CAPTURED BY CAPTIONS: ON MEMORIZATION AND ITS MITIGATION IN CLIP MODELS

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ABSTRACT

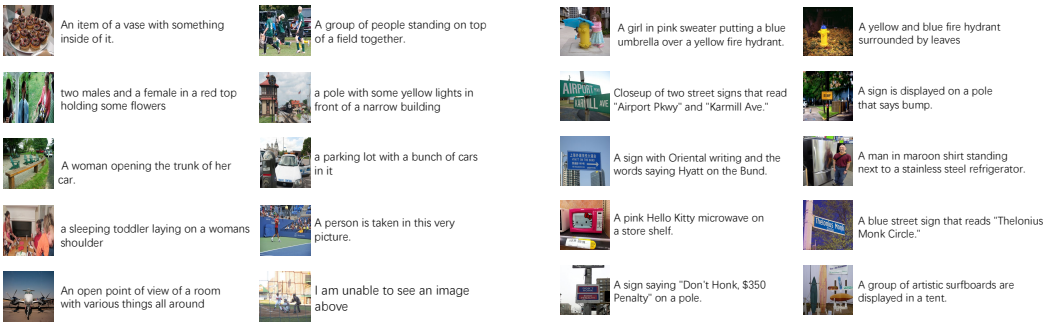
Multi-modal models, such as CLIP, have demonstrated strong performance in aligning visual and textual representations, excelling in tasks like image retrieval and zero-shot classification. Despite this success, the mechanisms by which these models utilize training data, particularly the role of memorization, remain unclear. In uni-modal models, both supervised and self-supervised, memorization has been shown to be essential for generalization. However, it is not well understood how these findings would apply to CLIP, which incorporates elements from both supervised learning via captions that provide a supervisory signal similar to labels, and from self-supervised learning via the contrastive objective. To bridge this gap in understanding, we propose a formal definition of memorization in CLIP (CLIPMem) and use it to quantify memorization in CLIP-style models. Our results indicate that CLIP's memorization behavior falls between the supervised and self-supervised paradigms, with "mis-captioned" samples exhibiting highest levels of memorization. Additionally, we find that the text encoder contributes more to memorization than the image encoder, suggesting that mitigation strategies should focus on the text domain. Building on these insights, we propose multiple strategies to reduce memorization while at the same time improving utility—something that had not been shown before for traditional learning paradigms where reducing memorization typically results in utility decrease.

1 INTRODUCTION

Multi-modal models, such as CLIP (Radford et al., 2021), have demonstrated strong performance in representation learning. By aligning visual and textual representations, these models achieve state-of-the-art results in tasks like image retrieval (Baldrati et al., 2022a;b), visual question answering (Pan et al., 2023; Song et al., 2022), and zero-shot classification (Radford et al., 2021; Ali & Khan, 2023; Wang et al., 2023; Zhang et al., 2022). Despite these successes, the mechanisms by which multi-modal models leverage their training data to achieve good generalization remain underexplored.

In uni-modal setups, both supervised (Feldman, 2020; Feldman & Zhang, 2020) and self-supervised (Wang et al., 2024b), models have shown that their ability to *memorize* their training data is essential for generalization. In supervised learning, memorization typically occurs for mislabeled samples, outliers (Bartlett et al., 2020; Feldman, 2020; Feldman & Zhang, 2020), or data points seen towards the end of training (Jagielski et al., 2022), while in self-supervised learning, high memorization is experienced particularly for atypical data points (Wang et al., 2024b). However, it is unclear how these findings extend to models like CLIP which entail elements from both supervised learning (via captions as supervisory signals) and self-supervised learning (via contrastive loss functions).

Existing definitions of memorization offer limited applicability to CLIP and cannot fully address this gap. The standard definition from supervised learning (Feldman, 2020) relies on one-dimensional labels and the model's ability to produce confidence scores for these labels, whereas CLIP outputs high-dimensional representations. While the SSLMem metric (Wang et al., 2024b), developed for self-supervised vision models, could, in principle, be applied to CLIP's vision encoder outputs, it neglects the text modality, which is a critical component of CLIP. Additionally, measuring memorization in only one modality, or treating the modalities separately, risks diluting the signal and under-reporting memorization. Our experimental results, as shown in Section 4.3, confirm this concern. Therefore, new definitions of memorization tailored to CLIP's multi-modal nature are necessary.



(a) Most Memorized: CLIPMem > 0.89 (b) Least Memorized: CLIPMem ≈ 0.0

Figure 1: **Examples of data with different levels of memorization.** Higher memorization scores indicate stronger memorization. We observe that atypical or distorted images, as well as those with incorrect or imprecise captions, experience higher memorization compared to standard samples and easy-to-label images with accurate captions. Results are obtained on OpenCLIP (Ilharco et al., 2021), with encoders based on the ViT-Base architecture trained on the COCO dataset.

The only existing empirical work on quantifying memorization in CLIP models (Jayaraman et al., 2024) focuses on Déjà Vu memorization (Meehan et al., 2023), a specific type of memorization. The success of their method relies on the accuracy of the integrated object detection method and on the availability of an additional public dataset from the same distribution as CLIP's training data, limiting practical applicability. To overcome this limitation, we propose *CLIPMem* that measures memorization directly on CLIP's output representations. Specifically, it compares the alignment—*i.e.,* the similarity between representations—of a given image-text pair in a CLIP model trained with the pair, to the alignment in a CLIP model trained on the same data but without the pair.

In our empirical study of memorization in CLIP-like models using CLIPMem, we uncover several key findings. First, examples with incorrect or imprecise captions ("mis-captioned" examples) exhibit the highest levels of memorization, followed by atypical examples, as illustrated in Figure 1. Second, removing these samples from training yields significant improvements in CLIP's generalization abilities. These findings are particularly noteworthy, given that state-of-the-art CLIP models are usually trained on large, uncurated datasets sourced from the internet with no guarantees regarding the correctness of the text-image pairs. Our results highlight that this practice not only exposes imprecise or incorrect data pairs to more memorization, often recognized as a cause for increased privacy leakage (Carlini et al., 2019; 2021; 2022; Song et al., 2017; Liu et al., 2021), but that it also negatively affects model performance. Furthermore, by disentangling CLIP's two modalities, we are able to dissect how memorization manifests within each. Surprisingly, we find that memorization does not affect both modalities alike, with memorization occurring more in the text modality than in the vision modality. Building on these insights, we propose several strategies to reduce memorization while simultaneously improving generalization—a result that has not been observed in traditional supervised or self-supervised learning, where any reduction of memorization causes decreases in performance. Finally, at a deeper level, our analysis of the model internals, following Wang et al. (2024a), shows that CLIP's memorization behavior sits between that of supervised and self-supervised learning. Specifically, neurons in early layers are responsible for groups of data points (*e.g.,* classes), similar to models trained using supervised learning, while neurons in later layers memorize individual data points, as seen in self-supervised learning.

In summary, we make the following contributions:

- We propose CLIPMem, a metric to measure memorization in multi-modal vision language models.
- Through extensive evaluation, we identify that "mis-captioned" and "atypical" data points experience the highest memorization, and that the text encoder is more responsible for memorization than the image encoder.
- Based on our insights, we propose and evaluate multiple strategies to mitigate memorization in CLIP. We show that in CLIP, contrary to traditional supervised and self-supervised learning, a reduction of memorization does not need to imply a decrease in performance.

2 Background and Related Work

CLIP. Contrastive Language-Image Pretraining (CLIP) (Radford et al., 2021) trains an image encoder f_{img} and a text encoder f_{txt} to map image-text pairs into a shared latent space. It trains these encoders by maximizing similarity for matching image-text pairs while minimizing it for non-matching pairs, using a contrastive loss function $\mathcal{L}$:

$$\mathcal{L} = -\frac{1}{N}\sum_{i=1}^{N}\log\frac{\exp(\text{sim}(f_{\text{img}}(x_i), f_{\text{txt}}(y_i))/\tau)}{\sum_{j=1}^{N}\exp(\text{sim}(f_{\text{img}}(x_i), f_{\text{txt}}(y_j))/\tau)},$$

where $\text{sim}(\cdot,\cdot)$ is cosine similarity, τ is a temperature parameter, and N is the batch size. The popular Language augmented CLIP (LaCLIP) (Fan et al., 2023) extends this approach by introducing text augmentions alongside the original image augmentations (crops) during training to reduce overfitting. We study the impact of this practice on memorization and find it to be a suitable mitigation method.

Memorization. Memorization refers to a model's tendency to store detailed information from training examples, rather than learning general patterns. (Zhang et al., 2016; Arpit et al., 2017; Chatterjee, 2018; Feldman, 2020). This can lead to privacy risks when sensitive data is memorized (Carlini et al., 2019; 2021; 2022; Song et al., 2017). To date, memorization has been studied mainly within *single modalities*. In **supervised learning**, models tend to memorize *mislabeled* (Feldman, 2020), *difficult*, or *atypical* examples (Arpit et al., 2017; Sadrtdinov et al., 2021), which can improve generalization on long-tailed data (Feldman, 2020; Feldman & Zhang, 2020). Similarly, in **self-supervised learning** (SSL) in the vision domain (Wang et al., 2024b), atypical samples experience higher memorization, and reducing memorization in SSL encoders leads to decreased performance in downstream tasks. A similar connection between memorization and generalization has been observed in the language domain (Antoniades et al., 2024; Tirumala et al., 2022). However, these papers consider single-modality models. How those insights transfer to multi-modal models remains unclear.

Memorization in self-supervised learning. Our CLIPMem builds on the SSLMem metric introduced by Wang et al. (2024b). This metric measures how much an SSL encoder memorizes a data point x by comparing the alignment of representations from its augmented views. Let $f : \mathbb{R}^n \to \mathbb{R}^d$ be an SSL encoder trained on an unlabeled dataset $S = \{x_i\}_{i=1}^m$ using an SSL algorithm $\mathcal{A}$. The data augmentations are represented as $\text{Aug}(x) = \{a(x)|a \in \text{Aug}\}$, where a is a transformation function applied to the data point x, mapping from $\mathbb{R}^n \to \mathbb{R}^n$. The encoder's output representation for a given data point x is denoted as $f(x)$. For a trained SSL encoder f, the alignment loss for a data point x is defined as

$$\mathcal{L}_{\text{align}}(f, x) = \mathop{\mathbb{E}}_{x',x''\sim\text{Aug}(x)}[d\left(f(x'), f(x'')\right)], \tag{1}$$

where x', x'' are augmented views of x and $d(\cdot,\cdot)$ is a distance metric, typically the ℓ_2 distance. SSLMem is then defined as

$$\text{SSLMem}(x) = \mathop{\mathbb{E}}_{g\sim\mathcal{A}(S\setminus x)}\mathcal{L}_{\text{align}}(g, x) - \mathop{\mathbb{E}}_{f\sim\mathcal{A}(S)}\mathcal{L}_{\text{align}}(f, x) \tag{2}$$

with f being an SSL encoder trained with data point x, and g, an encoder trained without x but otherwise on the same dataset. While this framework measures memorization using alignment loss for single-modality encoders, this approach is unsuitable to leverage the signal over both modalities from multi-modal encoders like CLIP, as we also highlight empirically in Section 4.3. However, we can build on the main concepts from SSLMem to define a new metric that can evaluate memorization in CLIP, by considering both image and text representations, as we will detail in Section 3.

