how the most frequently observed profiles can be realized.

By manual inspection, it is evident that the most common profiles of generation consist of: (A) a tightly-distributed 'cluster' of examples, (B) 'row'- and 'column'-like arrangements (varying widely along one dimension but not the other), and (C) a 'corners' arrangement with examples placed into disparate corners of the space. These four profiles are distinct in terms of the distribution of the generated category along each dimension: Whereas the cluster profile is tightly distributed along both dimensions, the row and column profiles are tightly distributed along just one dimension. Finally, the corners profile is widely distributed along both dimensions.

In the framework proposed by PACKER, the cluster and corners profiles arise based on different prioritization of within-category similarity versus between-category contrast, and the row and column profiles arise based on the prioritization of each dimension in the computation of similarity. For example, in the cluster profile, there is a high degree of within-category similarity along both dimensions, whereas in the corners profile there is minimal within-category similarity. Thus, PACKER's proposal is that these individual differences arise as a result of different priorities: While the tight cluster configuration can be considered PACKER's 'default' mode (as it maximizes within-category similarity), the corners profile can be produced when between-category contrast is put at a higher priority

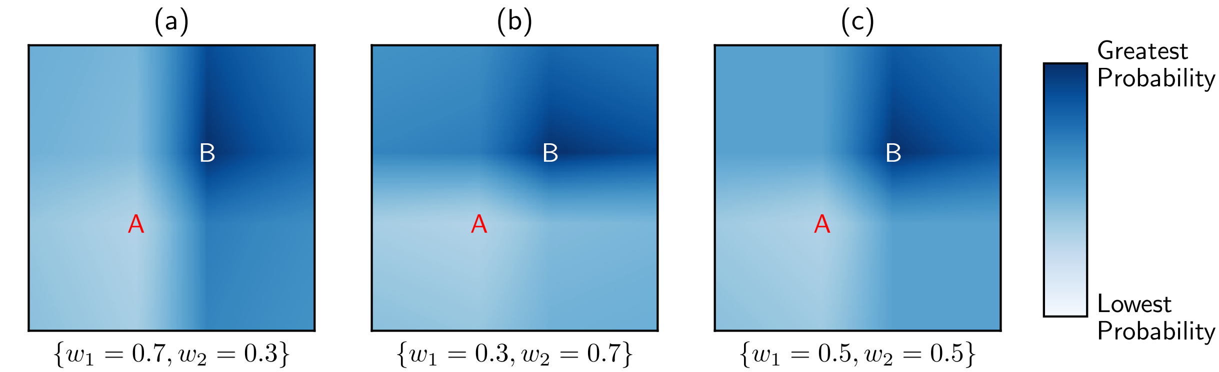

Figure 13: PACKER generation of a category ‘B’ example, following exposure to one member of category ‘A’ and one member of category ‘B’. Predictions are shown for different attention settings: *(a)* Increased weighting of the X-axis. *(b)* Increased weighting of the Y-axis. *(c)* Uniform weighting (identical to Figure 1).

(i.e., $\theta_c > \theta_t$).

Likewise, in the row and column profiles, there is a large degree of within-category similarity along one dimension but not the other. These differences likely arise due to a differential focus on one dimension over another, and thus they can be produced by changes to PACKER's attention weights, w_1 and w_2 (see Equation 1). Traditionally, the attention weights in exemplar models are thought to reflect the diagnostic value of each dimension towards classifying the known category members (Kruschke, 1992; Nosofsky, 1984, 1986), but within a generation context the weights specify the importance of within- and between-category similarity along each dimension. For example, if all of attention is allocated along the X-axis ($w_1 = 1$ and $w_2 = 0$), similarity along the Y-axis no longer influences performance. As a result, PACKER will create categories that are more widely distributed along the Y-axis, as similarity is not taken into account along that dimension. As a general principle, differentially weighting one dimension will result in the generation of categories that are more widely distributed along the ignored dimension, conforming to a row- or column-like arrangement. See Figure 13 for a depiction of how attention influences PACKER's performance.

As in PACKER, changes in the parameter settings of the copy-and-tweak model can also be used to produce different patterns of generation. Indeed, as copy-and-tweak is simply a special case of the PACKER model, the attention weights operate exactly as described above to produce row- and column-like categories. However, because the model is not influenced by category contrast, it is biased toward generating tightly clustered categories, as new items are always most likely to be generated near known examples of the target category. Thus, the lack of a contrast mechanism prevents the model from explaining why some individuals widely distribute their categories to the corners of the space.

For both the hierarchical Bayesian and the representativeness models, the prior domain covariance matrix Σ_0 can be used to explain the generation of row-like and column-like categories. This covariance matrix specifies the amount of variance assumed along each dimension (as well as the dimensional correlations) across the domain of categories. The covariance matrix for a newly generated category, Σ_B, is based on the assumed Σ_0 as well as the distributions of previously learned categories (see Appendix A). Thus, the importance of each feature can be coded into Σ_0 to alter the dimensional variance of generated categories. Because the hierarchical Bayesian model possesses no mechanism to account for category contrast, the model is most likely to generate new items that are similar to known examples of the target category with no regard for how different it is to the contrast category. However, the representativeness model predicts that new exemplars should provide more relative evidence to the 'Beta' category, accounting for the tendency of row-like and column-like profiles occupying the edge of the feature space.

While the copy-and-tweak and hierarchical Bayesian models possess mechanisms to explain row- and column-like categories, they cannot easily explain why some individuals widely distribute their generated categories into disparate corners of the space. This, however, reveals a more general limitation: According to the copy-and-tweak and hierarchical Bayesian models, the distributional structure of generated categories is *independent* of their location within the domain. For example, although the copy-and-tweak or hierarchical Bayesian models can be parameterized to generate row- or column-like categories, there is no mechanism in place to ensure that what is generated will be distinct from what is already known. In the next subsection, we explore this prediction through an analysis of the interdependence between distributional structure and location in category generation.

6.3 Category Location vs. Distributional Structure

As noted above, while all three models make clear claims about the internal structure of generated categories, the copy-and-tweak and hierarchical Bayesian models do not make any claims about how generated categories should differ from what is already known. However, as we observed in the results of Experiment 2, the distributional structure of a category is not always independent of its location within the domain. To demonstrate this point in more depth, we computed the X- and Y- axis ranges of every participant-generated category. Taking the difference between these values ($X - Y$) produces a measure of each category's orientation in the space: positive difference scores correspond to categories with more X-axis range (horizontally aligned, 'Row' categories), whereas negative difference scores indicate the opposite (vertically aligned, 'Column' categories). Neutral differences scores indicate there was an equal amount of X- and Y-axis range, which can be produced by a number of different category types ('Clusters', 'Corners', etc; see Figures 4 and 8). By plotting, for each possible stimulus, the difference scores of categories it was generated within, we can relate the distributional structure of generated categories to their location within the domain.

