

Visual Grounding Helps Learn Word Meanings in Low-Data Regimes

Chengxu Zhuang¹ and Evelina Fedorenko^{1,2,3} and Jacob Andreas⁴

¹McGovern Institute for Brain Research, MIT

²Department of Brain and Cognitive Sciences, MIT

³The Program in Speech and Hearing Bioscience and Technology, Harvard University

⁴Computer Science and Artificial Intelligence Laboratory, MIT

{chengxuz, evelina9, jda}@mit.edu

Abstract

Modern neural language models (LMs) are powerful tools for modeling human sentence production and comprehension, and their internal representations are remarkably well-aligned with representations of language in the human brain. But to achieve these results, LMs must be trained in distinctly un-human-like ways—requiring orders of magnitude more language data than children receive during development, and without perceptual or social context. Do models trained more naturalistically—with grounded supervision—exhibit more human-like language learning? We investigate this question in the context of *word learning*, a key sub-task in language acquisition. We train a diverse set of LM architectures, with and without auxiliary visual supervision, on datasets of varying scales. We then evaluate these models’ learning of syntactic categories, lexical relations, semantic features, word similarity, and alignment with human neural representations. We find that visual supervision can indeed improve the efficiency of word learning. However, these improvements are limited: they are present almost exclusively in the low-data regime, and sometimes canceled out by the inclusion of rich distributional signals from text. The information conveyed by text and images is not redundant—models mainly driven by visual information yield qualitatively different from those mainly driven by word co-occurrences. However, our results suggest that current multi-modal modeling approaches fail to effectively leverage visual information to build human-like word representations from human-scale data.

1 Introductions

Neural language models (LMs) have achieved remarkable success across a wide variety of language processing tasks (Devlin et al., 2018; Liu et al., 2019; Radford et al., 2019; Brown et al., 2020). They have also proven useful for predicting aspects of human language processing, both in behav-

ioral models of production (Arehalli and Linzen, 2020) and comprehension (Wilcox et al., 2020) as well as models of neural responses to linguistic inputs (Schrimpf et al., 2021; Caucheteux and King, 2022; Goldstein et al., 2022). LMs are therefore strong candidates as computational models of core aspects of human language processing. At present, however, these models are profoundly implausible as models of human cognitive *development*. The amount of training data required by effective LMs greatly exceeds the amount of linguistic input that human language learners receive during development (Zhang et al., 2020; Warstadt and Bowman, 2022): modern LMs are typically trained on tens of billions of sentences, whereas children only receive around a million sentences in the first three years of their lives (Bergelson and Aslin, 2017). Techniques for building LMs that *learn like humans* would immediately enable richer computational models of language acquisition and child language learning dynamics, and perhaps offer a path toward more sample-efficient learning in LMs targeted at NLP applications.

One of the most significant differences between how humans and LMs learn language is that humans *ground* language in perceptual signals spanning many different modalities, including vision, touch, and hearing (Schroer and Yu, 2023; West and Iverson, 2017; Seidl et al., 2023; Clerkin et al., 2017). In sighted learners, vision is hypothesized to play a central role, as it delivers detailed information that is often directly coupled to linguistic input (Clerkin and Smith, 2022). Researchers in the natural language processing community have argued that multi-modal training might offer a path toward more human-like language learning (Bisk et al., 2020). Promisingly, recent years have seen the introduction of a profusion of multi-modal models and learning algorithms, mostly targeted at tasks that require reasoning about data in both modalities simultaneously (Radford et al., 2021; Wang et al.,

2022; Alayrac et al., 2022; Singh et al., 2022; Lu et al., 2022). However, the extent to which these models actually acquire more human-like learning efficiency of *language itself* has received limited attention.

In this paper, we investigate whether visual grounding can improve a key aspect of language understanding—*word learning*—in neural LMs. We study a variety of visually grounded models, including CLIP (Radford et al., 2021), GIT (Wang et al., 2022), and Flamingo (Alayrac et al., 2022), which represent drastically different ways of fusing vision and language data. While training these models, we carefully control, and systematically vary, both dataset size and the amount of within-language distributional information provided by word co-occurrence statistics. We then characterize these models with a suite of tasks designed to benchmark various facets of word knowledge, via prediction of syntactic categories, lexical relations, semantic features, semantic similarity, and human neural representations.

We find that grounded word learning indeed can yield better performance than the control language-only models in capturing word similarity and semantic features. However, this benefit is only observed when training on datasets that are small even by the standards of human learning. More surprisingly, it is observed only when limiting models’ exposure to word co-occurrence information within language: in some cases, models actually exhibit *reduced* sample efficiency when learning from images and captions rather than images accompanied by single words. Although further analyses show that visual and distributional information are partially complementary, none of the models we study can integrate both perceptual and textual contexts to yield improved word representations.

Our results suggest that current models and training procedures remain far from serving as models of visually grounded language acquisition. In these models, learning of some, but not all, aspects of semantics can be facilitated by grounding, but distributional information contained within language can override (and perhaps interfere with) visually grounded learning.

2 Background

Word learning in children. The present study investigates how visual grounding can help acquire knowledge of words and their meanings. Research

has shown that children can correctly understand or produce words at a very young age, possibly even before the age of one (Frank et al., 2017; Bergelson and Swingley, 2012; Frank et al., 2021). Bergelson and Swingley (2012) measured children’s attention to visual inputs when prompted with words and found that meanings of several common words are known by children from the age of 6 months onward. Using a different approach to measure word learning, Frank et al. (2017) collected the responses of parents to questionnaires about whether their children can correctly understand or produce words. Given the small amount of data required by children to exhibit these behaviors, word learning thus offers an appealing test-bed for comparative studies of LMs in a low-data regime.

Multi-modality learning. In recent years, multi-modality learning has seen significant advancements. For example, the CLIP model (Radford et al., 2021) is trained contrastively on 300M noisy (image, caption) pairs. It yields transferable visual representations as well as word representations that perform well on some tests of words similarity (Wolfe and Caliskan, 2022). GIT (Wang et al., 2022), by contrast, is a generative model, conditioning next-word predictions using visual inputs. It achieves state-of-the-art performance on multiple visual-language tasks, including image captioning and visual question answering. As a final example, Flamingo (Alayrac et al., 2022) uses visual representations to modulate attention in a transformer language model, obtaining similar results. As CLIP, GIT, and Flamingo all differ significantly from each other in how vision and language are fused, we test all of them in this work to explore what algorithm designs best benefit grounded language learning.

Grounded and ungrounded learning algorithms as models of language acquisition. Chang and Bergen (2022) investigate the word-acquisition trajectories in language-only models. However, their trajectories are computed only by measuring the change of model surprisal towards one word throughout training, which is less relevant to knowing word meanings. Huebner et al. (2021) and Warstadt et al. (2023) aim to improve language models trained on small datasets but focus more on grammar learning. Within grounded models, Wang et al. (2023) train image captioning models on first-person videos children receive (Sullivan et al., 2020) and claim that visual information helps predict words in context. Berger et al. (2022) and Portelance et al. (2023) also propose using

multi-modality algorithms to understand word acquisition. Berger et al. (2022) specifically study acquisition of word categories, while Portelance et al. (2023) focus on learning function words from simplified visual stimuli. Our experiments aim at a significantly more general model of lexical knowledge, via a diverse collection of model architectures, more naturalistic visual supervision, and tests of numerous facets of word knowledge.¹

3 Methods

3.1 Evaluation Benchmarks for Word Learning

Comparing the learning efficiency between models and humans requires measuring their learning abilities on the same benchmark. However, it is challenging to directly ask models whether they can understand or produce words correctly, as is typically done in studies of child word learning (Fenson et al., 2007; Frank et al., 2017). Recording “attention” patterns to visual stimuli is also implausible for language-only models, which prevents a fair comparison between grounded and ungrounded models. We therefore evaluate LMs on tasks that measure the information content of their representations and the quality of their predictions.

As described by Miller (1999), knowing the interrelations between words is critical to mastering different words. We use two benchmarks to characterize these interrelations: word similarity and lexical relation prediction benchmarks:

Word similarity benchmark. Word similarity benchmarks, such as WordSim-353 (Finkelstein et al., 2001), SimLex-999 (Hill et al., 2015), SimVerb-3500 (Gerz et al., 2016), and MEN (Bruni et al., 2012), assess how well models capture semantic similarities between a pair of words. We use the human judgments on word relatedness collected by Bruni et al. (2012) (see examples in Fig. 1B). For all benchmarks, we focus only on words typically acquired by children under the age of 10 (using information from Kuperman et al. (2012)), though we find this filtering barely changes the results. To extract similarity judgments from models, we extract word representations from a hidden

layer, compute all pairwise cosine similarities between these word representations, and then compute Spearman correlations between model and human similarity judgments. The best layer is selected according to these correlations.

Lexical relation prediction benchmark. Lexical relation prediction benchmarks like CogALex-V (Santus et al., 2016a), ROOT09 (Santus et al., 2016b), and BLESS (Baroni and Lenci, 2011) focus on how accurate models can predict nuanced relations (synonym, hyponym, etc.) between words. We use the CogALex-V dataset (Santus et al., 2016a), which contains more than 2500 pairs of words in both training and test sets (see examples in Fig. 1B). This benchmark tests the accuracy of predicting the lexical-relation categories of two words using the difference of their hidden representations from models. These pairs are categorized into five lexical-relation categories: *synonymy*, *antonymy*, *hypernymy*, *part-whole meronymy*, and *random*. For this and the following two benchmarks, the evaluation procedure then trains a linear probe on each layer to predict the targets from representations of words in a training set. The best layer is then selected by the accuracy on a validation set and its accuracy on a held-out test set is reported.

Understanding a word also entails understanding more basic aspects of its meaning: such as the fact that *apples* are edible or *elephants* are large. We measure this with an additional benchmark:

Semantic feature prediction benchmark. In LMs, this can be assessed using semantic norm prediction tasks (McRae et al., 2005; Buchanan et al., 2019; Chronis et al., 2023). We use the dataset constructed by Buchanan et al. (2019), who ask human annotators to write down features of the word (see examples in Fig. 1B).