Memorization in CLIP. Even though CLIP is a widely used vision-language encoder, there has been limited work on measuring memorization in CLIP. The only existing work (Jayaraman et al., 2024) applies the empirical Déjà Vu memorization framework from (Meehan et al., 2023) to CLIP. It measures memorization by computing the overlap between unique objects in potentially memorized images and their nearest neighbors—identified in the CLIP embedding space—from a public dataset. However, the reliance on external public data from the same distribution, along with the required accuracy of the object detection (which may not perform well for all samples, especially atypical ones (Kumar et al., 2023; Dhamija et al., 2020), limits the applicability of this approach. We further expand on this in Appendix A.1. In contrast, our CLIPMem operates directly on CLIP's output representations and returns a joint score over both modalities.

3 DEFINING MEMORIZATION OVER MULTI-MODAL ENCODERS

3.1 PROBLEM SETUP

Consider a single image-text pair (I, T) from a dataset S and two CLIP models: a model f and a reference model g, trained on dataset S and $S' = S \setminus \{(I, T)\}$, respectively. We aim to quantify the memorization of (I, T) in f, trained on this data point, by leveraging model g not trained on the data point but otherwise on the same data, in a *leave-one-out* style of defining memorization (Feldman, 2020). We denote the image encoder in CLIP as $f_{\text{img}} : \text{Image} \to \mathbb{R}^d$ and the text encoder as $f_{\text{txt}} : \text{Text} \to \mathbb{R}^d$. For the image-text pair (I, T), we denote with $f_{\text{img}}(I)$ the output representation of f's image encoder on image I and with $f_{\text{txt}}(T)$ the output representation of f's text encoder on text T. To evaluate the *alignment* between the image and text representations, *i.e.,* to quantify how similar the two representations are, we use cosine similarity $sim(f_{\text{img}}(I), f_{\text{txt}}(T))$, as defined in the original CLIP paper (Radford et al., 2021).

3.2 ALIGNMENT WITH CONTRASTIVE OBJECTIVE

During training, the contrastive objective in CLIP maximizes the cosine similarity for correct image-text pairs while minimizing the cosine similarity for all the other $N - 1$ incorrect pairs in any given training mini-batch with N training samples. This means that for a given image I and text T, the training objective pulls $f_{\text{img}}(I)$ and $f_{\text{txt}}(T)$ closer together in the latent space, while pushing $f_{\text{img}}(I)$ away from the representations of all other $N - 1$ unrelated texts, and $f_{\text{txt}}(T)$ away from all other images. Hence, the intuition is that the quality of alignment in f, unlike in uni-modal self-supervised learning (Wang et al., 2024b), depends not only on the model's ability to create well-aligned text and image representations for a given text-image pair, but also on its ability to create distant representations for the $N - 1$ other representations.

To formalize this intuition into a metric that quantifies the alignment of f on the image-text pair (I, T), we define $\widehat{T_{test}}$ as a set of $N - 1$ randomly chosen testing samples that were not used in training f or g. Furthermore, when applicable, we denote random augmentations of the training data—*e.g.,* text augmentations in versions like LaCLIP (Fan et al., 2023)—as $T' \sim \text{Aug}(T)$ for texts and $I' \sim \text{Aug}(I)$ for images. Then, we define the alignment score of f on (I, T) as

$$\begin{aligned}\mathcal{A}_{\text{align}}(f, I, T) = &\mathop{\mathbb{E}}_{(I',T')\sim\text{Aug}(I,T)} [\text{sim}(f_{\text{img}}(I'), f_{\text{txt}}(T'))] \\ &- \mathop{\mathbb{E}}_{(\_,t)\in\widehat{T_{test}}} [\text{sim}(f_{\text{img}}(I), f_{\text{txt}}(t))] - \mathop{\mathbb{E}}_{(i,\_)\in\widehat{T_{test}}} [\text{sim}(f_{\text{img}}(i), f_{\text{txt}}(T))] ,\end{aligned} \tag{3}$$

where high scores indicate a better alignment of f on (I, T). In case no text augmentations are applied, as in standard CLIP training, the first term is calculated only over T.

3.3 DEFINING MEMORIZATION IN CLIP

Given our definition of alignment scores, we can define our CLIPMem in a similar vein to the definition of memorization in supervised learning (Feldman, 2020), in the leave-one-out style. Given the image-text pair (I, T) from dataset S and two CLIP models, f and g, trained on dataset S and $S' = S \setminus \{(I, T)\}$, respectively, we define CLIPMem as

$$\text{CLIPMem}(I, T) = \mathcal{A}_{\text{align}}(f, I, T) - \mathcal{A}_{\text{align}}(g, I, T). \tag{4}$$

If a model f has a significantly higher alignment score than model g on (I, T), this means that f memorizes this data point. Note that taking the difference between f and g is crucial to get a solid estimate of memorization. This is because without "context", a high or low alignment score of f does not express much information. The alignment of f can be high without memorizing (I, T), for example, if (I, T) is a simple (but not memorized) training example. In this case, the reference model g will also have a high score, such that the difference is again small. Thanks to this design of our CLIPMem, it will then correctly report low memorization.

4 EMPIRICAL EVALUATION

4.1 EXPERIMENTAL SETUP

Models and training. We build our experiments on OpenCLIP (Cherti et al., 2023), an open-source Python version of Open-CLIP (Ilharco et al., 2021). The standard architecture used for the experiments builds on ViT-Base, but we also include experiments using ViT-Large. We train the model on the COCO dataset (Lin et al., 2014). Since COCO is much smaller than OpenCLIP's standard training datasets, we reduce the training batch size to 128 and increase the epoch number from 32 to 100 to achieve similar performance. All other settings strictly follow OpenCLIP. For training DINO, as an example of an SSL vision encoder, we follow the default setting of Caron et al. (2021). The supervised model is trained as a multi-label classifier, also based on ViT-Base (with an additional fully connection layer) based on the first-level annotation captions in the COCO dataset. A full specification of our experimental setup is detailed in Appendix A.2. Additional experiments for measuring memorization on the BLIP (Li et al., 2022) model are presented in Appendix A.6.

Datasets. We use COCO (Lin et al., 2014), CC3M (Sharma et al., 2018), and the YFCC100M (Thomee et al., 2016a) datasets to pre-train the OpenCLIP models. For CC3M, we randomly sample 75000 examples from 2.91M total. We evaluate the models based on linear probing accuracy on ImageNet (Deng et al., 2009) with an added classification layer trained on top of the output representations. We use YFCC100M to simulate an infinite data regime, *i.e.,* using a single training run where no data point is repeated whereas we train iteratively using CC3M and COCO.

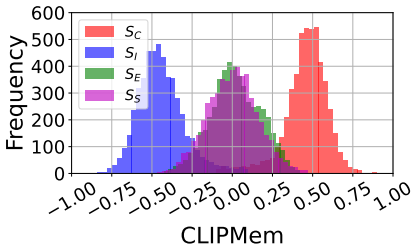
Measuring memorization. We follow Wang et al. (2024b) to approximate our CLIPMem. Since training a separate pair of models for every data point would be computationally intractable, we measure memorization across multiple data points simultaneously. Therefore, we divide the training set into four subsets: (1) S_S, data points that both model f and g were trained on, (2) S_C, data points used only for training f, (3) S_I, data points used only for training g, and (4) S_E, external "test" data points that none of the models was trained on. Note that $|S_C| = |S_I|$, such that f and g have the same number of training data points in total. For our experiments, following a similar approach to Wang et al. (2024b), we want to strike a balance when choosing the size of S_C. If the size is too large, then f and g might differ too much and not yield a strong memorization signal, but if it is too small, we would only have a memorization signal for too few data points. Concretely, for COCO and CC3M, we set $|S_S| = 65000$ and $|S_C| = |S_I| = |S_E| = 5000$. Memorization is reported as an average over all data points in S_C for model f, or per individual data point in S_C.

Generating captions and images. To generate additional captions for the training images, we use GPT-3.5-turbo. For each input image, we provide the representation produced by our trained OpenCLIP model and ask GPT to generate five new captions. Generated sample captions are presented in Figure 18. To generate additional images for the COCO dataset, we use Stable Diffusion v1.5 to generate five new images, one corresponding to each of the five per-image captions in the COCO dataset. Sample generated images are presented in Figure 17.

4.2 STUDYING MEMORIZATION USING CLIPMEM

We first analyze the general memorization in CLIP in order to identify which data points are memorized. To do this, we quantify CLIPMem over the different training subsets. Our results are presented in Figure 2a. In particular, we observe that CLIPMem for S_C, the data points only used to train model f, is significantly higher than for S_S, the data points shared between the two models. Memorization for S_S is comparable to that for S_E, *i.e.,* the external data not seen during training, indicating that f does not memorize these samples. The data in S_I causes negative CLIPMem scores, indicating that this data is memorized by g, not by f. This is the expected behavior according to the definition of our metric. In Appendix A.4, we additionally highlight that memorization increases with model size, *i.e.,* CLIP based on ViT-Large has a higher overall memorization with an average of 0.457 while CLIP based on ViT-Base only reaches 0.438 on average.

Additionally, we analyze individual data points by their reported CLIPMem. We give examples of highly memorized data points in Figure 1 and highly vs. little memorized samples in Figures 13,14,15, and 16 in Appendix A.9. Overall, high CLIPMem samples seem to be difficult examples or examples with imprecise or incorrect captions, whereas low CLIPMem samples are simpler and more precisely

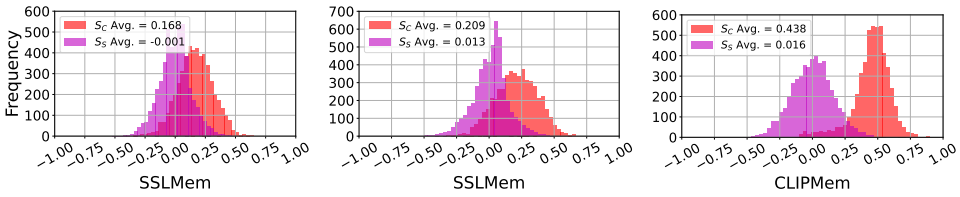


(a) Memorization scores across data subsets.