However, because many stimuli were infrequently generated (such items near members of the 'Alpha' category), we cannot simply compute the empirical average of the difference scores, as infrequently generated stimuli would be likely to show artificially strong differences. Instead, we used a Bayesian analysis to estimate the mean μ_x on the assumption that the scores x for each stimulus are normally distributed with an unknown mean and unknown standard deviation. The conjugate Normal-Inverse Gamma distribution provides a straightforward method for this estimation:

$$\mu_x = \frac{\nu_0 \mu_0 + \sum x}{\nu_0 + n} \tag{11}$$

where μ_0 is the prior mean, ν_0 is a prior scale parameter (controlling the weighting of the μ_0), and n is the number of categories in which the stimulus was a member (i.e., the number of scores in x). The default assumption is that there is an equal amount of range along the X- and Y-axes, and so we set $\mu_0 = 0$. Likewise, to give a moderate amount of weighting to the prior mean we set $\nu_0 = 1$, though the results are robust to a range of values. Within this approach, the resulting aggregation is a trade-off between the number of generations and the strength of the range difference within each generated category. Infrequently generated stimuli, as well as those with mixed positive and negative scores, are given neutral difference scores.

The results of our analysis are shown in Figure 14 for the experiment and model results[3]. The left-most column of Figure 14 displays the effect of category location and contrast on the distributional structure of the category generated by participants. These data reveal strong and consistent patterns across all the conditions we tested in Experiments 1 and 2: Generated categories are more tightly distributed along the axis in which they are distinct. For example, in the 'Cluster' condition, exemplars in the bottom-left of the space are more often generated into vertically aligned categories, and exemplars in the top-right are more often generated into horizontally aligned categories. Similarly, in the 'Bottom' and 'Middle' conditions, horizontally aligned categories are generated above and below the experimenter-defined categories, while vertically-aligned categories are generated to the sides. In the 'Row' condition, most categories are horizontally aligned, and lie along the upper areas of the space. There are no strong range difference patterns in the XOR condition.

These patterns of performance clearly depict the interdependence between the

[3] Prior to plotting, data were also processed using a Gaussian filter with $\sigma = 0.8$.

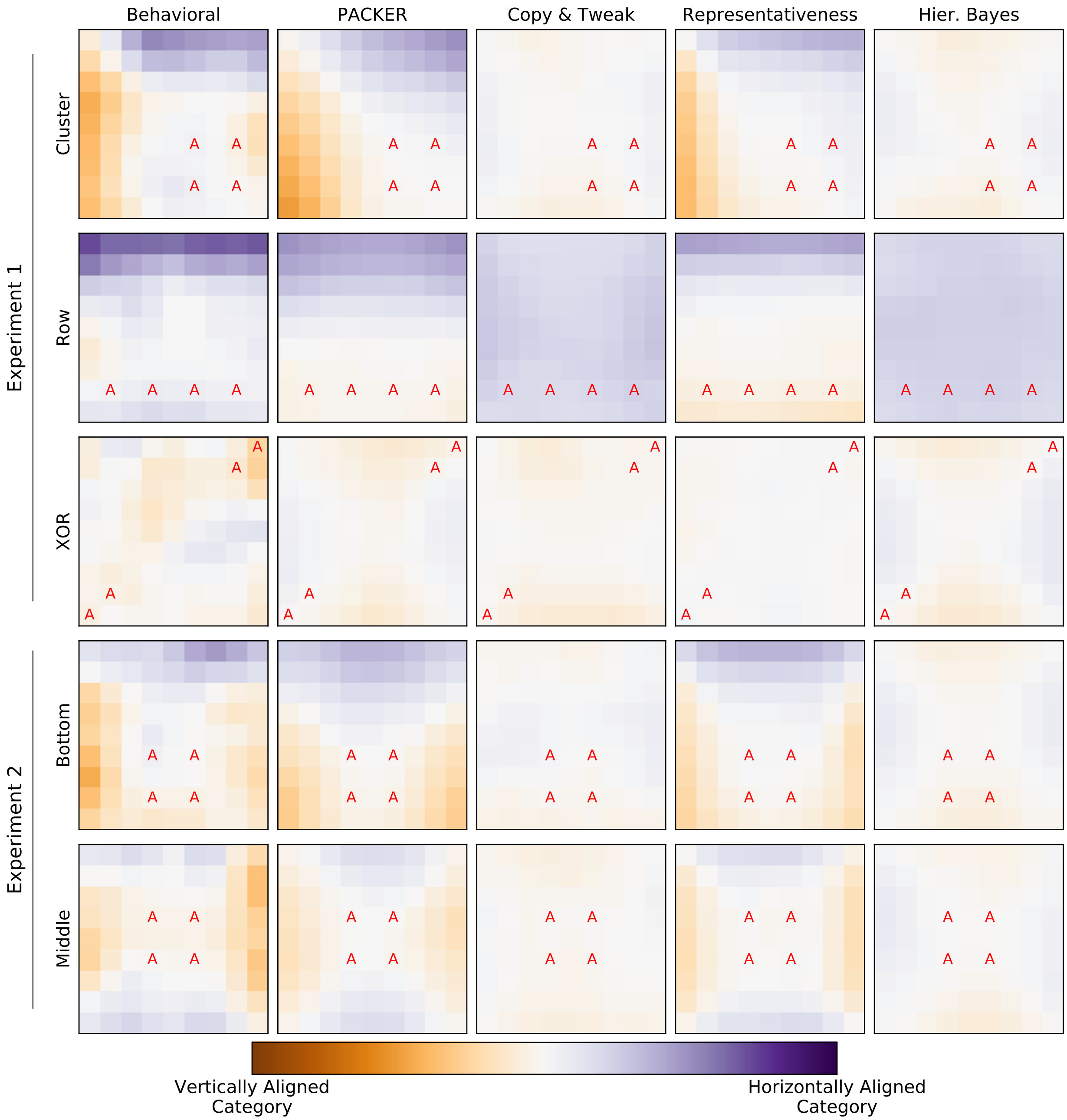

Figure 14: Behavioral and simulated range difference gradients. Each panel shows, for each stimulus, the dimensional orientation of the categories it was generated into: vertically aligned 'columns' (orange) versus horizontally aligned 'rows' (purple).

distributional structure and location of generated concepts. Our results can be interpreted in terms of local minimization of between-category similarity: By distributing the generated category away from members of the experimenter-defined category, participants may increase the degree of between-category distance without drastically altering the degree of within-category similarity.

To explore how well the PACKER, copy-and-tweak, representativeness, and hierarchical Bayesian models explain our findings, we conducted simulations using an individual-differences approach. As noted in Section 6.2, row- and column-like categories can be produced by each model through changes to the weighting of each dimension. Given this information, we may use the models to simulate each participant's generation separately, with the importance of each dimension set according to the relative range of the participant's generated category along each dimension.