Beyond word-level representations, the “contexts in which a word can be used to express a particular meaning are a critical component of word knowledge” (Miller, 1999). Our experiments assess this knowledge via part-of-speech prediction and context-based word-understanding tasks:

Part-Of-Speech prediction benchmark. This benchmark evaluates the accuracy of predicting corpus-based (Davies, 2010) part-of-Speech (POS) tags for single words. Each word is labeled with its most frequent part of speech in the corpus (see examples in Fig. 1B). All words contained in the aforementioned three benchmarks are included.

Context-based word-understanding benchmark. This benchmark evaluates whether models

¹Although children clearly leverage other modalities to augment their language learning (Seidl et al., 2023), visual information may not be strictly necessary for learning word meanings. A large body of work shows that congenitally blind adults are still able to acquire “semantically-rich representations of visual words” (Campbell and Bergelson, 2022; Bedny et al., 2019; Minervino et al., 2018).

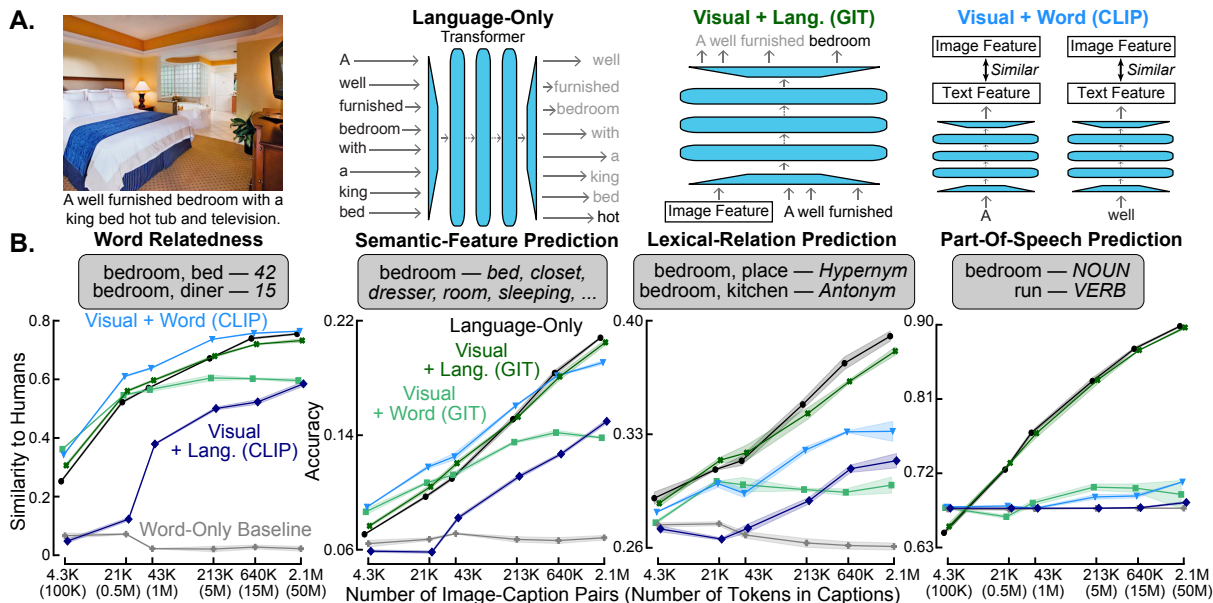


Figure 1: **In learning word meanings, visual information provides some help in low-data regime but only has limited additional utility relative to cross-word distributional information.** **A.** Pretraining schema for Language-Only, Visual + Word, and Visual + Language models. From left to right: an example image-caption pair; Language-Only models are trained on a next-token prediction objective; Visual + Language (GIT) models include the image features in the context to predict the next token; Visual + Word (CLIP) models optimize its text encoder to generate features that are similar to the corresponding image feature and dissimilar to other image features. **B.** Results on word-learning benchmarks for the Language-Only (●), Visual + Word (CLIP) (▼), Visual + Language (CLIP) (◆), Visual + Word (GIT) (■), Visual + Language (GIT) (✕), and Word-Only Baseline (⊕) models. The word-relatedness benchmark computes correlations between hidden representations of two words and compares these correlations to human ratings of how related these words are. The other three benchmarks evaluate the accuracy of predicting the corresponding features of words (or word pairs) from the hidden representations of words (or the differences between word representations). The X-axis is in the log scale. The width of lines in these plots represents the standard error of means across four models initialized from different random seeds.

can identify typical contexts in which words should appear. To create this benchmark, we first select real sentences containing each target word from `sentence.yourdictionary.com`, then minimally modify these sentences so that they are no longer appropriate environments for the target word. For example, if we have a target word *shoes* occurring in a sentence *Wear your shoes*, we might alter the containing sentence to read *Eat your shoes*, a significantly lower-probability environment for the target word. This is achieved by using a large-scale, pre-trained large LM (OPT-6.7B; Zhang et al., 2022) to select the best modification from all possibilities to have the modified sentence less likely but still grammatical. By repeating this process, we obtain 280K sentence pairs for nouns, 128K for verbs, and 72K for adjectives, yielding three sub-benchmarks. To evaluate models on these benchmarks, we measure the fraction of sentence pairs in which they assign a higher probability to the original sentence compared to the modified one.

Another method to evaluate how well models represent context is to compare their representations to neural data. Thus, our final benchmark uses models’ representations of sentences to predict the response of the language network in human brains:

Brain-Response prediction benchmark. We use the brain response dataset collected by Pereira et al. (2018), which is also used by Schrimpf et al. (2021). We follow the fitting procedure proposed by Kauf et al. (2023). A linear regression model is trained to predict the brain response to one sentence using its hidden representations. This model is then evaluated for its correlation between prediction and ground truth on the test set.

We show the results of pretrained LMs on these benchmarks in Appendix Fig. 6 and 7 as references.

3.2 Model Training

Dataset. We sample image-caption pairs from the Conceptual-Captions-12M (Changpinyo et al.,

2021) dataset (see Fig. 1A). Only images that were still valid as of August 2022 are used for training.

Language-only models. These models are trained on a next-token prediction objective using image captions alone, as in other neural language models (see Fig. 1A). In all experiments, we use a variant of the GPT-2 model architecture (Radford et al., 2019) with six layers. Other architectural parameters are the same as GPT-2 (see Appendix A.1). We also vary the number of layers and find it barely influences the results (see Appendix 8).

Visual encoders and image features. In visually grounded models (described below), we begin with pre-trained visual representations (trained without paired text-image data). These are taken from a Vision Transformer (ViT; Dosovitskiy et al., 2020) pretrained on unlabeled ImageNet images using DINO (Caron et al., 2021), a state-of-the-art unsupervised learning algorithm. We use DINO-ViT also because earlier work (Zhuang et al., 2021; Konkle and Alvarez, 2022; Zhuang et al., 2022) showed that these unsupervised models share similarities with the human visual cortex. We use the representations of the [CLS] token at the last hidden layer as image features.

Visual + language models (GIT). GIT (Wang et al., 2022) treats the image features as part of the context and trains the models to predict the next words (see Fig. 1A).

Visual + language models (CLIP). CLIP (Radford et al., 2021) optimizes its text encoder to maximize the correlation between the representations of matching pairs (an image and its caption) while minimizing the correlation between non-matching pairs. In this study, we adopt the objective function proposed by Radford et al. (2021) to train language models, utilizing visual features precomputed from unsupervised visual networks. While we refer to these language models trained in this manner as “CLIP” models, it is important to note that they are distinct from the pretrained CLIP models developed by Radford et al. (2021). This is because the visual features are from the unsupervised pre-trained models, the weights of the language module in our CLIP models are trained from scratch, and this module has fewer layers (six versus twelve).

Visual + single-word models (CLIP). To explore the isolated influence of visual information on word learning, we develop and test a single-word labeling method on images. These models, named Visual + Word models, are trained by first extracting all words from one caption and then treating

each of them separately as a label for the corresponding image. This single-word labeling method guarantees that word representations are learned exclusively from visual input, without incorporating (or receiving interference from) distributional information carried by co-occurring words. Compared to the whole-sentence labeling method, this method ablates both the syntactic information carried by the order of words and the co-occurring statistics. The same CLIP objective function is then used to train Visual + Word models (CLIP).

Visual + Word Models (GIT). Similarly, single-word labels and the GIT objective function are used to train these models.

Word-Only Baseline Models. These (trivial) models are optimized by predicting the single-word labels from just the [CLS] token inserted before the word. Here, the learning objective contains only information about word frequency, and no information about meaning or syntactic function.

Training Details. To explore how performance changes with respect to the dataset sizes, we vary the number of image-caption pairs from 4.3K to 2.1M (corresponding to 100K to 50M tokens or 64K to 32M words in captions). We then train models for multiple epochs, with training time determined independently for each dataset scale by the loss on the evaluation set (small datasets typically require more training than large datasets).

The code for training and evaluating can be found at <https://github.com/EvLab-MIT/LexiContrastiveGrd>. More details about training and evaluation can be found in Appendix A.1.

4 Results

4.1 Visual + Word models learn more efficiently than Language-Only models, but only on some benchmarks and with small datasets.

We first show the results of CLIP, GIT, and Language-Only models. These results show that when only a small amount of data is available, Visual + Word models are more efficient than Language-Only models in learning to relate words and predict semantic features (see the left two panels in Fig. 1B). CLIP achieves significantly higher efficiency than GIT in low-data regimes with single-word labels. However, Visual + Word models are worse than Language-Only models in identifying lexical relations between words and predicting POS tags of words (see the two right panels in

Fig. 1B). In fact, Visual + Word models barely outperform Word-Only Baseline models in the POS benchmark. Even on the other two benchmarks where visual information delivers notable benefits, Language-Only models achieve comparable or better performance than Visual + Word models when learning from 50M tokens. To confirm that the results of Language-Only models are robust, we experimented with additional architectural and algorithmic variants and found similar results (see Appendix Fig. 8). The lexical-relation results are also reproduced on two more datasets (see Appendix Fig. 9).