	Clean S_C	Poisoned S_C
Clean Model	0.438	N/A
Poisoned Model	0.440	0.586

(b) Average CLIPMem scores.

Figure 2: **Memorization with CLIPMem**. We train a CLIP model on COCO using standard image cropping and no text augmentations. (a) We present memorization scores according to CLIPMem per data subset. The significantly higher scores for S_C compared to S_S indicate that f memorizes S_C. (b) We also study how inserting training samples with imprecise or incorrect captions ("mis-captioned") affects memorization. We refer to the model trained with correct captions as **Clean Model**, and the model trained with S_C containing 4500 standard canaries (**Clean**) and 500 mis-captioned (**Mis-captioned**) as **Poisoned Model**. We report CLIPMem over the different subsets of candidates. We observe that the mis-captioned samples experience a significantly higher memorization while the memorization of the clean data points is (almost) not affected.



(a) SSLMem (Img). (b) SSLMem (Text). (c) CLIPMem.

Figure 3: **Measuring memorization on individual modalities is not able to extract a strong signal.** (a)–(b) We measure SSLMem (Wang et al., 2024b) on the individual encoders of our CLIP model trained on COCO. (c) Our CLIPMem extracts a stronger memorization signal by using both modalities in CLIP jointly.

captioned. In Appendix A.5, we show that these findings also hold when we operate in the *infinite data regime*, *i.e.,* when we perform only a single training run where no data point is repeated.

Motivated by this insight and findings from supervised learning, where models memorize random labels (Zhang et al., 2016) and where mislabeled data experiences highest memorization (Feldman, 2020), we test if the same effect can also be observed in CLIP. We "poison" CLIP's training data by randomly shuffling the captions among 500 of 5000 candidate data points in S_C, creating "mis-captioned" data points. We train a model on this data and see that the mis-captioned examples experience significantly higher memorization (CLIPMem of 0.586) compared to "clean" data points (CLIPMem of 0.440). Despite CLIP's contrastive training objective, memorization of clean data points is not significantly affected by training the model with the mis-captioned examples, as we can see by their CLIPMem that is 0.438 on the clean model and 0.440 on the poisoned model.

4.3 Measuring Memorization in one Modality does not Yield a Strong Signal

To assess the importance of considering both modalities in our definition of CLIPMem, we evaluate whether existing uni-modal encoder memorization metrics (Wang et al., 2024b) yield a sufficiently strong memorization signal in CLIP. Therefore, we apply SSLMem independently to CLIP's vision and text encoders. Since SSLMem relies on augmentations of the encoder input, we use image crops, like during CLIP training for the vision encoder, and the 5 COCO captions as augmentations for the text, like in (Fan et al., 2023). Our results in Figure 3 show that SSLMem and its naive adaptation to CLIP fail to yield a strong memorization signal. In particular, there is a high overlap in scores between the non-memorized samples from S_S, and candidate examples for memorization S_C. Additionally,

the highest reported memorization scores for S_C go up to around 0.65 (for SSLMem on the vision encoder) and 0.73 (for SSLMem on the text encoder). In contrast, our new CLIPMem is able to get a distinct signal for the candidates S_C with respect to S_S and reports a much higher memorization of 0.91. Thereby, our CLIPMem prevents under-reporting the actual memorization in CLIP.

4.4 Memorization between Modalities

Our results in Figure 3 indicate that memorization is higher in CLIP's text encoder than in the image encoder (the average SSLMem on S_C in the text encoder is 0.209 vs. 0.168 in the image encoder). To provide further insights into how memorization behaves between the modalities in CLIP, we first analyze the use of augmentations. We compare five cases: (1) no additional augmentations beyond the baseline (image cropping), (2) generating one image using a diffusion model for a given original caption, (3) generating five variations of each image using a diffusion model and randomly selecting one for each training iteration while keeping the caption fixed, (4) using the original image but randomly selecting one of the five COCO captions for each training iteration, and (5) randomly pairing each of the five generated images with one of the five COCO captions.

Table 1: Impact of augmentations.

Case	CLIPMem	Lin. Prob. Acc. (ImageNet)
1 Image, 1 Caption	0.438	63.11% $\pm$ 0.91%
1 Image (generated), 1 Caption	0.428	63.97% $\pm$ 0.79%
5 Images (generated), 1 Caption	0.424	64.60% $\pm$ 0.82%
1 Image, 5 Captions	0.423	64.88% $\pm$ 0.83%
5 Images (generated), 5 Captions	0.417	64.79% $\pm$ 0.99%

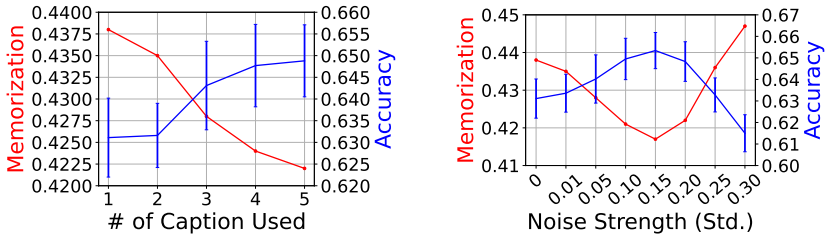
As shown in Figure 14, there is quite a variability in the COCO captions for the same sample. Hence, some images might not fit well with the chosen training caption. This imprecise captioning can cause an increase in memorization. We observe that the effect is mitigated when using the 5 images with the 5 captions (5th case, see Table 1). This phenomenon results most likely from the increased number of possible image-text pairs (25), such that individual incorrect or imprecise pairs are not seen so often during training. For the third case, *i.e.,* row three in Table 1, we generate five images with a diffusion model based on all five captions per image from the COCO dataset. However, as we only use the first caption during training, this would introduce many mis-captioned images which significantly lowers performance and increases memorization. To avoid this problem, we removed 6000 mis-captioned samples.

Our results in Table 1 highlight that augmenting text during training reduces memorization and increases performance more than augmenting images. However, applying augmentations of both text and images strikes the right balance between the reduction in memorization and the increase in performance. In fact, applying both augmentations reduces memorization most significantly. These results indicate that memorization in CLIP's is tightly coupled to the captions assigned to the training images with imprecise captions having a destructive effect on CLIP performance and memorization.

4.5 Relation to CLIP Memorization to (Self-)Supervised Memorization

We further provide insights on whether CLIP's memorization behavior is more alike to the one of supervised learning or SSL. This question is highly interesting since the captions in CLIP can be considered as a form of labels, like in supervised learning, whereas the contrastive training objective on the dataset resembles more SSL. We perform two experiments to gain a better understanding of the memorization behavior of CLIP with respect to supervised learning and SSL.

First, we compare an SSL vision encoder pair f and g with the same architecture as CLIP's vision encoder but trained from scratch on COCO using DINO, *i.e.,* standard SSL training. We train f and g using the same candidates as the pair of CLIP models in our previous experiments. Then, we use the SSLMem metric from Wang et al. (2024b) to quantify memorization in the CLIP vision encoder and the SSL encoder, respectively. The CLIP vision encoder has a significantly lower SSLMem than the SSL encoder (0.209 vs. 0.279). Hence, CLIP vision encoders experience lower SSL memorization than SSL trained encoders. To further investigate the difference, we also report the overlap between the top 10% memorized samples between the two models, measured according to SSLMem. With an overlap of only 47 out of 500 (9.4%) samples, we find that CLIP memorizes significantly different samples than SSL encoders. Wang et al. (2024b) had performed a similar experiment on SSL vs. supervised learning and found that the two paradigms also lead to different samples being memorized. While this is, on the one hand, an effect of the different objective function, the difference between the memorized samples in CLIP and SSL is likely also closely connected to the additional captions that



(a) Different numbers of captions. (b) Noising text embedding during training.

Figure 5: **Mitigating memorization in CLIP improves downstream generalization.** We train CLIP models with different "augmentations" in the textual domain. (a) We use multiple captions per image. (b) We directly noise the text embeddings using Gaussian noise with a mean of 0 and different standard deviations (adding $\mathcal{N}(0, 0.15)$ achieves the optimal balance of smallest memorization and highest performance). Both strategies successfully reduce memorization while improving performance.

CLIP takes into account. While SSL-trained encoders can memorize atypical images, CLIP encoders can memorize typical images when they have an atypical, imprecise, or incorrect caption.

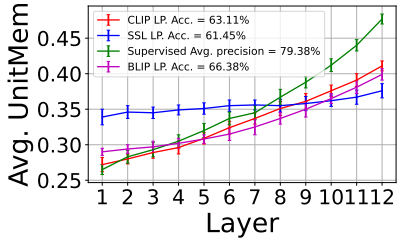


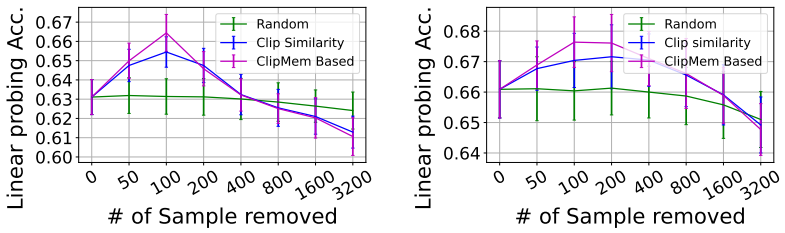
Figure 4: **UnitMem metric: CLIP is between supervised and SSL models.**

Additionally, we compare the memorization behavior of CLIP at the neuron level against supervised and SSL-trained models. To do so, we train two ViT-Base models on COCO using supervised and SSL (DINO) training. Then, we apply the UnitMem metric (Wang et al., 2024a) to measure how much individual neurons memorize individual samples from the training data. High UnitMem indicates neurons memorizing individual data points rather than groups/classes of points. Prior work found that supervised learning results in low UnitMem in lower-layer neurons, indicating group-based learning, while later-layer neurons highly memorize individual data points. In contrast, SSL maintains relatively constant UnitMem, with lower-layer neurons also memorizing individual data points. This difference was attributed to objective functions: supervised learning's cross-entry loss pulls same-class data points together, while SSL's contrastive loss pushes individual data points apart. (Wang et al., 2024a). Our results (Figure 4) reveal that CLIP's memorization behavior falls between supervised learning and SSL. In lower layers, it is much less selective than SSL, *i.e.,* it focuses on groups rather than individual data points, similar to supervised learning. Yet, in later layers, CLIP becomes more selective than SSL, *i.e.,* it memorizes individual data points more in individual neurons, though still less than supervised learning, which exhibits a much higher average per-layer UnitMem. We present additional insights on how memorization evolves over training in Appendix A.7.