In the PACKER and copy-and-tweak models, the attention weights, w, specify the importance of each dimension in the computation of similarity. While there exist methods to find the optimal attention weighting scheme given a classification (see Vanpaemel & Lee, 2012), for simplicity we assume that the 'Alpha' and 'Beta' categories are distinct along dimensions that the 'Beta' exemplarss do not vary on. In this case, the weighting for a given participant can be computed as:

$$w_k = \frac{\exp\{-\theta_w \cdot \text{range}(k)\}}{\sum_k \exp\{-\theta_w \cdot \text{range}(k)\}} \tag{12}$$

where θ_w is a free parameter controlling how differences in range correspond to differences in weights (functioning similarly to the θ parameter in each of the models), and range(k) is the range of examples generated by the participant along dimension k. We used $\theta_w = 1.5$ in our simulations, though the results are robust and similar for other θ_w values. The resulting w values are thus inversely proportional to the range of generated categories along each dimension, with less range corresponding to greater weighting.

Unlike the PACKER and copy-and-tweak models, the representativeness and hierarchical Bayesian model's dimensional variances correspond to the assumed variance of generated categories along each dimension (rather than the inverse of the variance). Thus, a different transformation is appropriate for incorporating the weights computed in Equation 12. For the hierarchical Bayesian model, we computed the dimensional variances according to: $\lambda(1 - w_k)2$, where λ is a free parameter specifying the overall assumed variance of the domain, and 2 corresponds to the number of dimensions in our experiments[4]. Under this approach, evenly distributed weights correspond to an assumed variance of λ. Likewise, larger values of w, which are produced when the generated category is tightly distributed along one dimension, correspond to smaller assumed variances.

Each model was used to simulate each participant's generation independently, with the importance of each dimension set according to the participant's generated category. The other free parameters within each model were set as in Table 2. Every participant's generation was simulated 2,000 times; given the 305 participants tested across the two experiments, each model generated 610,000 categories in total. For comparison with our behavioral results, we then computed the range difference gradient identically as with the behavioral data. The results are shown in Figure 14.

As in the more traditional model evaluation analysis described above, the contrast models (i.e., PACKER and the representativeness model) provided a much closer match to our behavioral results than the copy-and-tweak and hierarchical Bayesian models. In all conditions, the contrast models distribute categories similarly to the behavioral data: Horizontally-aligned categories tend to be placed above and below members of the experimenter-defined category, and vertically-aligned categories tend to be placed to the sides. Conversely, because the copy-and-tweak and hierarchical Bayesian models are insensitive to category contrast, these models do not produce any systematic patterns of association between category location and distributional structure. The sole exception is within the 'Row' condition of Experiment 1, in which the majority of participants

[4] This calculation applies only in two-dimensional domains, where $w_2 = 1 - w_1$.

generated a 'Row'-like category, widely distributed along the X-axis but not the Y-axis. In these cases, both models are initialized with weights that produce Row categories, but because category contrast is not considered, categories are uniformly generated across the entire domain, rather than concentrated within the upper-regions as observed behaviorally.

7 Experiment 3

Experiments 1 and 2 clearly establish the importance of contrast in category generation. Follow-up model-based analyses illustrated that both contrast models account for participant performance better than models that do not take into account contrast. We also found more support for contrast as representativeness hypothesis over contrast as exemplar dissimilarity hypothesis.

Although category generation is an intriguing aspect of human cognition, it has played a relatively limited role in the broader categorization literature. To establish that contrast plays a broader role in categorization, we conducted a traditional category learning study. In it, participants learned two categories, where the categories learned by each participant in Experiment 3 was yoked to the 'Alpha' shown and 'Beta' generated by each participant in Experiment 2. Our goal is to investigate whether model performance (in generating categories) is consistent with human performance (in learning those categories). Specifically, if contrast plays a broader role in categorization, then 'Beta' categories rated as "better" according to the contrast models should be easier for participants to learn.

7.1 Participants, Materials, and Procedure

Experiment 2 recruited 122 participants who each generated one set of four 'Alpha' and four 'Beta' category exemplars. Experiment 3 recruited the same number of participants.

Participants observed four blocks of eight trials. Each trial began with the presentation of a fixation cross for 500 ms. This was followed by the presentation of one

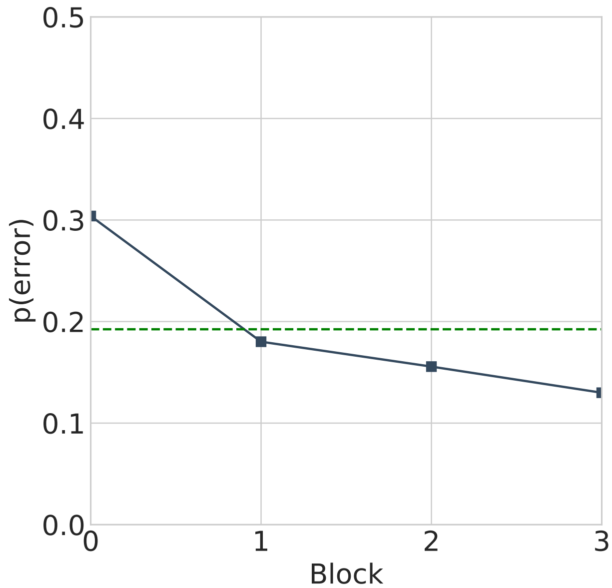

Figure 15: Average error rate for each successive block. Green discontinuous line represents the overall mean error rate.

exemplar randomly sampled without replacement from the unique category set. Participants were tasked with assigning the presented exemplar to either the 'Alpha' or 'Beta' category with no time limit imposed. Feedback was automatically displayed for 2500 ms after each response.

7.2 Results and Analysis

Among the 122 originally generated category sets were 102 unique sets (i.e., they contained a unique collection of 'Alpha' and 'Beta' exemplars). Consequently, for our subsequent analyses for this experiment we only use data from the first 102 participants that were presented with a unique category set.

Overall accuracy of the participants was high, with a mean error rate of .19 ($SD = .19$). Aggregated error rates for each block are presented in Figure 15.

In order to analyze the consistency between model and human performance, we optimized each model such that the Pearson correlation between the model's negative log-likelihood of generating each unique category set and the participant's error in learning that category set is maximized. As with the analysis in Section 6.3, we simulated the weighting of each dimension independently depending on the generated categories.

The greatest correlations were observed when fitting the contrast models. Specifically, PACKER correlated with human performance with $r = .65, 95\%\, CI\, [.48, .78]$, and the representativeness model correlated with human performance with $r = .59, 95\%\, CI\, [.40, .73]$[5]. Copy-and-tweak yielded a correlation of $r = .45, 95\%\, CI\, [.28, .62]$ and the hierarchical Bayesian model yielded a similar correlation of $r = .46, 95\%\, CI\, [.30, .62]$. These results are graphically presented in Figure 16.

To emphasize the strong influence of contrast in maximizing the association between category generation and category learning, we computed the correlations over wide range of $\theta_{contrast}$ values, with the other parameter values of PACKER held constant at their optimized levels. As presented in Figure 17, the correlation quickly increases with increasing weight on contrast, reaching a plateau above values of around 4.0.

