Demystifying Unsupervised Semantic Correspondence Estimation

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Abstract. We explore semantic correspondence estimation through the lens of unsupervised learning. We thoroughly evaluate several recently proposed unsupervised methods across multiple challenging datasets using a standardized evaluation protocol where we vary factors such as the backbone architecture, the pre-training strategy, and the pre-training and finetuning datasets. To better understand the failure modes of these methods, and in order to provide a clearer path for improvement, we provide a new diagnostic framework along with a new performance metric that is better suited to the semantic matching task. Finally, we introduce a new unsupervised correspondence approach which utilizes the strength of pre-trained features while encouraging better matches during training. This results in significantly better matching performance compared to current state-of-the-art methods.

Keywords: semantic correspondence, self-supervised learning

1 Introduction

In metaphysics, the correspondence theory of truth posits that without the notion of correspondence, there cannot be truth [15]. Analogously, correspondence estimation also holds a very important place as one of the core problems in computer vision. The ability to reliably obtain accurate pixel-level correspondence underpins a diverse range of tasks from stereo estimation, optical flow, structure-from-motion, through to visual tracking. Distinct from these lower-level objectives, semantic correspondence estimation, the task of matching different regions, parts, and landmarks across distinct object instances, is crucial to developing systems that can perform higher-level visual reasoning in diverse environments with objects that can vary significantly in both appearance and the configuration of their constituent parts.

Manually obtaining semantic correspondence supervision, for example in the form of annotated object landmarks, is an arduous and time consuming task. As a result, several works have instead attempted to understand to what extent semantic regions and parts emerge from conventionally trained supervised image classification networks [43, 72, 78, 17]. These works have shown such semantic information is indeed present in the representations encoded by these networks, at least to some degree. Recently, a body of work has emerged that aims to learn

semantic correspondence through self-supervision alone, i.e. without the need for ground truth supervision at training time [63, 61, 11, 29].

While we have observed progress on unsupervised semantic correspondence estimation, a number of questions are still underexplored and unanswered. For instance, it is not clear how well current approaches generalize beyond more simplified object categories such as human faces to more complex non-rigidly deforming categories that vary in terms of both pose and appearance. Recent works have also been able to avail of advances in self-supervised learning of general visual representations [11, 29], thus making it difficult to properly understand how they compare to older methods that do not utilize such self-supervised pre-training. In this work, we attempt to shine light on the above questions in addition to exploring the role other factors such as the impact of pre-training and finetuning data, backbone models, and the underlying evaluation criteria used to asses performance. Inspired by detailed benchmarking investigation in human pose estimation [55], we provide a thorough evaluation of the success and failure modes of current methods to provide guidance for future progress.

We make the following three contributions: (i) A standardized evaluation of multiple existing approaches for unsupervised semantic correspondence estimation across five challenging datasets. (ii) A new, conceptually simple, unsupervised training objective that results in superior semantic matching performance. (iii) A detailed breakdown of the current failure cases for current best performing approaches and our proposed new unsupervised method.

2 Related Work

Supervised Semantic Correspondence. Pre-deep learning work tackled semantic correspondence estimation as a local region matching problem using hand crafted features [40, 31, 6], or as offset matching using object proposals [19]. In the deep learning era, several works investigated if objects parts and regions emerge from image classification models [72, 78, 17], i.e. models trained only with image-level class supervision. [43] showed that deep CNN features could actually be used for semantic matching. Subsequent work built on this by proposing new architectures specifically designed for semantic matching [14, 20, 33, 51, 24, 38, 32]. Some of these approaches focused on combining multilevel features (i.e. hypercolumn features) from deep networks [64, 45, 47, 76], aggregating information from features using 4D convolutions [53, 52, 39, 37], leveraging geometric relations via Hough transforms [44], or using optimal transport [59, 41]. Some matching methods formulate the problem as one of flow estimation between images [40, 45]. However, unlike optical flow, semantic correspondence methods need to be able to handle intra and inter class variations when matching points. Recently, the use of transformer-based models has also been explored [12, 27]. In contrast to most of the above works, we focus on the unsupervised setting, whereby no supervised keypoint annotations are used to train our models.
Unsupervised Semantic Correspondence. Recent progress in self-supervised learning has resulted in a suite of methods that are capable of extracting dis-

criminative whole image representations without requiring explicit supervision [50, 70, 8, 18, 21]. While the majority of these methods optimize objectives to discriminate global image representations by using augmented image pairs, [11, 29] showed that these approaches can also be utilized in correspondence estimation. Recently, several approaches proposed optimizing alternative objectives on a denser level [54, 69, 3, 49, 67, 68, 77]. However, these methods have been applied to tasks such as object detection and segmentation, but not directly for semantic correspondence. Another line of work proposed methods to discover semantic keypoint locations in an unsupervised way [25, 74, 36, 26, 58].