4.6 Mitigating Memorization while Maintaining Generalization

Experiments in Table 1 suggest that augmentations during training can improve generalization while also reducing memorization. This is an unexpected synergy, since generalization was shown to decline when memorization decreases, in both supervised learning (Feldman, 2020) and SSL (Wang et al., 2024b). To further study how mitigating memorization affects CLIP's downstream generalization, we explore two orthogonal strategies for "augmenting" text, first in the input space and second in the embedding space. Additionally, we analyze the effect of removing memorized samples from training.

Multiple captions. We vary the number of captions used during training and report memorization and downstream performance in Figure 5a. We find that using more captions during training reduces memorization while improving linear probing accuracy. Our results in Table 3 highlight that using all captions equally often enhances utility without significantly affecting memorization. Since not all dataset have multiple captions, we explore generating them with a language model. Table 7 shows that training CLIP with GPT3.5-generated captions yields extremely similar results in utility and memorization, making this strategy widely applicable. Our findings that modifying text during training can reduce memorization align with Jayaraman et al. (2024), who proposed *text randomization*, *i.e.,* masking out a fraction of tokens during training as a mitigation for their Déjà Vu



(a) CLIP trained on COCO.

(b) CLIP trained on CC3M.

Figure 6: **Removing memorized samples according to CLIPMem has a stronger influence on the linear probing accuracy than removing random data points.** Removing the mislabeled samples based on CLIPMem improves the performance significantly, followed by a sharper drop when removing atypical samples.

memorization. However, unlike our GPT3.5-generated captions, this method reduces performance, likely due to the greater distribution shift introduced by masked tokens.

Noising the text embedding during training. To avoid any inherent distribution shifts, we propose applying "augmentations" directly in the embedding space. Specifically, we add small Gaussian noise to text embeddings before computing cosine similarity for contrastive loss. As shown in Figure 5b and Table 8, this strategy is effectively reduces memorization while improving downstream generalization.

Removing memorized samples. Finally, we investigate the effect of removing memorized samples on downstream performance. After training a CLIP model, we identify and remove the most memorized data points, then retrain on the remaining data points. We compare this to two baselines, where we either randomly remove samples or filter out the samples with the lowest CLIP similarity between the training data points' two modalities. We showcase the effect on the downstream linear probing accuracy on ImageNet in Figure 6 with CLIP models trained on COCO and on the CCM3 dataset. For the COCO dataset, when removing up to 100 most memorized data points, we first observe a sharp increase in downstream performance in comparison to removing random samples. Then, downstream performance starts dropping significantly more when removing memorized instead of random samples, until a cutoff point is reached (400-800 removed samples), where further removal based on memorization results in worse performance. For the CC3M dataset, this cutoff occurs later (1,600-3,200 removed samples). While filtering by CLIP similarity also improves performance, it is not as effective as CLIPMem, emphasizing the value of considering memorization as a lens to identify noisy samples. This finding is significantly different than for supervised learning and SSL, where removing highly memorized samples *constantly* harms performance more than the removal of random samples (Feldman, 2020; Wang et al., 2024b). We hypothesize that the effect observed in CLIP might result from the distinction between "mis-captioned" and atypical samples, where the former harms generalization while the latter helps the model learn from smaller sub-populations (Feldman, 2020). We empirically support this hypothesis in Appendix A.3.1. Our finding that CLIP generalization can be improved by identifying inaccurately captioned data points using our CLIPMem and removing them from training is of high practical impact, given that state-of-the-art CLIP models are trained on large, uncurated datasets sourced from the internet with no guarantees regarding the correctness of the text-image pairs. Overall, our results suggest that CLIPMem can help reduce memorization in CLIP while improving downstream generalization.

5 Conclusion

We presented CLIPMem, a formal measure to capture memorization in multi-modal models, such as CLIP. By not only quantifying memorization but also identifying *which* data points are memorized and *why*, we provide deeper insights into the underlying mechanisms of CLIP. Our findings highlight that memorization behavior of CLIP models falls between that of supervised and self-supervised models. In particular, CLIP highly memorizes data points with incorrect and imprecise captions, much like supervised models memorize mislabeled samples, but it also memorizes atypical examples. Furthermore, we find that memorization in CLIP happens mainly within the text encoder, which motivates instantiating mitigation strategies there. By doing so, we can not only *reduce memorization* in CLIP but also *improve* downstream generalization, a result that challenges the typical trade-offs seen in both supervised and self-supervised learning.

REFERENCES

Muhammad Ali and Salman Khan. Clip-decoder: Zeroshot multilabel classification using multimodal clip aligned representations. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pp. 4675–4679, 2023.

Antonis Antoniades, Xinyi Wang, Yanai Elazar, Alfonso Amayuelas, Alon Albalak, Kexun Zhang, and William Yang Wang. Generalization vs. memorization: Tracing language models' capabilities back to pretraining data. In *ICML 2024 Workshop on Foundation Models in the Wild*, 2024.

Devansh Arpit, Stanisław Jastrzebski, Nicolas Ballas, David Krueger, Emmanuel Bengio, Maxinder S Kanwal, Tegan Maharaj, Asja Fischer, Aaron Courville, Yoshua Bengio, et al. A closer look at memorization in deep networks. In *International conference on machine learning*, pp. 233–242. PMLR, 2017.

Alberto Baldrati, Marco Bertini, Tiberio Uricchio, and Alberto Del Bimbo. Conditioned and composed image retrieval combining and partially fine-tuning clip-based features. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 4959–4968, 2022a.

Alberto Baldrati, Marco Bertini, Tiberio Uricchio, and Alberto Del Bimbo. Effective conditioned and composed image retrieval combining clip-based features. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pp. 21466–21474, 2022b.

Peter L Bartlett, Philip M Long, Gábor Lugosi, and Alexander Tsigler. Benign overfitting in linear regression. *Proceedings of the National Academy of Sciences*, 117(48):30063–30070, 2020.

Nicholas Carlini, Chang Liu, Úlfar Erlingsson, Jernej Kos, and Dawn Song. The secret sharer: Evaluating and testing unintended memorization in neural networks. In *28th USENIX Security Symposium (USENIX Security 19)*, pp. 267–284, 2019.

Nicholas Carlini, Florian Tramer, Eric Wallace, Matthew Jagielski, Ariel Herbert-Voss, Katherine Lee, Adam Roberts, Tom Brown, Dawn Song, Ulfar Erlingsson, et al. Extracting training data from large language models. In *30th USENIX Security Symposium (USENIX Security 21)*, pp. 2633–2650, 2021.

Nicholas Carlini, Matthew Jagielski, Chiyuan Zhang, Nicolas Papernot, Andreas Terzis, and Florian Tramer. The privacy onion effect: Memorization is relative. *Advances in Neural Information Processing Systems*, 35:13263–13276, 2022.

Mathilde Caron, Hugo Touvron, Ishan Misra, Hervé Jégou, Julien Mairal, Piotr Bojanowski, and Armand Joulin. Emerging properties in self-supervised vision transformers. In *Proceedings of the IEEE/CVF international conference on computer vision*, pp. 9650–9660, 2021.

Satrajit Chatterjee. Learning and memorization. In *International conference on machine learning*, pp. 755–763. PMLR, 2018.

Mehdi Cherti, Romain Beaumont, Ross Wightman, Mitchell Wortsman, Gabriel Ilharco, Cade Gordon, Christoph Schuhmann, Ludwig Schmidt, and Jenia Jitsev. Reproducible scaling laws for contrastive language-image learning. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 2818–2829, June 2023.

Jia Deng, Wei Dong, Richard Socher, Li-Jia Li, Kai Li, and Li Fei-Fei. Imagenet: A large-scale hierarchical image database. In *2009 IEEE conference on computer vision and pattern recognition*, pp. 248–255. Ieee, 2009.

Akshay Dhamija, Manuel Gunther, Jonathan Ventura, and Terrance Boult. The overlooked elephant of object detection: Open set. In *Proceedings of the IEEE/CVF Winter Conference on Applications of Computer Vision*, pp. 1021–1030, 2020.

Lijie Fan, Dilip Krishnan, Phillip Isola, Dina Katabi, and Yonglong Tian. Improving clip training with language rewrites. In A. Oh, T. Naumann, A. Globerson, K. Saenko, M. Hardt, and S. Levine (eds.), *Advances in Neural Information Processing Systems*, volume 36, pp. 35544–35575. Curran Associates, Inc., 2023. URL https://proceedings.neurips.cc/paper_files/paper/2023/file/6fa4d985e7c434002fb6289ab9b2d654-Paper-Conference.pdf.

Vitaly Feldman. Does learning require memorization? a short tale about a long tail. In *Proceedings of the 52nd Annual ACM SIGACT Symposium on Theory of Computing*, pp. 954–959, 2020.

Vitaly Feldman and Chiyuan Zhang. What neural networks memorize and why: Discovering the long tail via influence estimation. *Advances in Neural Information Processing Systems*, 33:2881–2891, 2020.

Gabriel Ilharco, Mitchell Wortsman, Ross Wightman, Cade Gordon, Nicholas Carlini, Rohan Taori, Achal Dave, Vaishaal Shankar, Hongseok Namkoong, John Miller, Hannaneh Hajishirzi, Ali Farhadi, and Ludwig Schmidt. Openclip, July 2021. URL https://doi.org/10.5281/zenodo.5143773.

Matthew Jagielski, Om Thakkar, Florian Tramer, Daphne Ippolito, Katherine Lee, Nicholas Carlini, Eric Wallace, Shuang Song, Abhradeep Guha Thakurta, Nicolas Papernot, et al. Measuring forgetting of memorized training examples. In *The Eleventh International Conference on Learning Representations*, 2022.

Bargav Jayaraman, Chuan Guo, and Kamalika Chaudhuri. Déjà vu memorization in vision-language models, 2024. URL https://arxiv.org/abs/2402.02103.

Alex Krizhevsky, Geoffrey Hinton, et al. Learning multiple layers of features from tiny images. 2009.

Nishant Kumar, Siniša Šegvić, Abouzar Eslami, and Stefan Gumhold. Normalizing flow based feature synthesis for outlier-aware object detection. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 5156–5165, 2023.

Junnan Li, Dongxu Li, Caiming Xiong, and Steven Hoi. Blip: Bootstrapping language-image pre-training for unified vision-language understanding and generation. In *International conference on machine learning*, pp. 12888–12900. PMLR, 2022.

Tsung-Yi Lin, Michael Maire, Serge J. Belongie, Lubomir D. Bourdev, Ross B. Girshick, James Hays, Pietro Perona, Deva Ramanan, Piotr Doll'a r, and C. Lawrence Zitnick. Microsoft COCO: common objects in context. *CoRR*, abs/1405.0312, 2014. URL http://arxiv.org/abs/1405.0312.