8 General Discussion

The sensory impression of every stimulus and event is unique. Grouping distinct patterns of sensory information into categories is a fundamental task solved by the mind. Most work has focused on how people learn new categories that are provided to them through unlabeled, partially labeled, or fully labeled examples. How were these categories first determined? Some natural categories are likely to be the result of regularities in the dynamics of our environment. But, these are only a subset of the categories that people learn. Other categories, such as tools and ideas, were generated by people over time. What basic principles underlie how people generate categories?

While the bulk of prior research on categorization has focused on the classic finding that generated concepts tend to be distributionally similar to known concepts, there has

[5]Confidence intervals were obtained using a bootstrap method with 1000 bootstrap samples.

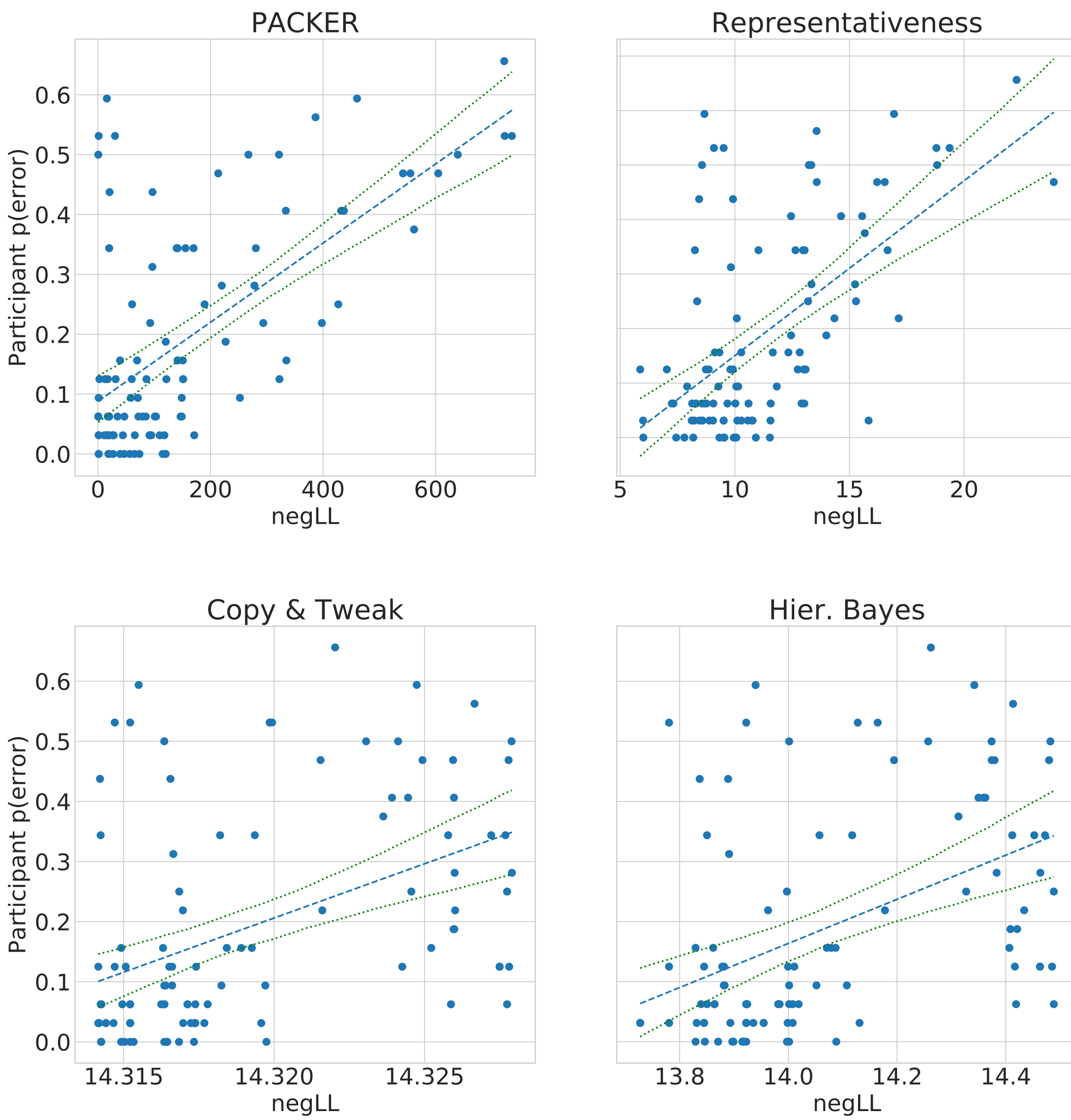

Figure 16: Scatterplots indicating the correlations between observed participant error and model fit. Blue discontinuous line are best-fit lines. Green discontinuous lines indicate boundaries generated by the 95% CI around the fitted correlations.

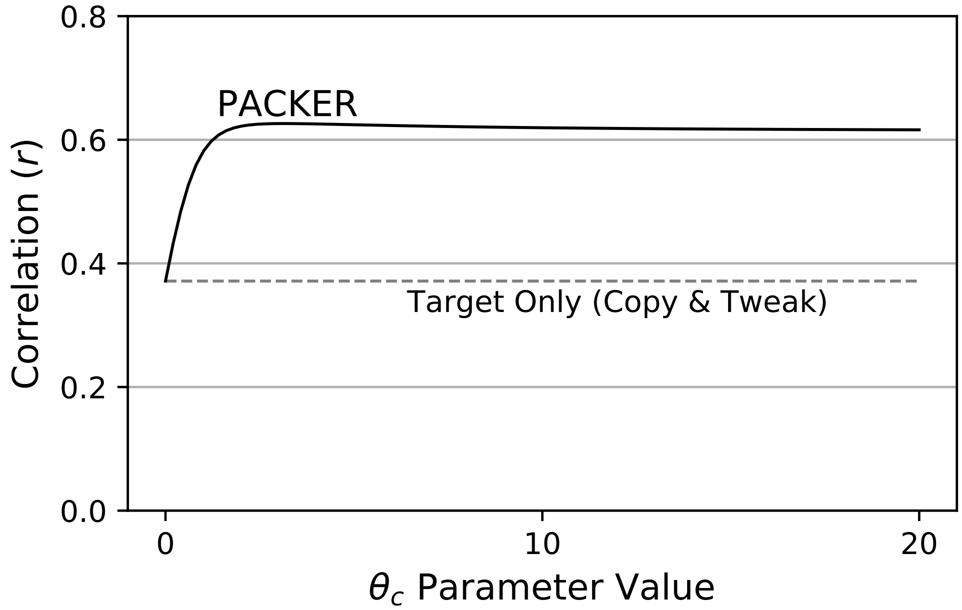

Figure 17: Correlation between PACKER's fit and participant error as a function of the $\theta_{contrast}$ parameter. To facilitate comparison, PACKER's other parameters (c, θ_{target}) were set to the best fitting values obtained for copy-and-tweak in Table 2. Grey dashed line represents the correlation between Copy & Tweak's fit and participant error.

been little work addressing the role of contrast in category generation: How is it that people are able to create something *different* from what is already known? We developed two novel models, each incorporating a different conceptualization of category contrast. One model is PACKER, which is an exemplar-based model that formally specifies the role of contrast in generation as exemplar dissimilarity. Specifically, the model proposes that categories are represented as exemplars in a multidimensional psychological space, and generation is constrained both by within-category and between-category similarity: Exemplars belonging to the same category should be similar to one another, and exemplars belonging to different categories should not be similar to one another. The second model is a novel hierarchical Bayesian model with a representativeness mechanism. This model generates exemplars that are more representative of (i.e., has greater relative evidence from) the novel category compared to the learned category.