Given that visual information is useful for some aspects of word learning, we might then expect that visual and cross-word distributional information might be combined to yield even better learning efficiency. However, the typical way to combine them, implemented as Visual + Language models, fails to show benefits over Language-Only models. The Visual + Language (CLIP) models perform significantly worse than the Visual + Word (CLIP) models, indicating that the CLIP architecture is particularly inefficient in associating visual information to single words when full captions are present. As for the GIT architecture, although the Visual + Language (GIT) models are better than Visual + Word (GIT) models on most conditions, their performance trajectories seem to follow those of Language-Only models closely, and the improvement is minor. This limited benefit from combining visual and cross-word distributional information indicates that these two information sources compete with each other, and new learning mechanisms are needed to resolve this competition.

4.2 Visual input helps learn concrete words.

The benchmark results illustrate that Visual + Word models diverge from Language-Only models; however, how this difference manifests per-word remains unclear. To better understand this difference, we first analyze three models with similarly strong performance on the word-relatedness benchmark: the Visual + Word (CLIP), the Visual + Language (GIT), and the Language-Only models trained with 2.1M image-caption pairs. By correlating model judgments with *each other*, rather than human judgments, we find that the Visual + Word (CLIP) and Language-Only models significantly differ in how they relate words, while the Visual + Language (GIT) model yields almost the same judgments as the Language-Only model (see Appendix A.2 for

details). This shows that visual information can yield a different and useful representation, and suggests that GIT learns word representations predominantly from cross-word distributional information, not visual information, when both are available.

To further analyze differences at the word level, we then develop a human-likeness measure for a pair of words by comparing the judgments of humans and models (see Appendix A.2 for details). This measure is sorted to get a normalized “rank in human-likeness” measure for each pair of words, where a larger value means more human-like. This measure is developed to reflect the model-to-human comparison process in the word-relatedness benchmark, where the Spearman correlation between model to human relatedness ratings is computed. Treating this measure as the dependent variable, we run linear regressions using different word features as independent variables (Tuckute et al., 2022): concreteness (Brysbaert et al., 2014), age of acquisition (Kuperman et al., 2012), Zipf lexical frequency (Van Heuven et al., 2014), and prevalence (Brysbaert et al., 2019). We find that the concreteness value best predicts the rank in human-likeness for the Visual + Word (CLIP) model, and clearly differentiates this model and the Language-Only model, as it is uncorrelated with the rank measure from the language-only model (see Fig. 2A and Appendix Fig. 10 to 12 for other features). This result shows one clear difference between Visual + Word and Language-Only models: grounded learning relates concrete words in a more human-like way than abstract words.

Since the dataset used in the word-relatedness benchmark contains mostly nouns and some adjectives (mostly color names) (Bruni et al., 2012), we extend this benchmark to other datasets to explore how the results change concerning word types. In another word similarity dataset focused exclusively on verbs (SimVerb-3500; Gerz et al., 2016), we find that Visual + Word models become significantly worse than Language-Only models (see the left panel of Fig. 2B). This is likely because image features from an unsupervised learning algorithm trained only on static images may contain very limited information for actions, which are better represented by dynamics in videos. In addition to verbs, we also find that the color words are differently related by visual models compared to human judgments (see the right panel of Fig. 2B). One potential explanation is that the human annotators view these color words as instances of a high-level

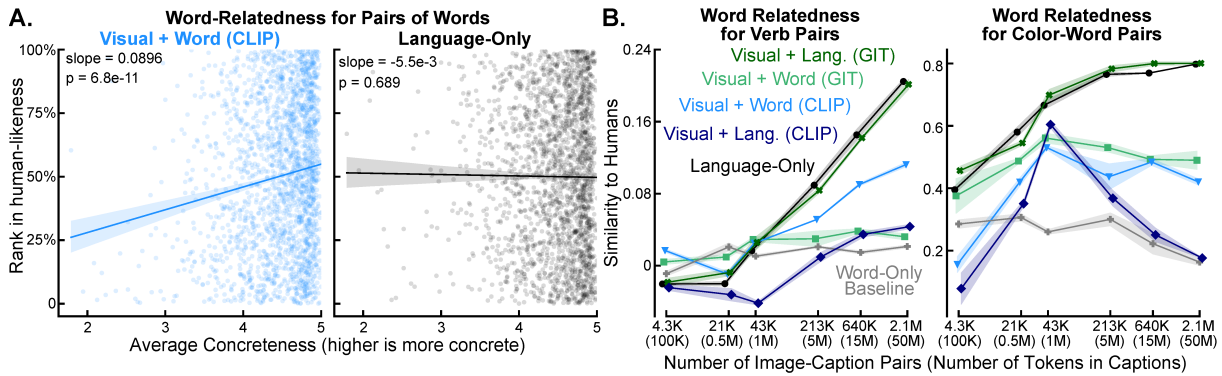


Figure 2: **Visual + Word and Language-Only models produce distinct representations.** **A.** Scatter plots for the word-relatedness benchmark. Each dot represents one pair of words. Its y-value represents the relative rank after sorting the word pairs using the difference between the human relatedness judgment and the correlation of model representations. A higher y-value means more human-like. Linear regression lines are plotted on the figure with the 95% confidence interval. **B.** The results of word-relatedness benchmarks on another dataset containing only verb words (SimVerb-3500, left) and the subset of color-word pairs in the previously used dataset. The marker-model mapping is the same as that in Figure 1.

word category, while Visual + Word models are over-dominated by the visual differences of color words. To confirm that these results are robust to the choice of word-relatedness datasets, we re-evaluate all models on SimLex-999 and find very similar results (see Appendix Fig. 13), meaning Visual + Word models are also better at relating nouns but worse on verbs than Language-Only models. Together, these additional word-relatedness results illustrate that learning only from static-image visual information cannot capture the full picture of human-relatedness judgments.

Finally, we extend our analysis to the semantic-feature prediction benchmark. Similarly, we find that Visual + Word models predict the features of concrete words more accurately than Language-Only models (see Appendix Fig. 14).

4.3 Narrower textual contexts in grounded models yield limited benefit.

Visual + Word and Visual + Language represent two extreme conditions about how much distributional information is included. To explore the role of intermediate forms of distributional information, we augment visual information with some, but not all, context around the words of interest (see the top part of Fig. 3). This leads to Visual + Context models and their ungrounded counterparts, Context-Only models. After testing these new models, we find that CLIP and GIT still fail to combine visual and distributional information to outperform Language-Only models. CLIP continues to illustrate a negative influence from incorporating more

context (see Fig. 3). Visual + Context (GIT) models only outperform Context-Only models on small dataset scales. These results underscore the fact that new multi-modal models are needed to integrate both information sources effectively.

4.4 Flamingo achieves worse results than CLIP and GIT.

To further evaluate the robustness of these results to choices of model architecture, we repeat a subset of our analysis in Flamingo models (Alayrac et al., 2022). This model architecture first extracts a summary vector from the image features and then modulates language representations using this vector through a cross-attention mechanism (see Appendix A.3 for details).

We find that these models underperform CLIP and GIT in leveraging visual information. On all benchmarks except the POS benchmark, Flamingo models perform no better than Language-Only models. Flamingo models also fail to benefit from more context than what is used in Visual + Context models. This might be why Visual + Language (Flamingo) models are more efficient learning in the POS benchmark, as Context-Only models also show similarly higher efficiency than Language-Only models on this benchmark. To confirm that this result is robust, we vary an important hyperparameter in Flamingo but find it barely influences the performance (see Appendix Fig. 15).

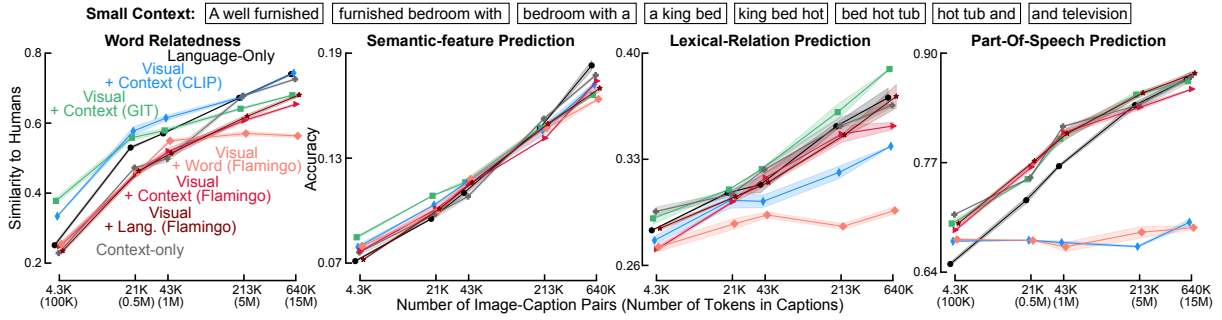


Figure 3: **Adding more context to Visual + Word models, or changing the model to Flamingo, offers little benefit.** The top row shows some of the small-context labels generated from the example caption in Fig. 1. Two models with different random seeds are trained in each condition. The results are from the Language-Only (●), Visual + Language (Flamingo) (★), Visual + Context (CLIP) (◆), Visual + Context (GIT) (■), Visual + Context (Flamingo) (▶), Visual + Word (Flamingo) (◆), and Context-Only (⊕) models.