Hongbin Liu, Jinyuan Jia, Wenjie Qu, and Neil Zhenqiang Gong. Encodermi: Membership inference against pre-trained encoders in contrastive learning. In *Proceedings of the 2021 ACM SIGSAC Conference on Computer and Communications Security*, pp. 2081–2095, 2021.

Casey Meehan, Florian Bordes, Pascal Vincent, Kamalika Chaudhuri, and Chuan Guo. Do ssl models have déjà vu? a case of unintended memorization in self-supervised learning. *arXiv e-prints*, pp. arXiv–2304, 2023.

Junting Pan, Ziyi Lin, Yuying Ge, Xiatian Zhu, Renrui Zhang, Yi Wang, Yu Qiao, and Hongsheng Li. Retrieving-to-answer: Zero-shot video question answering with frozen large language models. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pp. 272–283, 2023.

Alec Radford, Jong Wook Kim, Chris Hallacy, Aditya Ramesh, Gabriel Goh, Sandhini Agarwal, Girish Sastry, Amanda Askell, Pamela Mishkin, Jack Clark, et al. Learning transferable visual models from natural language supervision. In *International conference on machine learning*, pp. 8748–8763. PMLR, 2021.

Ildus Sadrtdinov, Nadezhda Chirkova, and Ekaterina Lobacheva. On the memorization properties of contrastive learning. *arXiv preprint arXiv:2107.10143*, 2021.

Piyush Sharma, Nan Ding, Sebastian Goodman, and Radu Soricut. Conceptual captions: A cleaned, hypernymed, image alt-text dataset for automatic image captioning. In *Proceedings of ACL*, 2018.

Congzheng Song, Thomas Ristenpart, and Vitaly Shmatikov. Machine learning models that remember too much. In *Proceedings of the 2017 ACM SIGSAC Conference on computer and communications security*, pp. 587–601, 2017.

Haoyu Song, Li Dong, Weinan Zhang, Ting Liu, and Furu Wei. Clip models are few-shot learners: Empirical studies on vqa and visual entailment. In *Proceedings of the 60th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pp. 6088–6100, 2022.

Bart Thomee, David A. Shamma, Gerald Friedland, Benjamin Elizalde, Karl Ni, Douglas Poland, Damian Borth, and Li-Jia Li. Yfcc100m: the new data in multimedia research. *Commun. ACM*, 59(2):64–73, January 2016a. ISSN 0001-0782. doi: 10.1145/2812802. URL https://doi.org/10.1145/2812802.

Bart Thomee, David A Shamma, Gerald Friedland, Benjamin Elizalde, Karl Ni, Douglas Poland, Damian Borth, and Li-Jia Li. Yfcc100m: The new data in multimedia research. *Communications of the ACM*, 59(2):64–73, 2016b.

Kushal Tirumala, Aram Markosyan, Luke Zettlemoyer, and Armen Aghajanyan. Memorization without overfitting: Analyzing the training dynamics of large language models. *Advances in Neural Information Processing Systems*, 35:38274–38290, 2022.

Wenhao Wang, Adam Dziedzic, Michael Backes, and Franziska Boenisch. Localizing memorization in ssl vision encoders. *arXiv preprint arXiv:2409.19069*, 2024a.

Wenhao Wang, Muhammad Ahmad Kaleem, Adam Dziedzic, Michael Backes, Nicolas Papernot, and Franziska Boenisch. Memorization in self-supervised learning improves downstream generalization. In *The Twelfth International Conference on Learning Representations (ICLR)*, 2024b.

Zhengbo Wang, Jian Liang, Ran He, Nan Xu, Zilei Wang, and Tieniu Tan. Improving zero-shot generalization for clip with synthesized prompts. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pp. 3032–3042, 2023.

Chiyuan Zhang, Samy Bengio, Moritz Hardt, Benjamin Recht, and Oriol Vinyals. Understanding deep learning requires rethinking generalization. In *International Conference on Learning Representations*, 2016.

Renrui Zhang, Wei Zhang, Rongyao Fang, Peng Gao, Kunchang Li, Jifeng Dai, Yu Qiao, and Hongsheng Li. Tip-adapter: Training-free adaption of clip for few-shot classification. In *European conference on computer vision*, pp. 493–510. Springer, 2022.

A Appendix

A.1 Extended Background

Déjà Vu Memorization in CLIP. The Déjà Vu memorization framework (Jayaraman et al., 2024) is the only existing other work that attempts to quantify memorization in vision-language models. It uses the text embedding of a training image caption to retrieve relevant images from a public dataset of images. It then measures the fraction of ground-truth objects from the original image that are present in the retrieved images. If the training pair is memorized, retrieved images have a higher overlap in ground truth objects, beyond the simple correlation. While valuable, several aspects warrant further consideration for broader applicability of the framework. First, its focus on object-level memorization ignores non-object information like spatial relationships or visual patterns that can also influence memorization (Feldman, 2020; Wang et al., 2024b). To perform object retrieval, the framework also relies on object detection and annotation tools, which may introduce variability based on the accuracy and robustness of these tools. Additionally, the assumption that public datasets with similar distributions to the training data are readily available may not always hold, necessitating alternative approaches. Moreover, the framework does not analyze why certain images are memorized limiting detailed analysis. Finally, while Déjà Vu must address the challenge of distinguishing between memorization and spurious correlations, CLIPMem avoids this by directly assessing memorization on the output representations of the model. One notable difference between the results of our approach and Déjà Vu's is that their findings show that their mitigation strategies can reduce memorization, but at the cost of decreased model utility. CLIPMem, in contrast, does not observe trade-offs between memorization and performance.

A.2 Extended Experimental Setup

General Setup. All the experiments in the paper are done on a server with 4 A100 (80 GB) GPUs and a work station with one RTX 4090 GPU(24 GB). We detail the setup for our model training, both CLIP and SSL (relying on DINO) in Table 2.

Table 2: **Experimental Setup.** We provide details on our setup for encoder training and evaluation.

	Model Training			Linear Probing		
	CLIP	DINO	Supervised ViT	CLIP	DINO	Supervised ViT
Training Epoch	100	300	100	45	45	45
Warm-up Epoch	5	30	5	5	5	5
Batch Size	128	1024	128	4096	4096	4096
Optimizer	Adam	AdamW	Adam	LARS	LARS	LARS
Learning rate	1.2e-3	2e-3	1e-3	1.6	1.6	1.6
Learning rate Schedule	Cos. Decay	Cos. Decay	Cos. Decay	Cos. Decay	Cos. Decay	Cos. Decay

Experimental Setup for SSLMem. To experimentally evaluate memorization using the SSLMem framework (Wang et al., 2024b), the training dataset S is split into four sets: *shared set* (S_S) used for training both encoders f and g; *candidate set* (S_C) used only for training encoder f; *independent set* (S_I) data used only for training encoder g; and an additional *extra set* (S_I) from the test set not used for training either f or g. For training encoders, encoder f is trained on $S_S \cup S_C$, while encoder g is trained on $S_S \cup S_I$. The alignment losses $\mathcal{L}_{\text{align}}(f, x)$ and $\mathcal{L}_{\text{align}}(g, x)$ are computed for both encoders, and the memorization score $m(x)$ for each data point is derived as the difference between these alignment losses, normalized to a range between -1 and 1. A score of 0 indicates no memorization, $+1$ indicates the strongest memorization by f, and -1 indicates the strongest memorization by g.

Normalization on CLIPMem. For improved interpretability, we normalize our CLIPMem scores to a range of $[-1, 1]$. A memorization score of 0 indicates no memorization, $+1$ indicates the strongest memorization on CLIP model f, and -1 indicates the strongest memorization on CLIP model g. We find the normalized CLIPMem score for a dataset using the following process: For each image-text pair (I, T), we first calculate the CLIPMem score as the difference in alignment scores between two CLIP models f and g. Once CLIPMem scores are computed for all data points, we normalize them by dividing each score by the range, which is the difference between the maximum and minimum scores in the dataset. Finally, we report the normalized CLIPMem score for a dataset as the average of these normalized values.

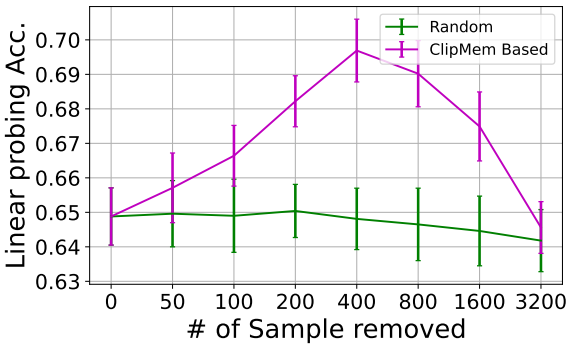


Figure 7: **Removing memorized samples.** We show the effect on downstream performance in terms of ImageNet linear probing accuracy and CLIPMem for a CLIP model trained on COCO using 5 text captions instead of 1, like done in Figure 6. We observe the same trend, with the difference that the peak is at roughly 500 removed samples rather than 100. This is likely due to the increase in captions (by factor 5) that causes increase in mis-captioned samples.

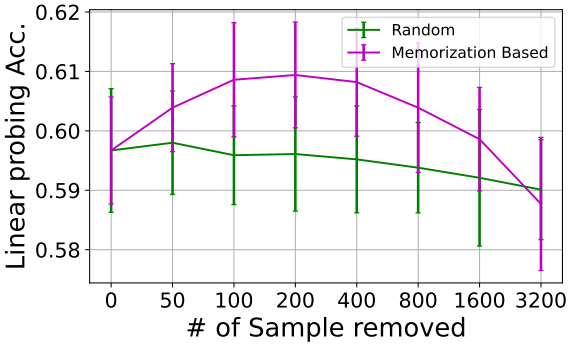


Figure 8: **Removing memorized samples in supervised learning.** We train a ViT-tiny on CIFAR10 (Krizhevsky et al., 2009) using supervised learning. We use our evaluation setup with S_C, S_S, S_I, and S_E to approximate the memorization metric from Feldman (2020). We use 5000 samples in S_C, but before training, we flip the labels of 200 samples. We calculate memorization over all samples in S_C and test the linear probing accuracy with ImageNet resized to 32*32 on the representations output before the original classification layer.

A.3 Additional Experiments

A.3.1 Memorization vs. Generalization in CLIP

Extending evaluation. In Figure 7, we perform the same experiment as in Figure 6, but on a CLIP model trained with 5 captions instead of 1. We observe the same trend, with the difference that the peak is at roughly 500 removed samples rather than 100. This is likely due to the increase in captions (by factor 5) that causes increase in mis-captioned samples.