We reported two experiments demonstrating systematic effects of category contrast in category generation. Members of participant-generated categories tended to be highly dissimilar from members of previously-learned categories, and were usually more similar to one another than to members of other categories. We also observed broad interdependence between the distributional structure (feature variance, correlation) and physical instantiation (location within the stimulus space) of generated categories: In Experiment 2, we found that the unoccupied regions of the domain influenced the distributional structure of categories, and in both experiments we observed that participants distributed their generated categories to increase contrast with what was already known.

We conducted simulations comparing the contrast models' account of our results to the classical proposals for category generation: a "copy-and-tweak" model (realized as a variant of PACKER with no sensitivity to category contrast), and a hierarchical Bayesian model designed to explain the classic distributional similarity effect. In all simulations, we found that the contrast models captured a previously unexplained and unexplored aspect of human category generation. In particular, by measuring PACKER's fit as a function of its prioritization of within- and between-category similarity, we observed that considering either constraint exclusively results in a relatively low-quality account. Instead, PACKER's best results were obtained when both constraints are considered, indicating that human learners do not generate novel concepts exclusively on the basis of within-category similarity or between class-contrast. This finding mirrors our behavioral results and demonstrates that both constraints influence generation when explained with an exemplar model. Ultimately, our category generation data were best explained by the representativeness model. The exact nature of its superiority over the other models is still not yet clear. However, as we explore in a later section, it is likely that the representativeness mechanism itself (i.e., independent of the hierarchical Bayesian foundation) captures a core aspect of both category generation and category learning.

8.1 Finding Contrast Effects in Prior Work

Although existing accounts of category generation broadly overlook the role of category contrast in determining what is novel versus familiar, it was implicitly assumed that learners in previous experiments were *successful* in creating new categories. Thus, if contrast plays a robust role in category genration, its effects should be discernable within the experimental results of these studies. To provide a test of the influence of category contrast within existing data, we conducted a novel analysis of Experiment 3 from Jern and Kemp (2013).[6]

Participants in their experiment were exposed to members of two experimenter-defined categories of 'crystals' varying in hue, saturation, and size. Each category possessed a unique hue, but varied in saturation and size: In the 'Positive' condition, there was a positive correlation between these features (i.e., larger sized crystals were more saturated), and in the 'Negative' condition this relation was reversed. In the

[6] Although Jern and Kemp (2013) reported four experiments, we focus on Experiment 3 because their first two experiments tested generation of items into known categories, and their fourth experiment was identical to Experiment 3 but with a restricted generation space.

'Neutral' condition, there was no correlation between saturation and size. After learning about the categories from each condition, participants were asked to generate six exemplars belonging to a novel class. As noted above, Jern and Kemp (2013) found that the generated categories tended to follow the distributional properties of the experimenter-defined categories: Generated categories were tightly distributed along the hue feature, and possessed the same saturation-size correlations as in the learned categories. Jern and Kemp (2013), however, did not analyze or discuss how the generated categories *differed* from the experimenter-defined categories.

Because each experimenter-defined category in the Jern and Kemp (2013) experiment possessed a distinct hue shared by all members of the category, it is sensible that participants might generate a category with a hue distinct from the experimenter-provided categories. If category generation were influenced by category contrast in this way, the hues of generated categories should be systematically different from those of the experimenter-defined categories. Unfortunately, stimulus hue was encoded and presented in the Hue-Saturation-Value (HSV) color space, which is device-dependent and not perceptually normed such that perceived color similarity corresponds to proximity in the color space (as opposed to a color space such as CIELAB that is device-independent and equidistant sets of points correspond to pairs of colors that have the same perceptual similarity; Wyszecki & Stiles, 1967). Further, they did not calibrate their monitor, and so we cannot know the precise colors presented to participants. As Jern and Kemp (2013) were interested in relations between the saturation and length of examples in generated into novel categories, these issues do not undercut their analyses and results. However, these issues pose a significant challenge to evaluating contrast between the experimenter-defined and participant-generated categories along the hue dimension. It is plausible that two uncalibrated monitors could display the same HSV color and the colors be perceived in different color categories (especially for color boundaries that vary over lightness, such as the yellow-brown boundary).

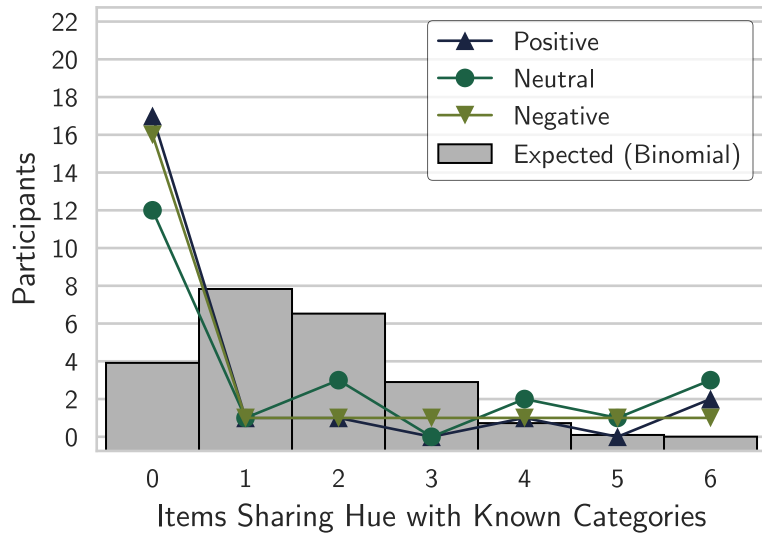

Figure 18: Analysis of data from Jern and Kemp (2013), Experiment 3. Plotted is the number of generated items that share a color group with one of the experimenter-defined classes. The "Expected" data follows a Binomial distribution with $p = 2/8 = 1/4$, given there were two experimenter-defined classes, and eight color groups.