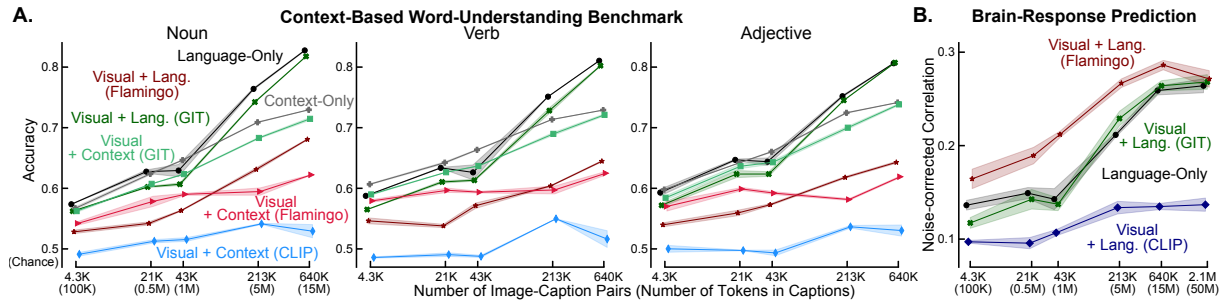


Figure 4: **Grounded models mostly underperform ungrounded models on context-based word-understanding and brain-response prediction benchmarks.** **A.** Performance of grounded and ungrounded models trained with small contexts (three consecutive words) or full captions as image labels on the context-based word-understanding benchmark. We present the results from the Language-Only (●), Visual + Language (GIT) (×), Visual + Language (Flamingo) (★), Visual + Context (CLIP) (◆), Visual + Context (GIT) (■), Visual + Context (Flamingo) (▶), and Context-Only (⊕) models. **B.** Brain-response fitting results for language-only and Visual + Language models. Four models with different random seeds are trained in each condition.

4.5 Visual information is unhelpful on sentence processing benchmarks.

Because the four benchmarks above test word representations outside the context of sentence-level language understanding, we additionally evaluate the context-based word understanding and brain-response benchmarks discussed in Section 3.

All Visual + Language and Language-Only models are evaluated on the context-based word understanding benchmark. To understand how the local context of words influences this benchmark’s performance, we also evaluate all Visual + Context models. Because these models are trained with at most three words (see Appendix 4.3), we split one sentence into multiple three-word segments and send these segments to context-based models to compute their probabilities, where the Visual + Context (CLIP) models additionally receive an averaged image feature for the center word and use its embedding matching score as a proxy

of the probability. The results of this benchmark show that grounded models underperform their ungrounded counterparts. CLIP and Flamingo are worse than the Language-Only models. Only GIT models reach comparable results to their counterparts, likely because their word representations are almost fully determined by text (see Sec. 4.2).

As for the brain-response prediction benchmark, we only evaluate the Visual + Language and Language-Only models. As shown in Fig 4B, only CLIP shows significantly lower efficiency on this benchmark. All models produce higher prediction correlations when being trained on more data. Flamingo interestingly yields better results on small scales, which might be related to its higher performance on the POS benchmark (see Appendix Fig. 3). But all models except CLIP reach similar results when trained on 2.1M image-caption pairs. To summarize, these two sentence-level benchmarks show visual information is unhelpful

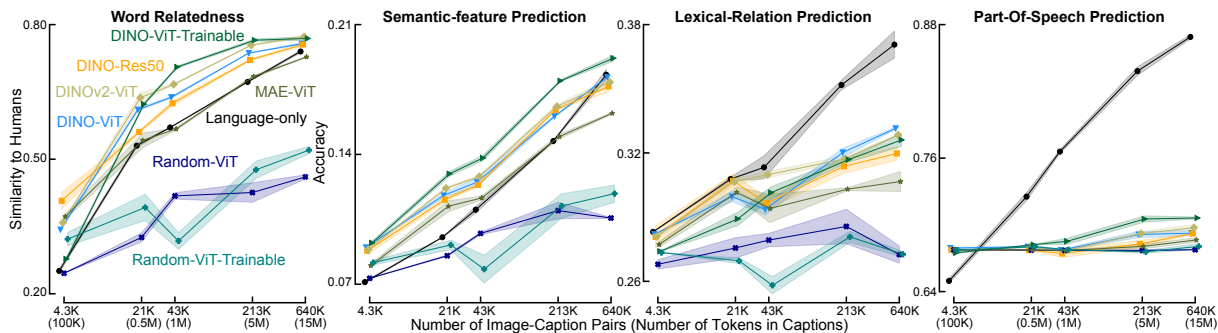


Figure 5: **Image representations have a small influence on word learning.** We show the results for the DINO-ViT (▼), DINOv2-ViT (◆), DINO-Res50 (■), DINO-ViT-Trainable (►), MAE-ViT (★), Language-Only (●), Random-ViT (✖), and Random-ViT-Trainable (⊕) models. The Visual + Word (CLIP) training regime is used for these experiments. The DINO-ViT model represents the Visual + Word (CLIP) models in previous figures. Two models with different seeds are trained in each condition.

for jointly understanding words and their context.

4.6 Different visual encoders give similar results.

The visual information used in current models is computed from a ViT pretrained by DINO, and this ViT is not finetuned with language models. We first try finetuning the visual encoders and find that this significantly improves performance on word-relatedness and semantic-feature prediction benchmarks, though it saturates on larger datasets (see Fig. 5). This result indicates the potential of jointly training vision and language models. We then vary the pretraining algorithms with weights fixed after pretraining. Three more pretraining algorithms are tested, including a fundamentally different unsupervised learning algorithm (Masked Auto-Encoder; He et al., 2021), an improved version of the same algorithm (DINOv2; Oquab et al., 2023), and a random initialization (see Appendix A.4). We find that DINOv2 yields slightly better results, while MAE is significantly worse. The randomly initialized ViT yields non-trivial results but underperforms models with pretrained visual encoders. Changing the architecture of the visual encoder also barely influences the results (see DINO-Res50).

5 Conclusion and Discussion

We have shown that language learning grounded in visual information helps current neural models acquire some aspects of word knowledge more efficiently than they can from text alone. Grounded models also learn qualitatively different representations from language-only models. But with reasonably large training data, ungrounded models become comparable to or even outperform grounded

models. Even in low-data regimes, this benefit from visual information requires limited exposure to distributional information, as current learning algorithms struggle to integrate visual and distributional information.

The strong performance of Visual + Word (CLIP) models in low-data regimes provides a compelling hypothesis about how children acquire language: they may also learn through mapping each visual input to single words that are “loosely” tied to the input. However, more work is needed to test this hypothesis through evaluating the models on the benchmarks or experiments where data from children are also available.

Our results show that visual information can boost the learning of word meanings according to multiple measures. Future grounded LMs might thus serve as candidate models of how visual input can be leveraged to acquire language.

Limitations

One limitation of the present study is that the visual information used to augment language learning only contains representations of static images. Such images likely represent only a very small subset of all the visual information available to (sighted) language learners, who have access to the rich dynamics inherent in streams of visual inputs instead of independent images. Human language learners also perceive simultaneously from many other modalities like smell, taste, and touch. Finally, more work is needed to validate that these algorithms learn high-quality word representations from the same distribution of visual inputs that children receive (e.g. Sullivan et al., 2020).

Another limitation is that we have only evaluated

three multi-modality learning algorithms (CLIP, GIT, and Flamingo). Although we believe that our results should generalize to many more models since the algorithms evaluated by us represent very diverse methodologies for merging visual and language information, it is possible that there are other algorithms that significantly differ from CLIP, GIT, and Flamingo, and thus will require more tests on our benchmarks.

Ethical Considerations

We do not anticipate any ethical concerns with this work.

Acknowledgments

Chengxu Zhuang is supported by the MIT ICoN Postdoctoral Fellowship. This research is part of the Language Mission, supported by the MIT Quest for Intelligence.

References

- Jean-Baptiste Alayrac, Jeff Donahue, Pauline Luc, Antoine Miech, Iain Barr, Yana Hasson, Karel Lenc, Arthur Mensch, Katherine Millican, Malcolm Reynolds, et al. 2022. Flamingo: a visual language model for few-shot learning. *Advances in Neural Information Processing Systems*, 35:23716–23736.
- Suhas Arehalli and Tal Linzen. 2020. Neural language models capture some, but not all, agreement attraction effects.
- Marco Baroni and Alessandro Lenci. 2011. How we blessed distributional semantic evaluation. In *Proceedings of the GEMS 2011 Workshop on GEometrical Models of Natural Language Semantics*, pages 1–10.
- Marina Bedny, Jorie Koster-Hale, Giulia Elli, Lindsay Yazzolino, and Rebecca Saxe. 2019. There’s more to “sparkle” than meets the eye: Knowledge of vision and light verbs among congenitally blind and sighted individuals. *Cognition*, 189:105–115.
- Elika Bergelson and Richard N Aslin. 2017. Nature and origins of the lexicon in 6-mo-olds. *Proceedings of the National Academy of Sciences*, 114(49):12916–12921.
- Elika Bergelson and Daniel Swingley. 2012. At 6–9 months, human infants know the meanings of many common nouns. *Proceedings of the National Academy of Sciences*, 109(9):3253–3258.
- Uri Berger, Gabriel Stanovsky, Omri Abend, and Lea Frermann. 2022. A computational acquisition model for multimodal word categorization. *arXiv preprint arXiv:2205.05974*.
- Yonatan Bisk, Ari Holtzman, Jesse Thomason, Jacob Andreas, Yoshua Bengio, Joyce Chai, Mirella Lapata, Angeliki Lazaridou, Jonathan May, Aleksandr Nisnevich, et al. 2020. Experience grounds language. *arXiv preprint arXiv:2004.10151*.
- Tom Brown, Benjamin Mann, Nick Ryder, Melanie Subbiah, Jared D Kaplan, Prafulla Dhariwal, Arvind Neelakantan, Pranav Shyam, Girish Sastry, Amanda Askell, et al. 2020. Language models are few-shot learners. *Advances in neural information processing systems*, 33:1877–1901.
- Elia Bruni, Gemma Boleda, Marco Baroni, and Nam-Khanh Tran. 2012. Distributional semantics in technicolor. In *Proceedings of the 50th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 136–145.
- Marc Brysbaert, Paweł Mandera, Samantha F McCormick, and Emmanuel Keuleers. 2019. Word prevalence norms for 62,000 english lemmas. *Behavior research methods*, 51:467–479.
- Marc Brysbaert, Amy Beth Warriner, and Victor Kuperman. 2014. Concreteness ratings for 40 thousand generally known english word lemmas. *Behavior research methods*, 46:904–911.
- Erin M Buchanan, Kathrene D Valentine, and Nicholas P Maxwell. 2019. English semantic feature production norms: An extended database of 4436 concepts. *Behavior Research Methods*, 51:1849–1863.
- Erin E Campbell and Elika Bergelson. 2022. Making sense of sensory language: Acquisition of sensory knowledge by individuals with congenital sensory impairments. *Neuropsychologia*, 174:108320.
- Mathilde Caron, Hugo Touvron, Ishan Misra, Hervé Jégou, Julien Mairal, Piotr Bojanowski, and Armand Joulin. 2021. Emerging properties in self-supervised vision transformers. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pages 9650–9660.
- Charlotte Caucheteux and Jean-Rémi King. 2022. Brains and algorithms partially converge in natural language processing. *Communications biology*, 5(1):134.
- Tyler A Chang and Benjamin K Bergen. 2022. Word acquisition in neural language models. *Transactions of the Association for Computational Linguistics*, 10:1–16.
- Soravit Changpinyo, Piyush Sharma, Nan Ding, and Radu Soricut. 2021. Conceptual 12m: Pushing web-scale image-text pre-training to recognize long-tail visual concepts. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 3558–3568.