Verifying the hypothesis on memorizing mis-captioned samples through supervised learning. We repeat the same experiment in the supervised learning setup to understand where the increase and then decrease in linear probing accuracy stems from. To test our hypothesis that it stems from "mis-captioned" samples, we "poison" our supervised model by flipping the labels of 200 data points before training. Then, we approximate the memorization metric from Feldman (2020) in our setup and remove highly memorized vs. random data points. In the same vein as in Appendix A.3.1, we first observe an increase in linear probing accuracy when removing memorized samples (instead of random samples). The peak is at roughly 200 data points, *i.e.,* the number of deliberately mislabeled samples. Until the cutoff point at roughly 3200 examples, linear probing accuracy is still higher when removing most memorized rather than random samples, which might suggest that there are other

Table 3: **Using different/multiple captions during training.** We evaluate CLIPMem how memorization on different data subsets and linear probing accuracy on ImageNet differ when using 1 caption (baseline), 5 COCO captions, one chosen at random at every round (random), and 5 COCO captions, but all chosen equally often, *i.e.,* 20 out of 100 training epochs (balanced). We observe that increasing the number of captions reduces highest memorization. Yet, only when we balance the usage of caption, also model performance increases.

	baseline	random	balanced
Avg. CLIPMem (Top 10 samples)	0.792	0.788	0.790
Avg. CLIPMem (Top 20%)	0.552	0.531	0.540
Linear Probing Acc.	63.11% $\pm$ 0.91%	62.44% $\pm$ 1.18%	64.88% $\pm$ 0.83%

Table 4: **The CLIPMem and linear probing accuracy of model trained with original coco captions and captions generated by GPT3.5.** For 'Single Caption', only one caption is used during training. For 'Five Caption', all five caption are used equally during training (every caption trained for 20 epoch out of 100). The linear probing accuracy is tested on ImageNet

	COCO		GPT3.5	
	Single Caption	Five Caption	Single Caption	Five Caption
CLIPMem	0.438	0.423	0.430	0.411
LP. Acc.	63.11% $\pm$ 0.91%	64.88% $\pm$ 0.83%	63.09% $\pm$ 1.12%	64.47 $\pm$ 0.72%

outliers or inherently mislabeled samples whose removal improves model performance. After the cutoff, we observe the behavior as observed in prior work (Wang et al., 2024b; Feldman, 2020) that reducing memorization harms generalization more than reducing random data points from training.

A.3.2 The Effect of Captions

In Table 3, we show that using more captions during training reduces memorization and that by using each caption at the same frequency over the training epochs, we can additionally improve model performance. Additionally, we show that captions generated by GPT3.5 have the same effect as the original COCO captions on memorization and linear probing accuracy in Table 4.

A.4 The Effect of Model Size

In Table 5, we present how the model size affects the memorization level of CLIP models. Both models are trained using the same dataset and settings. We observe that with more parameters (larger model size), encoders have higher memorization capacity. This aligns with findings from previous research (Wang et al., 2024b; Feldman, 2020; Meehan et al., 2023).

A.5 Verification of infinite data regimes

To evaluate CLIPMem over infinite data regimes (*i.e.,* using a single training run where no data point is repeated), we use a subset D (containing 7050000 samples) of YFCC100M dataset (Thomee et al., 2016b) to train another pair of ViT-Base models for only 1 epoch. Following our definition of CLIPMem, we further divide D into S_S with 6950000 samples, S_C with 50000 samples, and S_I with 50000 samples. The reason we use 7M (6950000+50000) samples to train either model f or model g is to make sure the newly trained model has the same number of training samples as the model trained with K-epoch runs (70000 samples/epoch * 100 epoch). The results in Table 6 show that the model trained with infinite data regimes has higher linear probing accuracy on ImageNet as a downstream task and lower memorization scores, as measured by CLIPMem. This aligns with the fact that duplicated data points increase the memorization level and make the model over-fit, hence reducing the generalization (Wang et al., 2024b; Feldman, 2020). The results in Figure 9 show that the most memorized samples according to CLIPMem in the model trained with infinite data regimes are also samples with imprecise or incorrect captions. This aligns with our statements in Section 4.5.

Table 5: **CLIPMem and linear probing accuracy of models with different sizes.** The models are trained using identical settings and the same subset of the COCO dataset. Linear probing accuracy is tested on the ImageNet dataset as the downstream task.

Model	CLIPMem	Lin. Prob. Acc. (ImageNet)
ViT-base (Baseline in main paper)	0.438	63.11% ± 0.91%
ViT-large	0.457	67.04% ± 1.05%

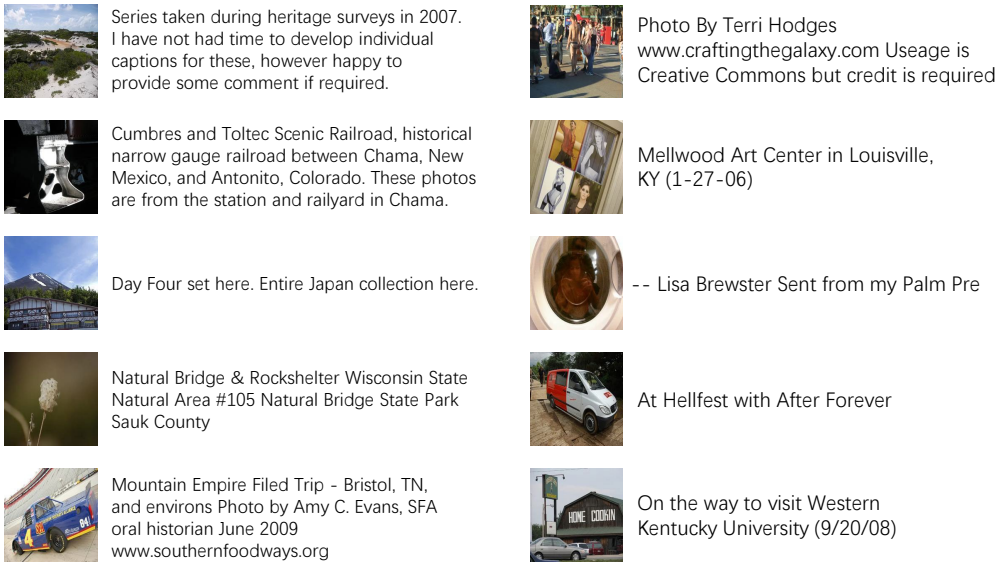


Figure 9: **Top 10 memorized samples according to CLIPMem in the model trained under infinite data regimes on YFCC100M.** The model is trained for one epoch, *i.e.,* seeing each training data point exactly once. Even in this setup, the most memorized samples are still the ones with imprecise or incorrect captions.

A.6 Evaluation on BLIP

To verify the effectiveness of CLIPMem over other similar multi-modal models, we train a BLIP model on COCO dataset following the same settings as the baseline model in the main paper. We present the results for CLIPMem over all 4 data subsets in Figure 10, which is in agreement with the results of the CLIP model in Figure 2a. We also present the UnitMem results for BLIP model in Figure 4, which is also very similar to the result of CLIP models

A.7 Memorization distribution During training

We present the distributions of neurons with highest UnitMem during training in Figure 11. These results highly consistently indicate that in the early stages of training, neuronal memory occurs mainly in the lower layer of the clip model, while in the middle and later stages of training, neuronal memory is more concentrated in the later layer of the model.

A.8 Human vs Machine Generated Captions

For each image in the COCO dataset, we use GPT 3.5 (specifically, gpt-3.5-turbo) to generate 5 captions (from scratch). We use the following instruction in the OpenAI API:

```
def generate_description_for_image(image_caption, clip_features):
    prompt = f"Here is an image with the caption: '{image_caption}'. "
    prompt += f"Based on this caption and the visual features
    represented by this embedding '{clip_features}',
    please generate a new detailed description."
```

Table 6: **Evaluation of CLIPMem under infinite data regimes, *i.e.*, seeing every data point only once during training vs training with 100 epochs.** We observe that both setups reach comparable downstream accuracy and memorization.

Model	CLIPMem	Lin. Prob. Acc. (ImageNet)
ViT-Base (YFCC 7M, 1 epoch)	0.425	64.83% ± 1.04%
ViT-Base (COCO 70K, 100 epochs)	0.438	63.11% ± 0.91%

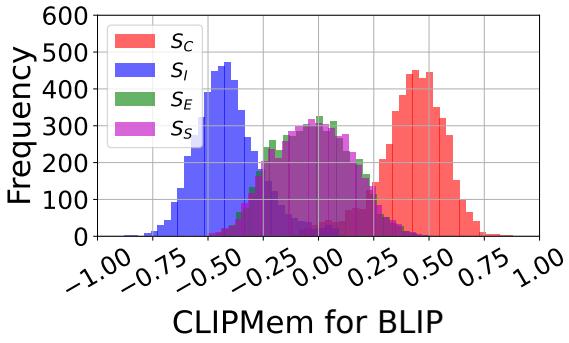
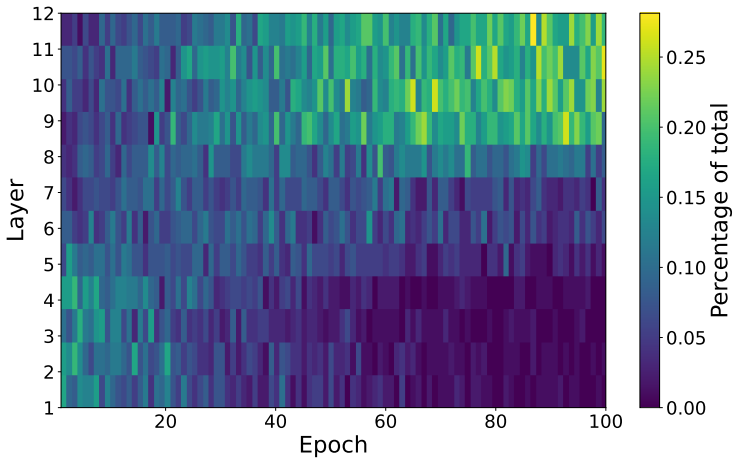


Figure 10: **Memorization scores across data subsets on BLIP models.** We train a BLIP model on COCO standard image cropping and no text augmentation. We present the results for CLIPMem over all four data subsets, which is in agreement with the results of the CLIP model in Figure 2a.