Although we cannot know the precise colors that were displayed or perceived, we can still analyze their results from a coarse perspective to see whether there is preliminary support for contrast. To do so, we binned all possible hues into one of eight uniformly-spaced color groups: {*Red*: $0 - 0.063$, $0.938 - 1$, *Yellow*: $0.063 - 0.188$, *Yellow-Green*: $0.188 - 0.313$, *Green-Teal*: $0.313 - 0.438$, *Teal*: $0.438 - 0.563$, *Teal-Blue*: $0.563 - 0.688$, *Purple*: $0.688 - 0.813$, *Pink*: $0.813 - 0.938$}. In the Jern and Kemp (2013) experiment, the hue of each experimenter-defined category was selected from one of six possible values, each of which falls into one of the color groups above (two color groups were not used as a possible hue for the experimenter-defined categories). By categorizing the participant-generated crystals likewise, we can obtain a broad measure of category contrast by determining the proportion of participant-generated crystals that fall into the same groups as the experimenter-defined categories: If contrast influences the hues of the generated categories, we should observe minimal overlap between in the color groupings.

These data, shown in Figure 18, reveal a clear pattern: The majority of participants in each condition ($n = 22$) generated categories possessing entirely distinct hues; with 0/6 exemplars sharing a hue with the experimenter-defined categories. These results can be compared to the predictions of a Binomial model, which proposes that participants generate hues at random. That is, if hue selection is not systematic, the probability that any given example will lie in the same color group as an experimenter-defined category is given by a Binomial distribution with $p = 2/8 = 1/4$, as there were two experimenter-defined categories and eight possible color groups. Chi-square goodness-of-fit tests reveal that the observed distribution in each condition is highly inconsistent with the hues being chosen at random, all $\chi^2(6, N = 22) > 200$, $p < .001$. Participants tended to generate items that were perceptually distinct from the categories they had learned, and were less likely to generate hues possessed by members of the experimenter-defined categories.

It is possible, however, that this data can be explained by a process that does not involve contrast. Specifically, since participants were trained on exemplars that share the same hue within a category, it is plausible that they generate exemplars that all share a common hue. If this were the case, given a $6/8 = .75$ probability that a hue distinct from the experimenter-defined categories is selected, there is a corresponding .75 probability (or about 17 out of 22 participants) that the generated category will have no exemplars that share a hue with any of the experimenter-defined categories. In addition, that there is a $2/8 = .25$ probability (about 6 out of 22 participants) that the generated category will have all six exemplars that share a hue with any of the experimenter-defined categories. This prediction of regularity across categories is much closer to the data than the prediction from a Binomial model and does not require any mechanism of category contrast.

However, upon analyzing the consistency of hues in the generated categories, it is clear that participants do not generally produce categories with entirely similar hues across all exemplars. Specifically, only 55% of all generated categories comprised exemplars with a common hue. Consequently, the assumption of regularity across categories may be inappropriate for this data set, leaving the contrast-based explanation as the most plausible for our purposes.

Re-analyzing the results from Jern and Kemp (2013) provides some corroborating support for contrast playing a role in category generation. Taken alongside the analyses reported by Jern and Kemp (2013), our analysis suggests that generated categories tend to be distinct from *and* distributionally similar to what is already known. However, it is worth noting that our analysis is still limited: The color groups defined above are imprecise, and it is not clear that our color grouping is consistent with the psychological color boundaries perceived by participants. While we did obtain similar results using a variety of alternative groupings, the hue dimension used in the Jern and Kemp (2013) study does not lend itself straightforwardly to the computation of similarities, and thus we cannot be certain of whether our coding accurately approximates the psychological space of the stimuli. This precludes traditional applications of categorization models to their data as it is usually necessary to encode objects in psychological space in order to accurately determine the similarity between objects. By consequence, although these results likely indicate that contrast exerts *some* influence, they do not precisely describe the nature of that influence.

8.2 Similarity and Contrast in Cognition

The proposal that category contrast is a primary constraint in categorization is, in some ways, entirely commonsense. For categories to be useful, they should not all be identical, or in other words, they should be different. Thus, a newly generated category should be different than pre-existing categories. Beyond its role in category generation specifically, category contrast is also of fundamental importance in categorization more broadly. All other factors held constant, new categories are easier to learn if they are dissimilar to members of other categories, and knowledge of highly distinct categories is applied more accurately than that of ill-defined categories (Ashby, Boynton, & Lee, 1994; Imai & Garner, 1965). Likewise, basic-level categories (Rosch et al., 1976) are thought to be abstracted in order to maximize within-category similarity while minimizing between-category similarity. Finally, the act of forming category representations affects similarity judgments about category members and nonmembers, with category members being viewed as more similar to one another than members of other categories (Goldstone, 1994, 1996; Goldstone, Lippa, & Shiffrin, 2001).

Beyond categorization, one can find instances of the trade-off between within and between-class similarity in linguistic categories over perceptual dimensions. For example, Regier et al. (2007) showed that the partitioning of color categories reflects such a trade-off in a psychological space – colors are partitioned into groups with members that are viewed as highly similar to one another yet distinct from other colors. A similar trade-off can be observed in phoneme categories. Different exemplars of the same phoneme must be similar to one another, while contrasting from other phonemes, such that a listener can infer the appropriate phoneme. This pattern has been found and modeled in the natural acoustics of American English vowels (Feldman, Griffiths, Goldwater, & Morgan, 2013; Hillenbrand, Getty, Clark, & Wheeler, 1995). As linguistic categories must have been created at some point in human history, it is revealing that the constraints of emulating distributional structure across categories and having categories contrast from one another still bias human category generation today.

The dual forces of within-class similarity and between-class contrast influence cognitive functions in a wide variety of domains. The PACKER model is notable in that it explicitly interprets this trade-off within the domain of categorization, and allows us to begin to understand the relatively understudied processes involved in category generation through our more well-developed tools for understanding human categorization.

8.3 Implications for Creative Cognition

Although the focus of this article has been to address the role of contrast in category generation and learning, our findings and approach have relevant implications for research in creative cognition. A central focus of the creative cognition approach has been to explain acts of creativity in terms of the mental representations and processes that are commonly studied in cognitive psychology and cognitive science (Finke, Ward, & Smith, 1992; S. M. Smith et al., 1995). However, unlike other fields in the study of cognition, creative cognition research rarely employs quantitative models to evaluate the explanatory value of such representations and processes. Our modeling results provide a concrete example of how formal approaches may be used to gain insight into the nature of creative cognition.

In addition to demonstrating the utility of formal modeling for studying creative cognition, the contrast models here specifically offer an additional interpretation of some of the field's most central findings. For example, perhaps the most foundational principle from this literature concerns the limiting influence of prior knowledge: Individuals create new categories composed of features from existing classes, and what is created can be influenced drastically through the introduction of cues or examples (Marsh et al., 1999; S. M. Smith et al., 1993). In this paper, we have identified another important aspect of the constraining influence of prior knowledge: What is generated cannot be the same as what is already known. Further, there is systematicity in how generated categories differ from prior knowledge. The results of our simulations suggest that this conceptualization of difference can be addressed in at least two different ways. Specifically, simulations with PACKER demonstrate that the constraining influence of difference is concisely explained in terms of a trade-off between within-category similarity and between-category dissimilarity. Conversely, the representativeness model shows that this influence can also be the result of enhancing the representativeness of generated exemplars to their category.