- Gabriella Chronis, Kyle Mahowald, and Katrin Erk. 2023. A method for studying semantic construal in grammatical constructions with interpretable contextual embedding spaces. *arXiv preprint arXiv:2305.18598*.
- Elizabeth M Clerkin, Elizabeth Hart, James M Rehg, Chen Yu, and Linda B Smith. 2017. Real-world visual statistics and infants’ first-learned object names. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372(1711):20160055.
- Elizabeth M Clerkin and Linda B Smith. 2022. Real-world statistics at two timescales and a mechanism for infant learning of object names. *Proceedings of the National Academy of Sciences*, 119(18):e2123239119.
- Mark Davies. 2010. The corpus of contemporary american english as the first reliable monitor corpus of english. *Literary and linguistic computing*, 25(4):447–464.
- Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. 2018. Bert: Pre-training of deep bidirectional transformers for language understanding. *arXiv preprint arXiv:1810.04805*.
- Alexey Dosovitskiy, Lucas Beyer, Alexander Kolesnikov, Dirk Weissenborn, Xiaohua Zhai, Thomas Unterthiner, Mostafa Dehghani, Matthias Minderer, Georg Heigold, Sylvain Gelly, et al. 2020. An image is worth 16x16 words: Transformers for image recognition at scale. *arXiv preprint arXiv:2010.11929*.
- Larry Fenson et al. 2007. Macarthur-bates communicative development inventories.
- Lev Finkelstein, Evgeniy Gabrilovich, Yossi Matias, Ehud Rivlin, Zach Solan, Gadi Wolfman, and Eytan Ruppín. 2001. Placing search in context: The concept revisited. In *Proceedings of the 10th international conference on World Wide Web*, pages 406–414.
- Michael C Frank, Mika Braginsky, Daniel Yurovsky, and Virginia A Marchman. 2017. Wordbank: An open repository for developmental vocabulary data. *Journal of child language*, 44(3):677–694.
- Michael C Frank, Mika Braginsky, Daniel Yurovsky, and Virginia A Marchman. 2021. *Variability and consistency in early language learning: The Wordbank project*. MIT Press.
- Daniela Gerz, Ivan Vulić, Felix Hill, Roi Reichart, and Anna Korhonen. 2016. Simverb-3500: A large-scale evaluation set of verb similarity. *arXiv preprint arXiv:1608.00869*.
- Ariel Goldstein, Zaid Zada, Eliav Buchnik, Mariano Schain, Amy Price, Bobbi Aubrey, Samuel A Nastase, Amir Feder, Dotan Emanuel, Alon Cohen, et al. 2022. Shared computational principles for language processing in humans and deep language models. *Nature neuroscience*, 25(3):369–380.
- Kaiming He, Xinlei Chen, Saining Xie, Yanghao Li, Piotr Dollár, and Ross Girshick. 2021. Masked autoencoders are scalable vision learners. *arXiv preprint arXiv:2111.06377*.
- Felix Hill, Roi Reichart, and Anna Korhonen. 2015. Simlex-999: Evaluating semantic models with (genuine) similarity estimation. *Computational Linguistics*, 41(4):665–695.
- Philip A Huebner, Elior Sulem, Fisher Cynthia, and Dan Roth. 2021. Babyberta: Learning more grammar with small-scale child-directed language. In *Proceedings of the 25th conference on computational natural language learning*, pages 624–646.
- Carina Kauf, Greta Tuckute, Roger P Levy, Jacob Andreas, and Evelina Fedorenko. 2023. Lexical semantic content, not syntactic structure, is the main contributor to brain similarity of fmri responses in the language network. *Neurobiology of Language*, pages 1–81.
- Talia Konkle and George A Alvarez. 2022. A self-supervised domain-general learning framework for human ventral stream representation. *Nature communications*, 13(1):491.
- Victor Kuperman, Hans Stadthagen-Gonzalez, and Marc Brysbaert. 2012. Age-of-acquisition ratings for 30,000 english words. *Behavior research methods*, 44:978–990.
- Yinhan Liu, Myle Ott, Naman Goyal, Jingfei Du, Mandar Joshi, Danqi Chen, Omer Levy, Mike Lewis, Luke Zettlemoyer, and Veselin Stoyanov. 2019. Roberta: A robustly optimized bert pretraining approach. *arXiv preprint arXiv:1907.11692*.
- Ilya Loshchilov and Frank Hutter. 2017. Decoupled weight decay regularization. *arXiv preprint arXiv:1711.05101*.
- Jiasen Lu, Christopher Clark, Rowan Zellers, Roozbeh Mottaghi, and Aniruddha Kembhavi. 2022. Unified-io: A unified model for vision, language, and multimodal tasks. *arXiv preprint arXiv:2206.08916*.
- Ken McRae, George S Cree, Mark S Seidenberg, and Chris McNorgan. 2005. Semantic feature production norms for a large set of living and nonliving things. *Behavior research methods*, 37(4):547–559.
- George A Miller. 1999. On knowing a word. *Annual review of psychology*, 50(1):1–19.
- Ricardo A Minervino, Alejandra Martín, L Micaela Tavernini, and Máximo Trench. 2018. The understanding of visual metaphors by the congenitally blind. *Frontiers in psychology*, 9:1242.
- Maxime Oquab, Timothée Darcet, Théo Moutakanni, Huy Vo, Marc Szafraniec, Vasil Khalidov, Pierre Fernandez, Daniel Haziza, Francisco Massa, Alaaeldin El-Nouby, et al. 2023. Dinov2: Learning robust visual features without supervision. *arXiv preprint arXiv:2304.07193*.

- Francisco Pereira, Bin Lou, Brianna Pritchett, Samuel Ritter, Samuel J Gershman, Nancy Kanwisher, Matthew Botvinick, and Evelina Fedorenko. 2018. Toward a universal decoder of linguistic meaning from brain activation. *Nature communications*, 9(1):963.
- Eva Portelance, Michael C Frank, and Dan Jurafsky. 2023. Learning the meanings of function words from grounded language using a visual question answering model. *arXiv preprint arXiv:2308.08628*.
- Peng Qi, Yuhao Zhang, Yuhui Zhang, Jason Bolton, and Christopher D Manning. 2020. Stanza: A python natural language processing toolkit for many human languages. *arXiv preprint arXiv:2003.07082*.
- Alec Radford, Jong Wook Kim, Chris Hallacy, Aditya Ramesh, Gabriel Goh, Sandhini Agarwal, Girish Sastry, Amanda Askell, Pamela Mishkin, Jack Clark, et al. 2021. Learning transferable visual models from natural language supervision. In *International conference on machine learning*, pages 8748–8763. PMLR.
- Alec Radford, Jeffrey Wu, Rewon Child, David Luan, Dario Amodei, Ilya Sutskever, et al. 2019. Language models are unsupervised multitask learners. *OpenAI blog*, 1(8):9.
- Enrico Santus, Anna Gladkova, Stefan Evert, and Alessandro Lenci. 2016a. The cogalex-v shared task on the corpus-based identification of semantic relations. In *Proceedings of the 5th Workshop on Cognitive Aspects of the Lexicon (CogALex-V)*, pages 69–79.
- Enrico Santus, Alessandro Lenci, Tin-Shing Chiu, Qin Lu, and Chu-Ren Huang. 2016b. Nine features in a random forest to learn taxonomical semantic relations. *arXiv preprint arXiv:1603.08702*.
- Martin Schrimpf, Idan Asher Blank, Greta Tuckute, Carina Kauf, Eghbal A Hosseini, Nancy Kanwisher, Joshua B Tenenbaum, and Evelina Fedorenko. 2021. The neural architecture of language: Integrative modeling converges on predictive processing. *Proceedings of the National Academy of Sciences*, 118(45):e2105646118.
- Sara E Schroer and Chen Yu. 2023. Looking is not enough: Multimodal attention supports the real-time learning of new words. *Developmental Science*, 26(2):e13290.
- Amanda H Seidl, Michelle Indarjit, and Arielle Borovsky. 2023. Touch to learn: Multisensory input supports word learning and processing. *Developmental Science*, page e13419.
- Amanpreet Singh, Ronghang Hu, Vedanuj Goswami, Guillaume Couairon, Wojciech Galuba, Marcus Rohrbach, and Douwe Kiela. 2022. Flava: A foundational language and vision alignment model. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pages 15638–15650.
- Jess Sullivan, Michelle Mei, Amy Perfors, Erica H Wojcik, and Michael C Frank. 2020. Saycam: A large, longitudinal audiovisual dataset recorded from the infant’s perspective.
- Greta Tuckute, Aalok Sathe, Mingye Wang, Harley Yoder, Cory Shain, and Evelina Fedorenko. 2022. Sentspace: Large-scale benchmarking and evaluation of text using cognitively motivated lexical, syntactic, and semantic features. In *Proceedings of the 2022 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies: System Demonstrations*, pages 99–113.
- Asahi Ushio, Jose Camacho-Collados, and Steven Schockaert. 2021. Distilling relation embeddings from pre-trained language models. *arXiv preprint arXiv:2110.15705*.
- Walter JB Van Heuven, Pawel Mandera, Emmanuel Keuleers, and Marc Brysbaert. 2014. Subtlex-uk: A new and improved word frequency database for british english. *Quarterly journal of experimental psychology*, 67(6):1176–1190.
- Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. 2017. Attention is all you need. *Advances in neural information processing systems*, 30.
- Jianfeng Wang, Zhengyuan Yang, Xiaowei Hu, Linjie Li, Kevin Lin, Zhe Gan, Zicheng Liu, Ce Liu, and Lijuan Wang. 2022. Git: A generative image-to-text transformer for vision and language. *arXiv preprint arXiv:2205.14100*.
- Wentao Wang, Wai Keen Vong, Najoung Kim, and Brenden M Lake. 2023. Finding structure in one child’s linguistic experience. *Cognitive science*, 47(6):e13305.
- Alex Warstadt and Samuel R Bowman. 2022. What artificial neural networks can tell us about human language acquisition. *Algebraic Structures in Natural Language*, pages 17–60.
- Alex Warstadt, Leshem Choshen, Aaron Mueller, Adina Williams, Ethan Wilcox, and Chengxu Zhuang. 2023. Call for papers—the babylm challenge: Sample-efficient pretraining on a developmentally plausible corpus. *arXiv preprint arXiv:2301.11796*.
- Kelsey L West and Jana M Iverson. 2017. Language learning is hands-on: Exploring links between infants’ object manipulation and verbal input. *Cognitive Development*, 43:190–200.
- Ethan Gotlieb Wilcox, Jon Gauthier, Jennifer Hu, Peng Qian, and Roger Levy. 2020. On the predictive power of neural language models for human real-time comprehension behavior. *arXiv preprint arXiv:2006.01912*.