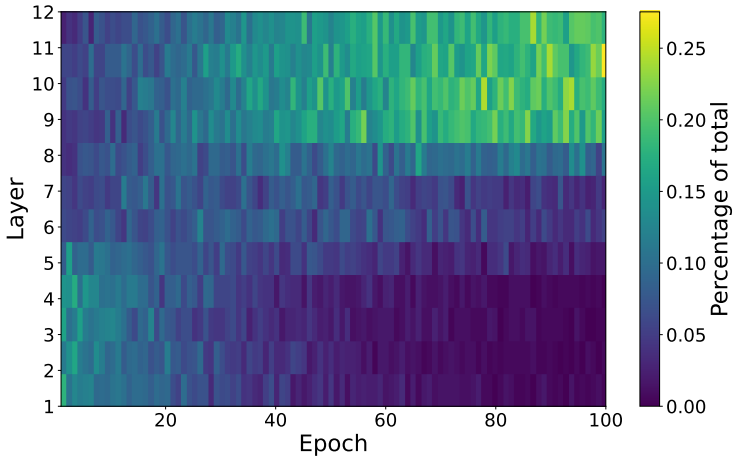
```
response = openai.ChatCompletion.create(
    model="gpt-3.5-turbo",
    messages=[
        {"role": "system", "content": "You are a helpful
        assistant that generates captions for images."},
        {"role": "user", "content": prompt}
    ]
)
return response['choices'][0]['message']['content']
```

We present the obtained captions in Figure 18. In Figure 12b, we analyze the pairwise cosine similarity in the original COCO and the GPT3.5 generated captions. We find that the GPT3.5 generated captions are slightly more uniform than the original COCO captions, reflecting in a higher pairwise cosine similarity.

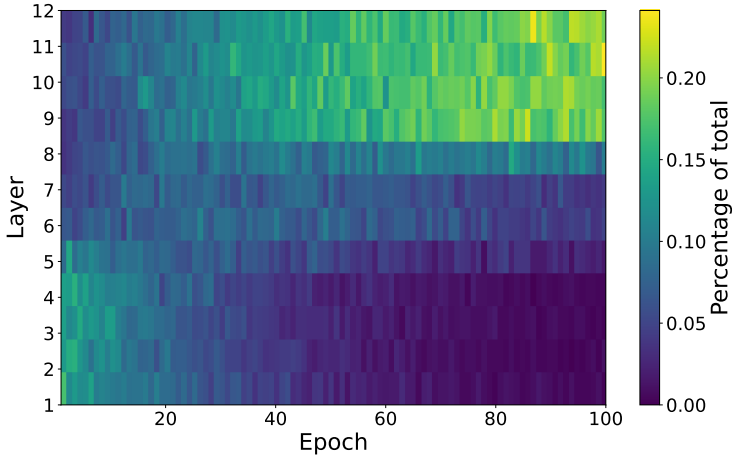
A.9 Examples for Memorized Samples



(a) **Top 1% neurons**



(b) **Top 3% neurons**

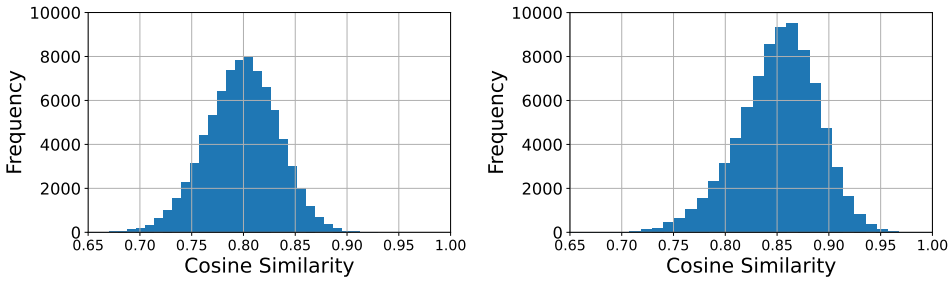


(c) **Top 5% neurons**

Figure 11: **Distribution of top 1%, 3%, and 5% neurons with highest UnitMem during training.** We train a CLIP model on COCO standard image cropping and no text augmentation following the settings of baseline model in main paper. We record the neurons with top 1%, 3%, and 5% of highest UnitMem during training (every epoch). We observe that while during early training stages, memorization focuses on lower layers, during later stages of training, it is mainly in the last layers.

Table 7: **The machine generated captions provide similar performance to the original human-generated captions.** We report the CLIPMem and linear probing accuracy of model trained with original COCO captions and captions generated by GPT 3.5. For the 'Single Caption', only a single caption is used during training. For 'Five Captions', all five captions are used equally during training (every caption trained for 20 epochs out of 100). The linear probing accuracy is tested on the ImageNet dataset as the downstream task.

	COCO		GPT 3.5	
	Single Caption	Five Captions	Single Caption	Five Captions
CLIPMem	0.438	0.423	0.430	0.411
Linear Probing Accuracy (ImageNet)	63.11% ± 0.91%	64.88% ± 0.83%	63.09% ± 1.12%	64.47 ± 0.72%



(a) **COCO (Average: 0.798)** (b) **GPT3.5 (Average: 0.851)**

Figure 12: **Pairwise cosine similarity of 5 captions from COCO and generated by GPT3.5.**

Noise	CLIPMem	Lin. Prob. Acc. (ImageNet)
None	0.438	63.11% ± 0.91%
$\mathcal{N}(0.01)$	0.435	63.36% ± 0.88%
$\mathcal{N}(0.05)$	0.428	64.02% ± 1.12%
$\mathcal{N}(0.10)$	0.421	64.95% ± 0.96%
$\boldsymbol{\mathcal{N}(0.15)}$	**0.417**	**65.34% ± 0.84%**
$\mathcal{N}(0.20)$	0.422	64.83% ± 0.92%
$\mathcal{N}(0.25)$	0.436	63.28% ± 0.79%
$\mathcal{N}(0.30)$	0.447	61.50% ± 0.86%
$\mathcal{N}(0.50)$	0.491	57.04% ± 1.11%
$\mathcal{N}(0.75)$	0.501	52.28% ± 0.98%
$\mathcal{N}(1.00)$	0.504	51.92% ± 1.03%

Table 8: **Noising text embedding during training.** We present the impact of adding noise to the text embedding during training for the ViT-base trained on COCO.

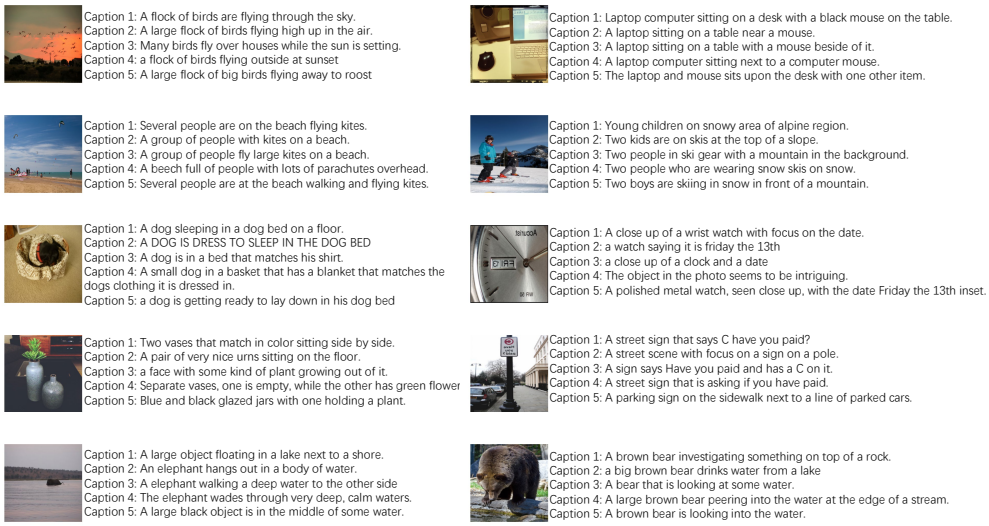


Figure 13: **The 10 samples with lowest CLIPMem in the CLIP model trained with all 5 captions.** We can see that these samples contain clear concepts and precise captions.

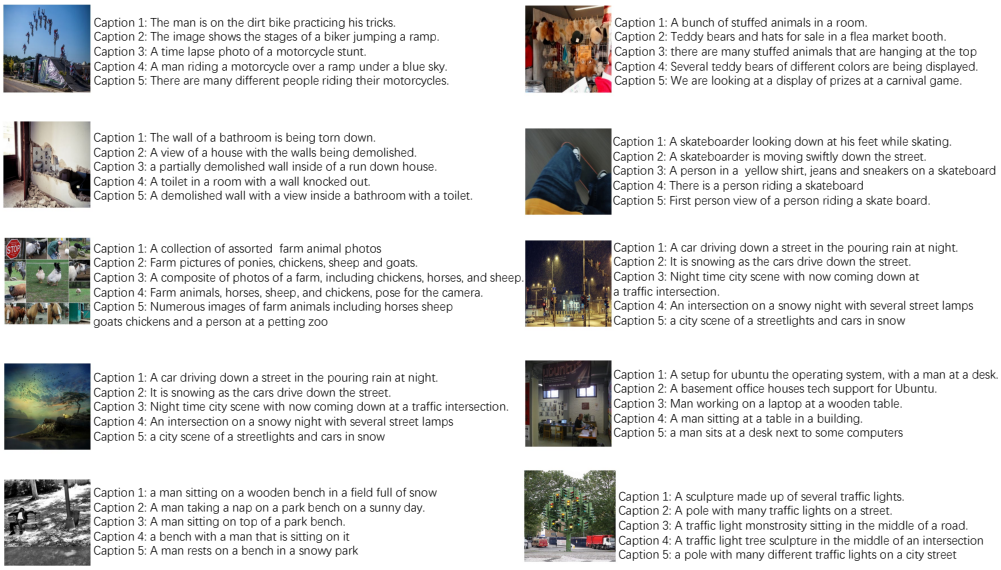


Figure 14: **The 10 samples with highest CLIPMem in the CLIP model trained with all 5 captions.** We can see that these samples contain atypical, difficult samples with imprecise or incorrect captions.