PACKER may offer an additional interpretation of existing accounts of creative generation. Most notably, a leading account within the creative cognition literature, the Path of Least Resistance (Ward, 1994, 1995), also explains generation in terms of an exemplar-based retrieval process. This account was designed to explain the creative generation of natural categories (e.g., new species of plants and animals) and as a result relies strongly on the hierarchical organization of these categories: Individuals are thought to retrieve an example of the higher-level category being generated (e.g., *bird* may be retrieved from the category *animal*), and then systematically alter what was retrieved to make something new. As the PACKER model does not assume knowledge is hierarchically organized (this is true of the exemplar view more broadly, see Murphy, 2016), the model may be viewed as a formal instantiation of the Path of Least Resistance for application in a traditional artificial categorization domain (when there is no established hierarchy of categories). PACKER's success in explaining generation within an artificial domain motivates future work exploring the nature of category contrast within a more naturalistic setting.

The broader study of creativity currently involves a wide breadth of different approaches,(for a review see Kozbelt, Beghetto, & Runco, 2010), such as those based on free association (Mednick, 1962) and conceptual combination (Estes & Ward, 2002; Murphy, 1988). In addition, recent work in the machine learning literature has explored using neural networks to address the overall problem of creative generation (e.g., Chen et al., 2016; Goodfellow et al., 2014; Ho & Ermon, 2016; Kingma et al., 2016). In contrast to these varied investigations, we reduced our focus by studying a highly complex behavior (category generation) as it applies within a well-established domain (artificial category learning). We hope that future work incorporates and highlights the importance of contrast into theories of creativity.

8.4 Implications For Categorization

Categorization research addresses the representations and processes that underlie the learning and use of categories. Category learning tasks are generally about figuring out which items belong to which category. Once learned, categories are generally used to classify new stimuli and to make inferences beyond the available information. Our work is fairly unique in that people learn a single category through positive examples and then create another category that would make sense in the domain. In other words, only one category is provided to be learned and the use that is required of that category is to generate a contrast category. Such scenarios have direct application to real-world situations. For instance, consider being stranded in an unfamiliar environment where you eat and get sick from a plant with certain features. In avoiding such plants and seeking alternative sources of nutrition, it would behoove you to imagine what features an edible, safe plant would possess (e.g., if the poisonous plant was bright red, perhaps a non-red plant would be safe to consume). In the present studies, we have learned something about the form that such expectations are likely to take.

We can think of the category generation task in our studies as asking a person to formulate an idea about what set of items in the domain are most interestingly *not* members of the original category. To meet this condition, the items must take some form of coherence that aligns with that of the original category and some form of distinctiveness relative to the original category. Reflecting the basic level of organization in natural categories, it makes sense to generate a set of items that possess strong within-category coherence (by importing or systematically transforming the internal structure of the original category) as well as strong between-category differentiation (by creating maximum contrast with the original category, be it through exemplar-based dissimilarity or the maximization of exemplar-category representativeness). In this sense one can see the patterns of performance in the category generation task as recapitulating the order of semantic organization.

The current work also suggests exciting directions for related investigations into unsupervised categorization. While the unsupervised categorization literature is primarily interested in the generation of categories within a set of observed exemplars where no prior categories are learned, our category generation studies are focused on the production of novel category exemplars themselves. Despite this distinction, both types of categorization research are ultimately interested in the question of how categories can be formed. The results of our current work indicate that the formation of categories is constrained by some measure of contrast. To our knowledge, this explicit investigation of category contrast has not yet been attempted in the unsupervised categorization literature.

Interestingly, the unidimensional sort bias that is commonly observed in unsupervised cateogorization (Ahn & Medin, 1992; Imai & Garner, 1965; Milton & Wills, 2004), where participants sort unlabelled family resemblance category exemplars by focusing on a single feature, was not consistently observed in our tasks. In our experiments we only observed this bias in the row condition of Experiment 1, whereas in other conditions participants generated categories that typically varied along both dimensions. This may be unsurprising at face value, since participants in conditions other than the row condition were trained on a prior category that varied on both dimensions. However, these results suggest that the unidimensional sort bias is not universal to all types of category construction – or more specifically, the unidimensional bias may not apply when participants need to generate categories with entirely new exemplars.

8.5 Exemplar Dissimilarity and Representativeness in Categorization

Although both PACKER and the representativeness model perform better than the classical models, they appear to be capturing fundamentally different aspects of contrast in categorization. Specifically, while the representativeness model excelled in predicting our category generation data, PACKER was the best-fitting model in accounting for participant error in category learning. Given the history of their development, this is perhaps not entirely surprising. PACKER is implemented as an extension of the GCM, which was originally developed for (and has been highly successful in) category learning (Nosofsky, 1986; Nosofsky et al., 1994). Conversely, the representativeness mechanism was conceived as a heuristic describing the relative extent to which an individual observation is generated from some unobserved population (Abbott et al., 2016; Kahneman & Tversky, 1972). This generative nature of the representativeness mechanism intuitively lends itself to the prediction of category generation data.

While the contrast models were born quite naturally out of the corresponding classical models, it is worth considering if similar benefits in prediction would be seen if the contrast mechanisms were applied to different classical models. Although there is no clear way to adapt the exemplar dissimilarity mechanism to the current hierarchical Bayesian model, it is a fairly straightforward process applying the representativeness mechanism to an exemplar model. Specifically, by treating the similarity measure (Equation 1) in the current implementation of copy-and-tweak as a density estimate for the representativeness mechanism (Equation 4), we gain a new model of representativeness that is based on exemplar similarity instead of a multivariate Gaussian likelihood.[7]

How well does a representativeness model that uses exemplar similarity to represent the categorys density over features explain our experimental results? We find that this model substantially outperforms its classical counterpart, but not to the extent of PACKER or the representativeness model. Specifically, fitting this model to the category generation data yielded $L = -4815$ and $AIC = 9633$ for the entire set of data from Experiments 1 and 2, and $L = -3474$, $AIC = 6953$ for data excluding the first trials. When used to predict the error rates of participants in the category learning task (Experiment 3), the performance of the copy-and-tweak with representativeness model correlated with participant error with $r = .56, p < .001$. These results suggest that the predictive advantages to including the representativeness mechanism is not limited to a hierarchical Bayesian model, but can also be found when applied to an exemplar model. Although its performance is not as strong as either of the fully-developed contrast models, there is a benefit to the representativeness mechanism that is independent from any interaction with a hierarchical Bayesian framework.

Ultimately, the source of the discrepancy between the performance of the two contrast mechanisms in category generation versus category learning is still not entirely

[7] An analogous implementation of the representativeness mechanism to PACKER results in both θ_c and θ_t adding to constant value that is independent of the similarity to contrast and target exemplars respectively. Consequently, it becomes equivalent to a copy-and-tweak model with representativeness.

clear. Our results could be an indication of a fundamental difference between the processes involved where exemplar dissimilarity is a larger factor in category generation while representativeness exerts more influence in category learning. Alternatively, it is possible they are both approximating some factor that we still have not fully identified. While a thorough investigation is beyond the scope of the current article, the preliminary results of this section indicate that further work to disentangle these two mechanisms would be promising. In the following section, we explore some other limitations of the current work and provide more recommendations for future research.