Thomas Wolf, Lysandre Debut, Victor Sanh, Julien Chaumond, Clement Delangue, Anthony Moi, Pierric Cistac, Tim Rault, Rémi Louf, Morgan Funtowicz, et al. 2020. Transformers: State-of-the-art natural language processing. In *Proceedings of the 2020 conference on empirical methods in natural language processing: system demonstrations*, pages 38–45.

Robert Wolfe and Aylin Caliskan. 2022. Contrastive visual semantic pretraining magnifies the semantics of natural language representations. *arXiv preprint arXiv:2203.07511*.

Susan Zhang, Stephen Roller, Naman Goyal, Mikel Artetxe, Moya Chen, Shuohui Chen, Christopher Dewan, Mona Diab, Xian Li, Xi Victoria Lin, et al. 2022. Opt: Open pre-trained transformer language models. *arXiv preprint arXiv:2205.01068*.

Yian Zhang, Alex Warstadt, Haau-Sing Li, and Samuel R Bowman. 2020. When do you need billions of words of pretraining data? *arXiv preprint arXiv:2011.04946*.

Chengxu Zhuang, Ziyu Xiang, Yoon Bai, Xiaoxuan Jia, Nicholas Turk-Browne, Kenneth Norman, James J DiCarlo, and Dan Yamins. 2022. How well do unsupervised learning algorithms model human real-time and life-long learning? *Advances in Neural Information Processing Systems*, 35:22628–22642.

Chengxu Zhuang, Siming Yan, Aran Nayebi, Martin Schrimpf, Michael C Frank, James J DiCarlo, and Daniel LK Yamins. 2021. Unsupervised neural network models of the ventral visual stream. *Proceedings of the National Academy of Sciences*, 118(3).

A Methods

A.1 Training and Evaluating Details

Network Architecture and Tokenizer. We use a six-layer Transformer network (Vaswani et al., 2017) for all models. The dimension for its per-token hidden representations is 768. There are 12 attention heads in each layer. The dimension of the intermediate layer in the post-attention feedforward layers is 3072. The tokenizer is from BERT (Devlin et al., 2018), whose vocabulary size is 30,522. The weights of the word-embedding layer are tied with the weights in the final output layer, which we find is critical to getting good performance for grounded models. As for the visual encoder, the features are extracted using the pretrained weights shared on Huggingface (Wolf et al., 2020), whose model ID is facebook/dino-vitb16.

Optimization Details. All models are then trained on the image-caption datasets for multiple epochs. The number of training epochs depends on the dataset sizes and is determined by monitoring loss values on the evaluation dataset. For all

models except CLIP, we utilize a batch size of 128; CLIP is trained with a larger batch size of 512. We use AdamW (Loshchilov and Hutter, 2017) as the optimizer for training. The learning rate is linearly increased from 0 to $1e-4$ over the initial 5000 steps, stabilizing at $1e-4$ thereafter. The 100K-token models are trained for 200 epochs. The 500K-token models are trained for 40 epochs. The 1M-token models are trained for 60 epochs. The 5M-token models are trained for 20 epochs. The 15M-token and 50M-token models are trained for 10 epochs. These numbers are determined by observing how their validation loss changes.

Word-Relatedness Benchmark. We mainly use the human judgments on word relatedness collected by (Bruni et al., 2012), who asked annotators to judge whether one pair of words are more related than another pair of words. The authors selected words that are frequent both in online corpora including the British Web corpus (ukWaC) and as image tags (Bruni et al., 2012), yielding mostly concrete nouns. Each pair of words is compared to 50 other pairs that are randomly sampled. The relatedness of two words is quantified as the number of times this pair is judged as more related than the other pair in these 50 tests (see examples in Fig. 1B). Such relatedness scores are collected for 3000 pairs of words, of which 2057 pairs are used on this benchmark to focus only on words that are typically acquired by children under the age of 10 (Age of Acquisition is from (Kuperman et al., 2012)). As for models, we use the cosine similarity between the hidden representations of two words from the same layer as the relatedness value for these two words. When the tested word contains more than one token, we use the representation from the last token. Finally, we compute the Spearman correlations between these similarity values from models and the relatedness scores from humans as results on this benchmark. For each model, we report the highest correlation across the results from all layers.

Semantic-Feature Prediction Benchmark. We use the dataset of psycholinguistic feature norms constructed by (Buchanan et al., 2019). The authors asked annotators to write down features of the word that they can think of. The response was then processed to generate single-word features (see examples in Fig. 1B), whose frequency of occurrences is used as the quantitative measure for the strength of this feature for one word. The original dataset contains 3,981 features and 4,436 words.

These words undergo a further filtering process to retain only those with an Age of Acquisition (AoA) measure under 10, resulting in a final selection of 3,554 words. When testing models on this benchmark, we train a linear regressor to predict the feature strength of a word from its hidden representations. All the words are split into training (80%), validation (10%), and testing (10%) subsets and we generate two independent train-validation-test splits to reduce noise. Following the practice of (Chronis et al., 2023), we train a partial least squares (PLS) regressor, where the number of components is set to be 100. We report the mean average precision (MAP) over the non-zero features of one word as the prediction accuracy. To compute this MAP, we first get the top- k predicted features, where k is the number of non-zero features in the ground truth, then count the number of overlapping features between the prediction and the ground truth, and finally normalize this count by k . We determine which layer in the network to utilize for generating hidden representations based on the average accuracy observed in the validation set. The accuracy in the test set for this selected layer is reported as the evaluation result of one model on this benchmark.

Lexical-Relation Prediction Benchmark. The CogALex-V dataset (Santus et al., 2016a) includes 3,054 pairs of words in its training split and 4,260 pairs in the test split. The words whose AoA measures are higher than 10 are removed from the dataset, leaving 2704 training pairs and 3900 test pairs. The majority of the word pairs are in the *random* category (1944 of 2704 for training and 2770 of 3900 for test). To test models, we extract the hidden representations of two words and compute their difference as the representation for this pair of words. Following the practice of (Ushio et al., 2021), we train a Multi-Layer-Perceptron network to predict the lexical relations. We use the default settings in the `MLPClassifier` class of `sklearn`, as we find varying these parameters only yields negligible performance difference. The macro average of F1 scores on the test set from the best layer is reported as the result of one model on this benchmark.

Part-Of-Speech Prediction Benchmark. The tags are generated by running Stanza (Qi et al., 2020) on the COCA-Fiction corpus (Davies, 2010), which contains around 100M words. For one word, we use the most frequent tag for it as its label on this benchmark (see examples in Fig. 1B). We include

all words contained on the other three benchmarks and create four independent train-validation-test splits across words similarly in a 80-10-10 ratio. In each split, a linear Support Vector Classifier (LinearSVC) is trained. The average performance on all the validation sets is used to determine the best layer and the best hyperparameter (C) among (0.01, 1, 100). The test-set performance is reported as the result of one model on this benchmark.

Context-Base Word-Understanding Benchmarks. We select 140 nouns, 80 verbs, and 60 adjectives known to be acquired by young children (Frank et al., 2017), with 20 distractor nouns for each noun, 79 distractor verbs for each verb, and 59 distractor adjectives for each adjective. One pair of target and distractor words has 20 pairs of sentences. We download the example sentences for each target word from website <https://sentence.yourdictionary.com>. We then filter these sentences to only include sentences containing exactly one target word in its original form (singular for noun and present tense for verb). For each pair of target and distractor words, we sort all examples by the surprisal of the original sentence minus the surprisal of a changed sentence with the distractor replacing the target word (also called as the distractor-present-original sentence). This surprisal value is computed from the OPT-6.7B (Zhang et al., 2022) model. The smaller this difference is, the more reasonable this sentence is for this pair of words. We take the top 20 sentences with the smallest difference. For one sentence, we enumerate all possible replacements on all word positions except the target word. Each replacement yields one possible new sentence. A distractor-present-new sentence is further built from this new sentence by replacing the target word using the distractor word. The surprisal values for both the distractor-present-original sentence and the distractor-present-new sentence are computed from OPT-6.7B. A new sorting criterion is computed by $1.5 * S(dist_{new}) - S(dist)$, here $S(dist_{new})$ means the surprisal of the distractor-present-new sentence and $S(dist)$ means the surprisal of the distractor-present-original sentence. The new sentences from different ways of changing the original sentence are sorted by this new sorting criterion to get the sentence with the smallest criterion. This procedure is done to all 20 sentences to generate the 20 pairs of sentences for this target-distractor pair.