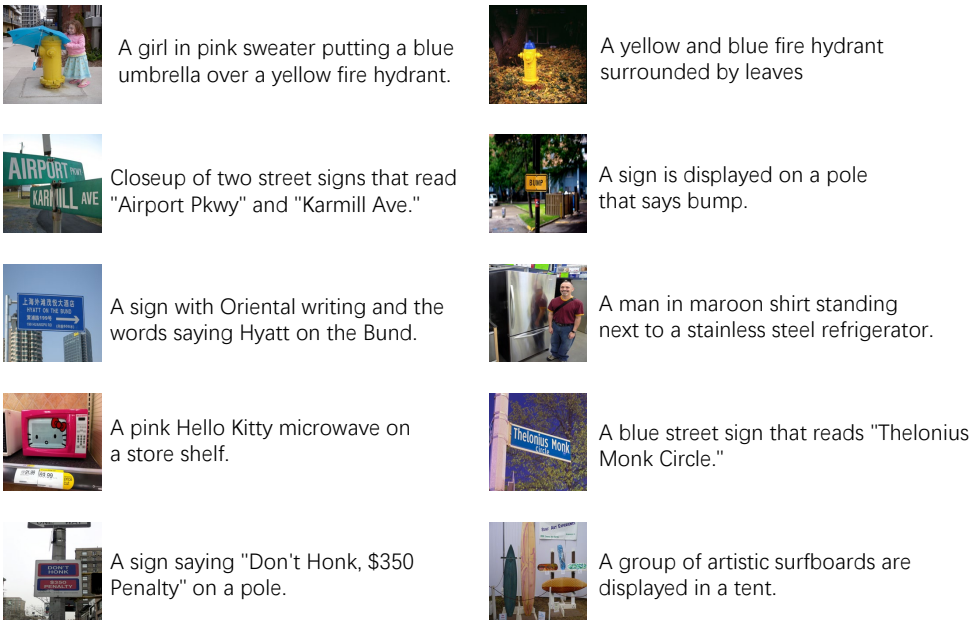


Figure 15: **The 10 samples with lowest CLIPMem in the CLIP model trained with 1 caption.** We can see that these samples contain clear concepts and precise captions.

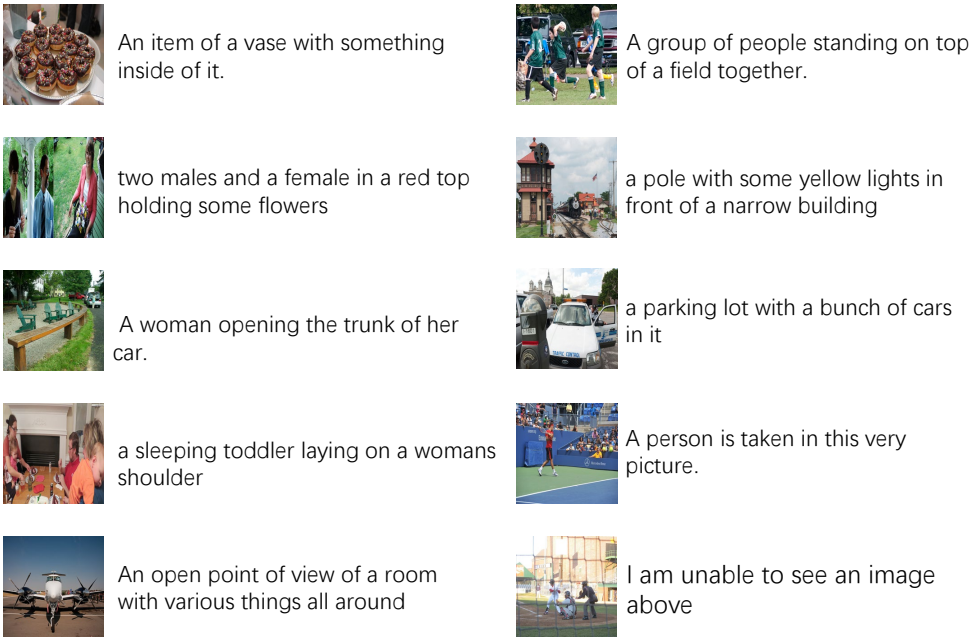


Figure 16: **The 10 samples with highest CLIPMem in the CLIP model trained with 1 caption.** We can see that these samples contain atypical, difficult samples with imprecise or incorrect captions.

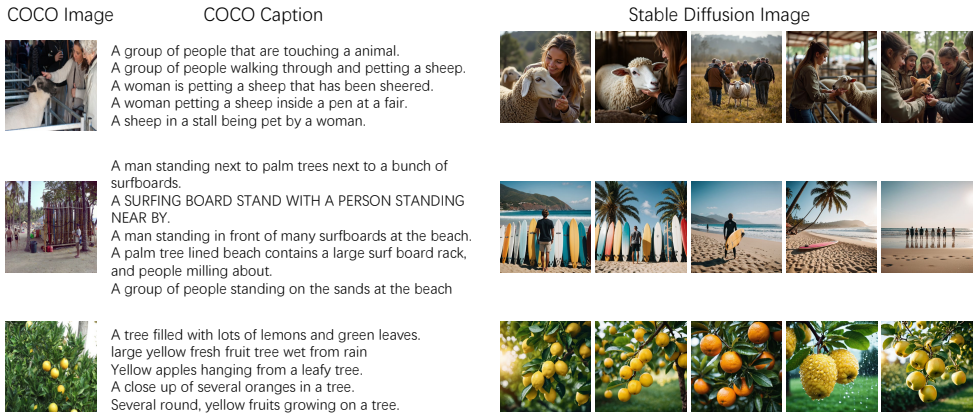


Figure 17: **Samples of images generated by Stable Diffusion.** We present the generated images based on the COCO captions.

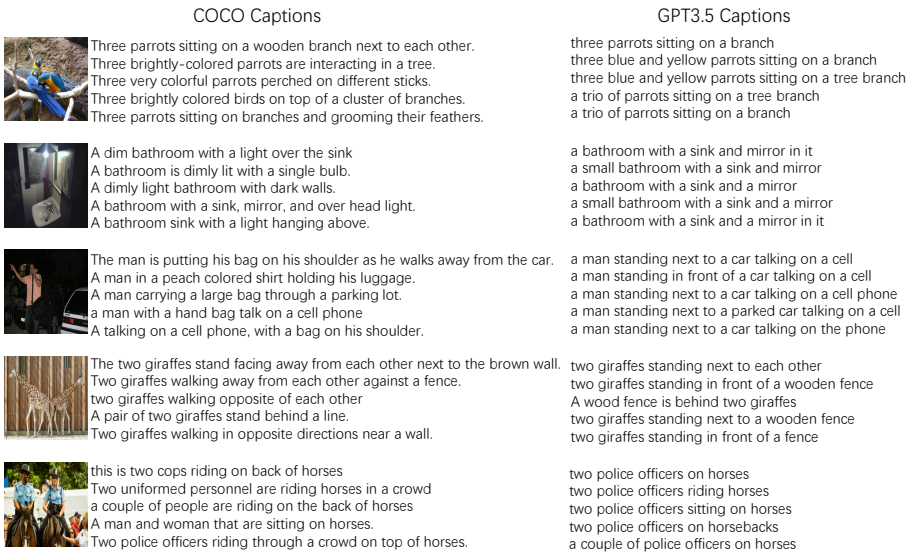
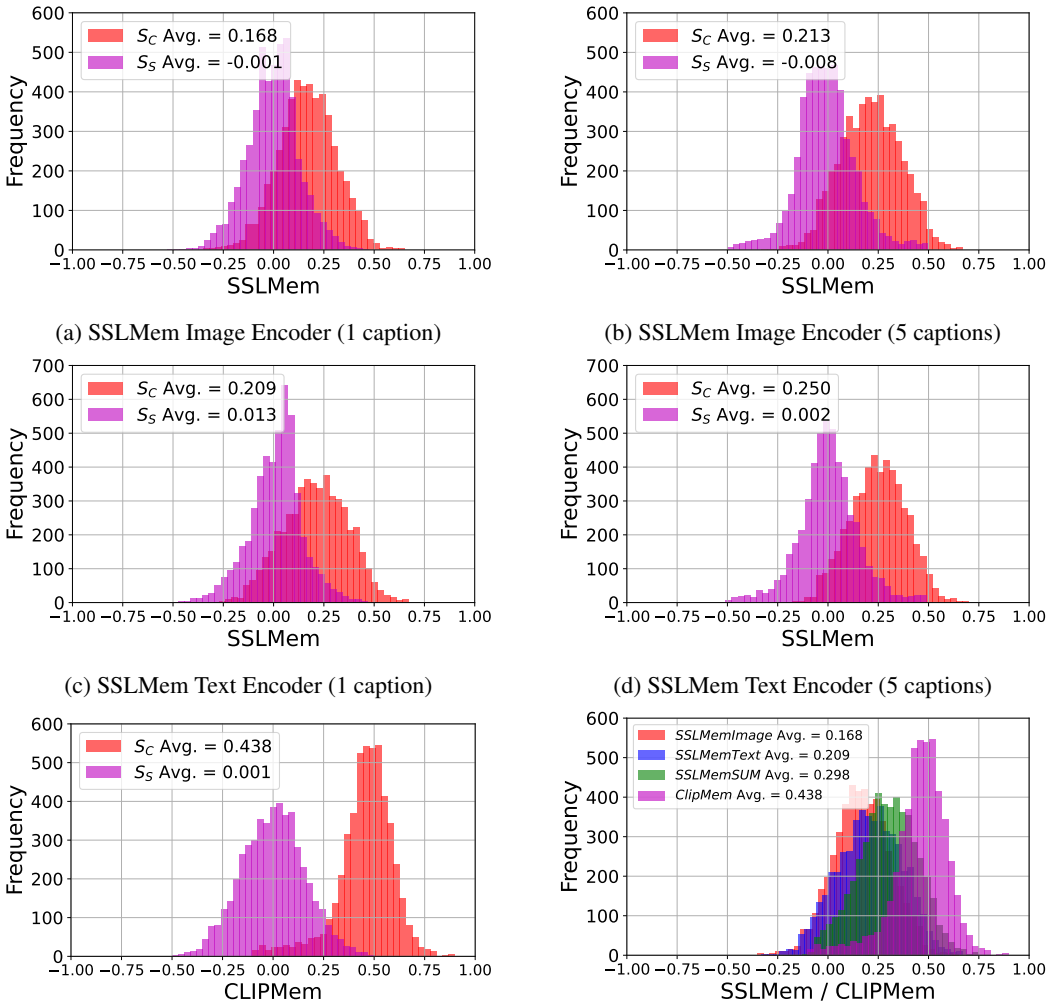


Figure 18: **Sample captions generated by GPT3.5.** We present the generated captions and the original image and captions from COCO.



(a) SSLMem Image Encoder (1 caption)

(b) SSLMem Image Encoder (5 captions)

(c) SSLMem Text Encoder (1 caption)

(d) SSLMem Text Encoder (5 captions)

(e) CLIPMem

(f) SSLMem, Naive Sum of SSLMem and CLIPMem

Figure 19: **Evaluation of SSLMem and CLIPMem on a CLIP model trained on COCO.** Extended version of Figure 3 where we also include SSLMem calculated on encoders trained with 5 captions instead of 1. The trends in both cases are the same. SSLMem for the CLIP Models trained with the 5 captions is slightly higher since SSLMem uses the captions as augmentations for the calculation of the memorization. Overall, our CLIPMem reports the strongest memorization signal for CLIP.