8.6 Limitations and Future Directions

Although successful in explaining our results in all three studies (albeit not as well as the representativeness model for Experiments 1 and 2), PACKER does not provide a full account of what is known about category generation. Most notably, in this paper we have not evaluated the model's ability to explain the classic finding that generated categories tend to share distributional commonalities with previously learned categories (see Jern & Kemp, 2013; Ward, 1994). While we successfully replicated this effect in Experiment 1, we also found that its influence was limited in comparison to the fundamental constraints imposed by category contrast. Even within Experiment 1, we found systematic inconsistencies: by generating exemplars into unoccupied regions of the space, participants who learned an 'XOR' category, composed of members that are widely distributed along both features and are positively correlated in space, tended to generate categories with an opposite (negative) correlation. More generally, PACKER inherits the strengths and weaknesses of exemplar models of categorization: It provides a simple and flexible model that explains many results, but deviates systematically from human performance in some cases.

Nonetheless, these classic effects are a core element of the phenomenology of category generation, and PACKER does not include any mechanisms that explain them.

Instead, through the development and evaluation of the PACKER model, we have sought to add new elements into such a phenomenology: The broad and strong influence of category contrast, and the interdependence between category location and distributional structure. It may be possible to combine the hierarchical Bayesian approach proposed by Jern and Kemp (2013) with PACKER's underlying claims to obtain a "best of both worlds" model, capable of explaining the role of contrast in category generation, as well as the emulation of distributional structure. However, as noted in the introduction, the incorporation of category contrast is antithetical to the core principles of a traditional, semi-conjugate Bayesian approach. This suggests that category generation is a fundamentally different computational-level problem (different from those posed by Jern & Kemp, 2013; Kemp & Jern, 2014).

Characterizing that problem and conducting a rational analysis is an important direction for future research. To that aim, we plan to explore the connection between exemplar modeling as an Importance Sampling approximation (Shi, Griffiths, Feldman, & Sanborn, 2010), and see what sort of computational-level problem PACKER approximates. Once formalized in probabilistic terms, it should also be straightforward to incorporate distributional factors into the model. This would unite PACKER with the Bayesian representativeness model, and they would differ in terms of their assumptions about how people represent category distributions (as exemplars or prototypes, respectively). Alternatively, it may be possible to integrate the core principles of either model of contrast into other categorization models (e.g., Kurtz, 2007; Love et al., 2004; D. J. Smith & Minda, 2000).

9 Conclusions

The generation of new concepts and ideas is a highly interesting topic, but it is difficult to study in a controlled experimental environment. In this paper, we have provided such an examination of category generation as it applies within an artificial categorization experiment. Extending the literature on creative cognition, our experiments provide a detailed picture of the role of category contrast in generation: People seek to create concepts that are distinct from what they already know, and the nature of what is created can be influenced by what does not yet exist. Our simulations with traditional exemplar models, as well as a hierarchical Bayesian model, provide strong support for the claim that category contrast is of fundamental importance to categorization. More broadly, our results demonstrate that popular explanatory approaches from basic research in cognitive science can offer a precise, quantitative account of a behavior as complex as that of category generation, and in exploring them, we can increase our understanding of categorization as well.

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A The Hierarchical Bayesian Model of Concept Generation

Jern and Kemp (2013) demonstrated how a hierarchical Bayesian model could explain the distributional correspondences between observed and generated categories. In their model, exemplars of generated categories were viewed as samples from a multivariate Normal distribution over the dimensions of stimulus space. The mean of the generated category was independent of the observed categories, but the covariance matrix (encoding feature variances and correlations) was based on a common prior distribution. Generating a new category was thus completed by sampling a new category mean (uniform over stimulus space) and covariance matrix from the common prior distribution. Because the shared prior distribution's parameters were unobserved, the hierarchical Bayesian approach was used to infer its parameters from the previous categories (their feature variances and correlations), and then to generate the covariance matrix of the new category.

In our implementation of their model[8], each category's exemplars are viewed as samples from a multivariate Normal distribution with parameters (μ, Σ). Category covariance matrices (specifying variance and covariance along k-dimensions), are assumed to be Normal-Inverse-Wishart distributed with parameters: ν $(> k-1)$, κ (> 0), and Σ_D. ν and κ are treated as free parameters in our simulations, and Σ_D is the domain-wide covariance matrix from which all categories are viewed as samples. Assuming a given Σ_D, a category covariance matrix Σ can be computed on the basis of its examples:

$$\Sigma = \left[\Sigma_D \nu + C + \frac{\kappa n}{\kappa + n}(\bar{x} - \mu)(\bar{x} - \mu)^T\right](\nu + n)^{-1} \tag{A.1}$$

where $\bar{x}$ and C are the empirical mean and covariance of the category's known members, and n is the number of observed members of the category. When there are fewer than two

[8]Note that Jern and Kemp (2013)'s model is slightly different, as they used a semi-conjugate model. Their model acts very similarly to our version.

known members of the category (and thus no covariance to speak of), $\Sigma = \Sigma_D \nu$.

The category mean, μ, can be computed as:

$$\mu = \frac{\kappa \mu_0 + n\bar{x}}{\kappa + n} \tag{A.2}$$

where μ_0 is the prior mean. In our simulations, μ_0 is set to the center of the domain. However, when no examples of the target category have been observed, generation is assumed to be random. In practice, the model's best fits are achieved when the κ parameter, which controls the influence of μ_0 on μ, is set very close to zero (hence, the influence of μ_0 is minimal).

Importantly, the domain-wide covariance matrix Σ_D is unobserved and needs to be inferred from the observed categories. For conjugacy, if Σ_D is viewed as a sample from an Inverse-Wishart distribution with scale Σ_0, Σ_D can be computed as:

$$\Sigma_D = \Sigma_0 + \sum_y C_y \tag{A.3}$$

where Σ_0 is the prior covariance in the domain. In our simulations, $\Sigma_0 = \lambda \mathbf{I}$, where λ is a free parameter controlling the expected variance of dimensions (dimensions of the domain covariance matrix are expected to be uncorrelated) and $\mathbf{I}$ is a k-by-k identity matrix.

Generated exemplars are drawn from a multivariate Normal distribution specified by (μ, Σ). Thus, $p(y)$ is

$$p(y \mid x) = \frac{\exp\{\theta \cdot \text{Normal}(y; \mu, \Sigma)\}}{\sum_i \exp\{\theta \cdot \text{Normal}(y_i; \mu, \Sigma)\}} \tag{A.4}$$

where θ is a response determinism parameter and $\text{Normal}(y; \mu, \Sigma)$ denotes a multivariate Normal density evaluated at y.