Brain-Response Prediction Benchmark. We

use both two stimuli sets constructed by (Pereira et al., 2018): one has 384 sentences split into 94 text passages and the other one has 243 sentences split into 72 text passages. For one stimulus set, the passages are randomly split into training (90%) and test (10%) subsets (Kauf et al., 2023). A linear regressor is trained on the training subset and evaluated on the test subset. This regressor uses the hidden representations of one layer of a model at the last token of the sentence to predict the corresponding voxel-wise brain responses. The performance of this regressor is computed as the Pearson correlation between the predicted and ground truth response, averaged across all voxels, and then normalized by the noise ceiling of this ground truth. This performance is further averaged across 10 splits and both stimulus sets to generate the benchmark result for one layer of a model. The best layer is selected based on its performance and generates the final score for this model.

A.2 Analysis of Learned Representations

We compute the correlation between the judgments of different models, just like how these models are compared to humans. The correlation between the Visual + Word (CLIP) and the Language-Only models is only 0.70, which is significantly lower than their self-correlation values across different seeds (0.96 for the Language-Only model and 0.92 for the CLIP model). The Visual + Language (GIT) model yields almost the same word-relatedness judgments as the Language-Only model, as the correlation between these two models is 0.95, which is close to their self-correlation values (both 0.96).

The human-likeness measure for a pair of words between models and humans is defined as following. As the word-relatedness benchmark computes the Spearman correlation between a model and human judgments, we calculate two rank values for each pair of words, where one is from sorting all pairs by the model judgment and the other is from sorting all pairs by human judgments. The absolute difference between these two ranks is used to approximate how human-like one pair of words is represented by the model. To normalize this human-likeness measure, all pairs of words are further sorted from less human-like (larger absolute difference) to more human-like (smaller absolute difference) to get a “rank in human-likeness” measure for each pair of words, where a larger value means more human-like.

We also analyze whether this concreteness fea-

ture influences the performance of the semantic-feature prediction benchmark. The visual and language-only models trained with 640K image-caption pairs (15M tokens in captions) are used in this analysis, as their accuracy on this benchmark is very close. To compare these two models, we compute the accuracy difference between them for each word and find that the concreteness feature also positively correlates with this difference (see Appendix Fig. 14).

A.3 Flamingo Training Details

The Flamingo architecture worked by having additional cross-attention layers modulating the outputs of text transformers, and these cross-attention layers were inserted at equal intervals of text transformer layers. The visual feature is processed by a Perceiver Resampler, whose number of layers is two and has 64 latents. Unlike GIT and CLIP models, the visual features sent to Flamingo models contain representations of all visual tokens. We test both inserting the cross-attention layers after every text transformer layer or after every two text transformer layers. The results of these two methods are in Appendix Fig. 15. We train the Perceiver Resampler, the cross-attention layers, and the text transformer layers from scratch using next-word prediction loss on image-caption pairs.

A.4 Varying Visual Encoders

We use the MAE weights from Huggingface with model ID facebook/vit-mae-base. The outputs from the last hidden layer are averaged across all visual tokens to yield the image features. As for DINO-V2, we use the model facebook/dinov2-base.

A.5 Computational Resources

We train our models on A100 gpus. Each model has around 70M trainable parameters. Our implementation majorly uses pytorch and huggingface packages. The training of all models takes around 1600 GPU hours.

B Figures

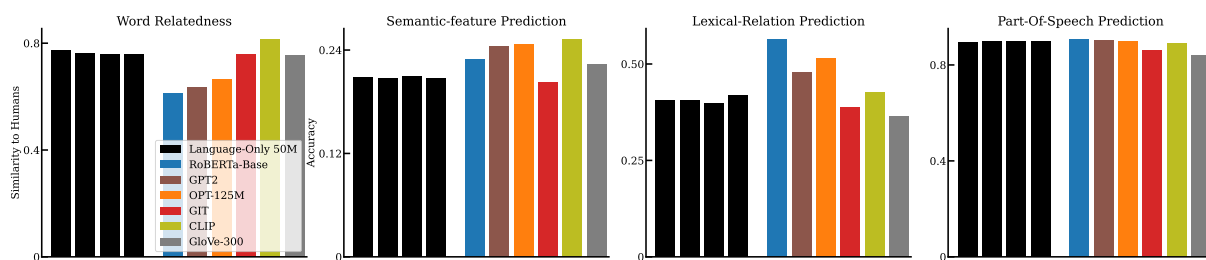


Figure 6: **Performance of pretrained models on word-learning benchmarks.** Bars with the same color represent models trained with different seeds. The Language-Only models shown here are trained on 50M tokens (2.1M image-caption pairs). Pretrained models are from huggingface. Their model ids are: “roberta-base”, “gpt2”, “facebook/opt-125m”, “microsoft/git-base”, and “openai/clip-vit-base-patch32”. Note that only “microsoft/git-base” has the same architecture as the Language-Only models shown here.

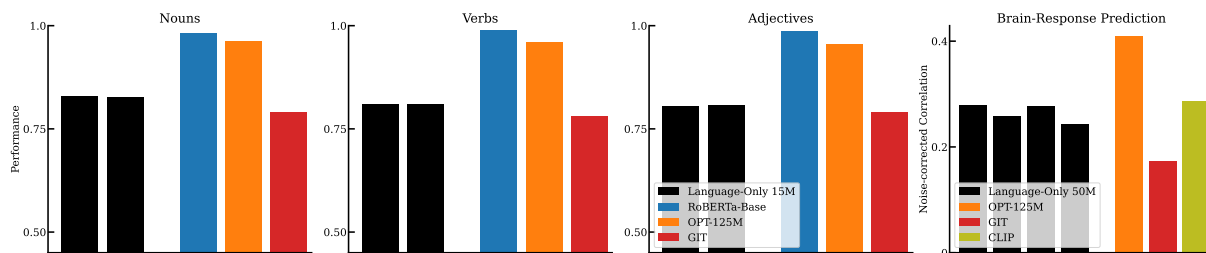


Figure 7: **Performance of pretrained models on context-relevant benchmarks.** Bars with the same color represent models trained with different seeds. The three left benchmarks are for context-based word-understanding benchmarks.

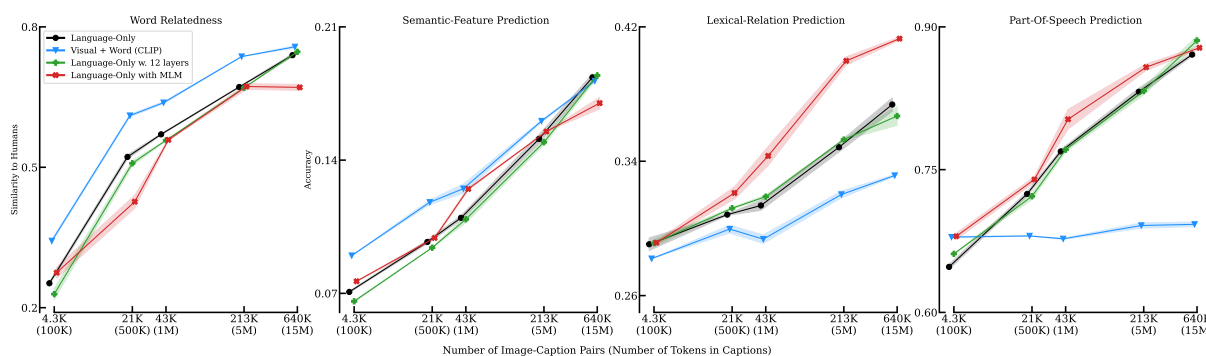


Figure 8: **Changing the network architecture or learning objective function in Language-Only models does not change the main conclusion.** MLM means Masked Language Modeling. Two models with different random seeds are trained in each condition. Although MLM models show strong performance in the lexical-relation prediction benchmark, they still underperform the Vis + Word (CLIP) models in the word relatedness and semantic feature prediction benchmarks.

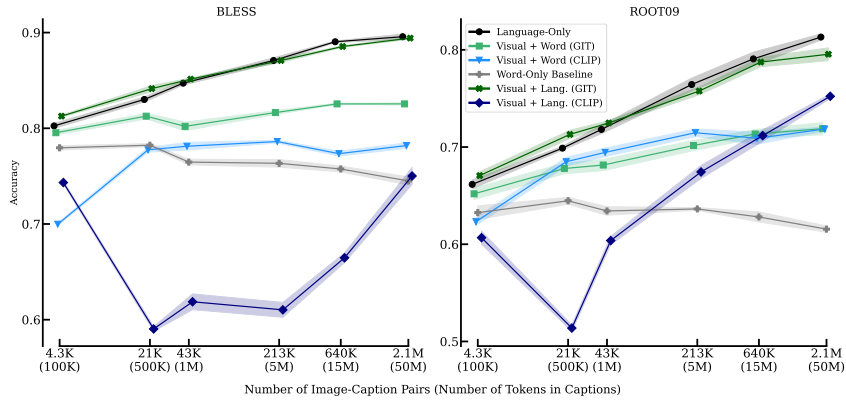


Figure 9: Results of lexical relation prediction benchmarks on two more datasets: BLESS and ROOT09. Four models with different random seeds are trained in each condition.

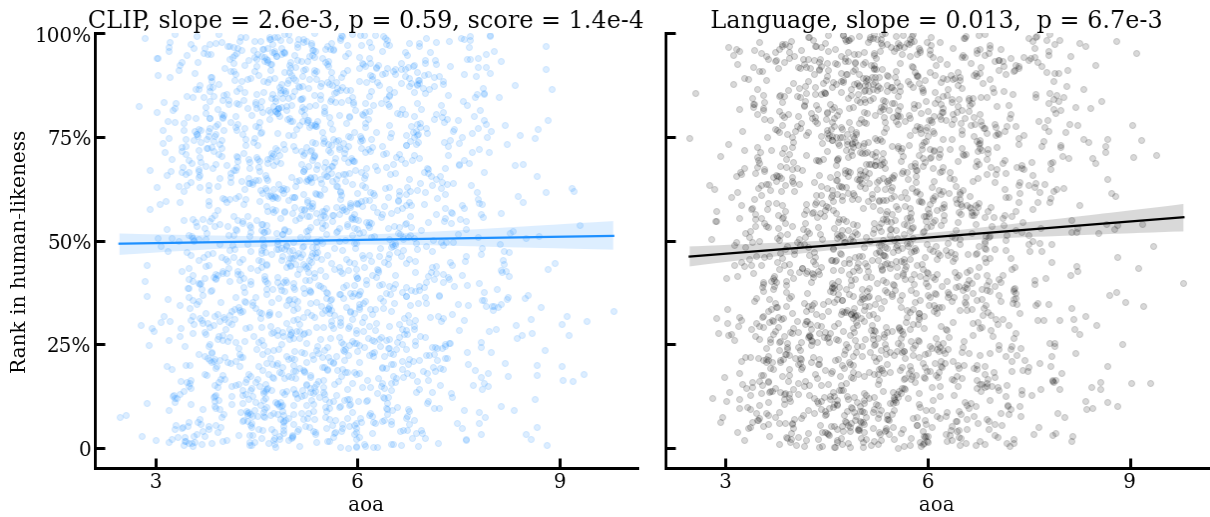


Figure 10: Scatter plots for the word-relatedness benchmark. The format is the same as Fig. 2A. Metric used here is AoA. The score means regression score (coefficient of determination), which is 0.021 for concreteness.

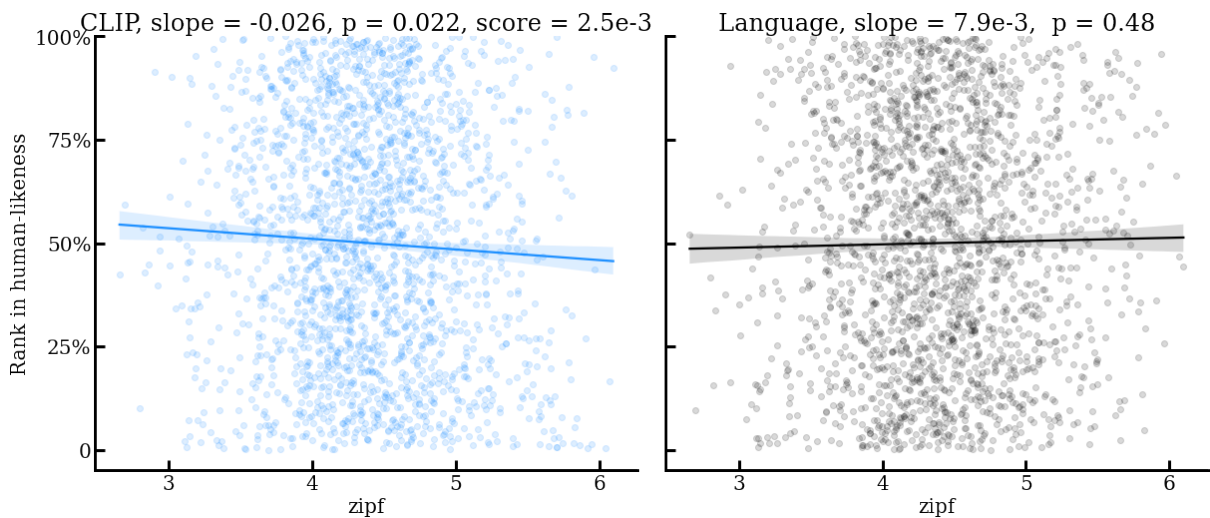


Figure 11: Scatter plots for the word-relatedness benchmark. The format is the same as Fig. 2A. Metric used here is Zipf.

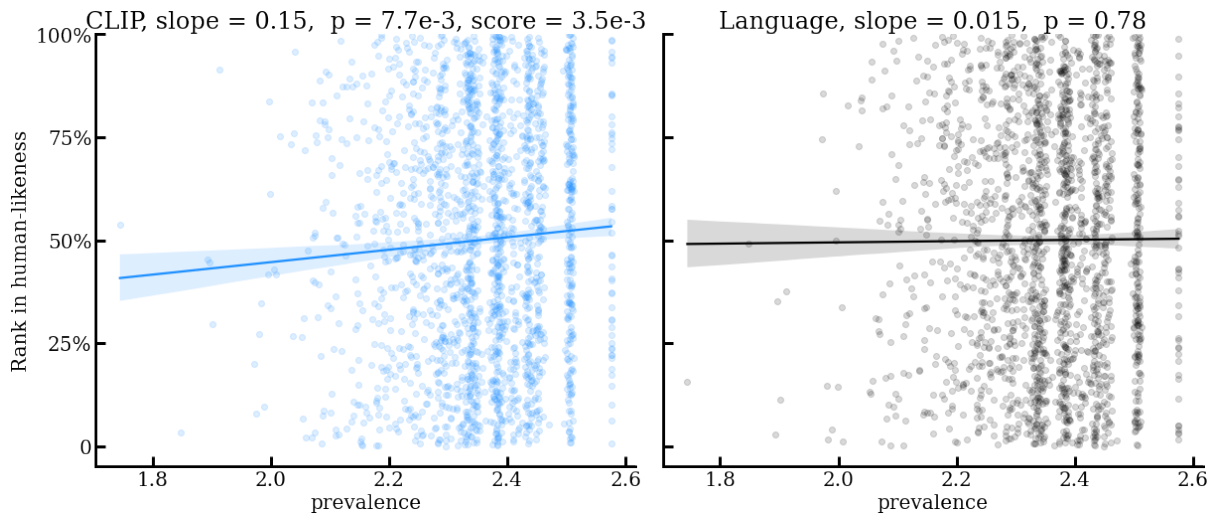


Figure 12: Scatter plots for the word-relatedness benchmark. The format is the same as Fig. 2A. Metric used here is Prevalence.

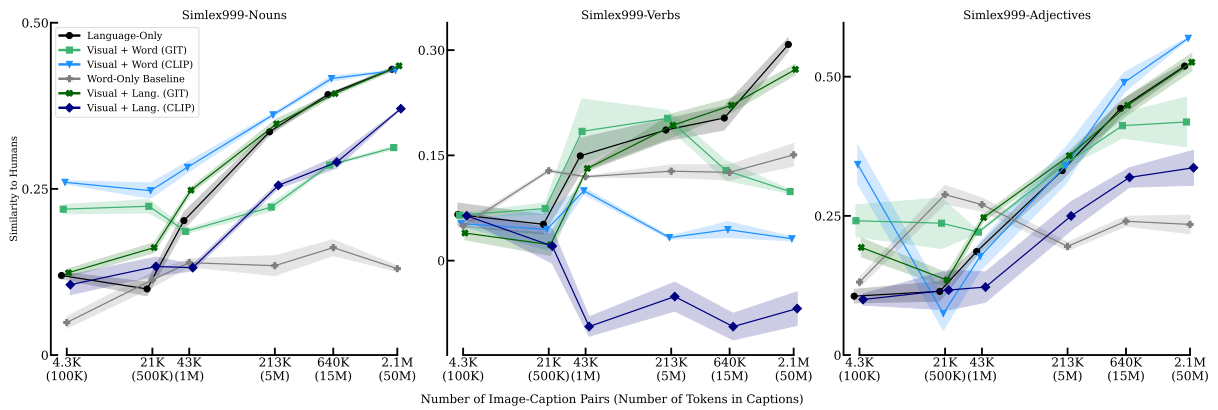


Figure 13: Results of word-relatedness benchmark on SimLex-999 (Hill et al., 2015) split by word categories.

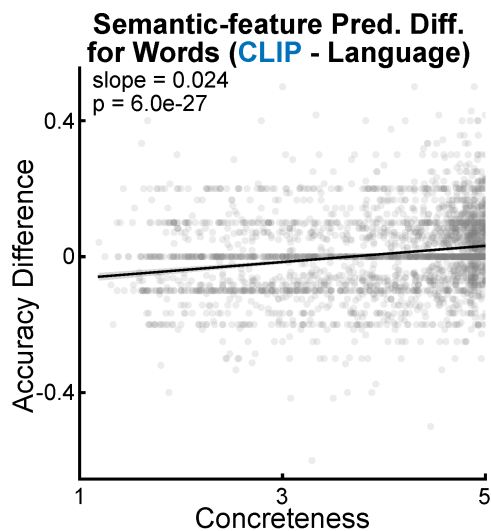


Figure 14: Relationship between the concreteness rating of one word and the accuracy difference between the CLIP and the language-only models.

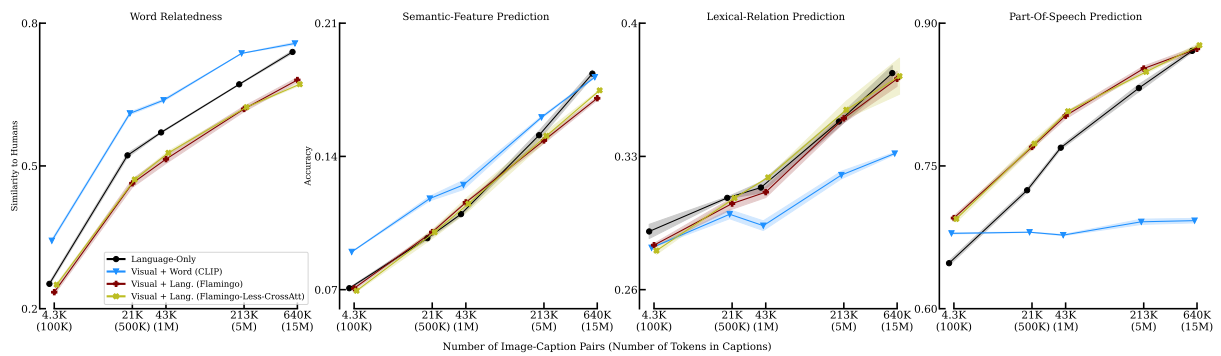


Figure 15: Reducing the number of cross-attention layers in Flamingo does not change its performance. Flamingo-Less-CrossAtt only has 3 cross-attention layers, while Flamingo used in the main paper has 6 cross-attention layers. Two models with different random seeds are trained in each condition.