For the problem of correspondence estimation, images augmented with artificial spatial deformations were used by [28, 51] to learn transformations between image pairs without any external supervision. Instead of learning a function to match image pairs, [63, 62] framed the problem as one of learning a function that can extract local features which can be used for semantic matching across all instances of a category of interest. To introduce greater invariance for intra-category differences, DVE [61] extended EQ [62] with the use of additional non-augmented auxiliary images during training.

More recent work has been able to make use of advances in self-supervised learning in order to learn more effective representations. CL [11] proposed a two-stage approach, combining image-level instance-based discrimination [21] together with dense equivariant learning. They trained a linear projection head on top of frozen learned features computed via an image-level self-supervised pre-training task, where the goal of the projection step was to enforce the dense features to be spatially distinct within an image. LEAD [29] also followed a similar two-stage approach, starting with instance-level discrimination using [18]. In the second stage, instead of encouraging the features to be spatially distinct, their projection operation minimized the dissimilarity between feature correlation maps from the instance-level features and correlation maps from the projected features. This can be viewed as a form of dimensionality reduction as the projected features are smaller in size compared to the original features.

The above methods, while effective on some datasets, have limitations. EQ [62] is only able to learn invariances that can be expressed via image augmentations. DVE [61] assumes that the images have the same visible keypoints, and can thus be negatively impacted by incorrect matches on background pixels. The projection step used by CL [11] runs the risk of discarding invariances learned during the pre-training stage. While LEAD [29] maintains learned invariances from the first stage, if the pre-trained features generate incorrect matches, their loss can end up optimizing possibly incorrect feature correlations. In this work, we thoroughly benchmark the performance of these approaches by evaluating them on several challenging datasets. We also propose a new semantic correspondence loss, which learns more effective dense features by both preserving the learned invariances while also making the features more distinct.

Performance Evaluation and Error Diagnosis. Benchmarking model performance with a single summary metric is one of the best tools that we have for objectively measuring progress on a given task. However, accurately under-

standing the limitations and improvements provided by new methods is even more crucial for future progress. Several works have introduced different diagnostic tools and frameworks to analyze methods across a variety of problems [23, 56, 16, 73, 60, 1]. For the semantic correspondence problem, the vast majority of existing works only report performance via single summary metrics, e.g. the Percentage of Correct Keypoints (PCK) with a fixed distance threshold. This allows us to get an overall sense of performance but does not reveal *why* a given method performs better than others. Recent works [48, 13] have emphasized the importance of detailed evaluation in order to better understand what components specific performance improvements can be attributed to. In this work, in the spirit of [55], we introduce a more thorough evaluation for analyzing semantic correspondence methods. We also propose a new version of PCK which better captures correspondence errors and present standardized baseline results across multiple datasets to fairly compare semantic correspondence performance.

3   Semantic Correspondence Estimation

3.1   Problem Setup

Given a source-target image pair, $\mathbf{x}_s$ and $\mathbf{x}_t$, the goal of correspondence estimation is to find the locations of a set of points of interest from the source image in the target image. Unlike in optical flow or stereo estimation, where the task is to compute correspondence across time or viewpoint, in the case of semantic correspondence, the goal is to find matching locations across different depictions of the same object category. This is a challenging setting as the objects of interest can vary in terms of appearance, pose, and shape, in addition to difficulty arising from other nuisance factors such as the background, occlusion, and lighting.

   We pose the correspondence problem as a nearest-neighbor matching task in a learned local feature embedding space. Formally, for a pixel location, $u \in \Omega = \{1, ..., H\} \times \{1, ..., W\}$, in a source image of size $H \times W$, we find the corresponding point $\hat{u}$ in the target image $\mathbf{x}_t$ as, $\hat{u} = \arg\max_{k \in \Omega} f(\Phi_u(\mathbf{x}_s), \Phi_k(\mathbf{x}_t))$, where $\Phi_u(\mathbf{x}_s)$ represents an embedding vector of the point u from image $\mathbf{x}_s$, and f is a similarity function. We use a deep neural network as our embedding function Φ, and the similarity is computed via the dot product of the ℓ_2 normalized embedding vectors. In practice, we decompose the embedding function into a feature encoder, followed by a projection step, i.e. $\Phi(\mathbf{x}) = \rho(\Psi(\mathbf{x}))$, where the encoder is deep network. The purpose of the projection is to reduce the dimensionality of the feature, and could be a linear operation [11] or a network [29].

   In the next section, we review several existing unsupervised methods designed for learning dense representations with an emphasis on matching (see Fig. 1 for an overview). While more sophisticated methods have been proposed for estimating semantic correspondence, e.g. using optimal transport [59, 41], distance re-weighting with spatial regularizers [45], or restricting the search area with class activation maps [78] as in [41], we focus on learning embedding functions as recent work has shown that combining self-supervised representation learning with correspondence specific finetuning produces state of the art results [11, 29].
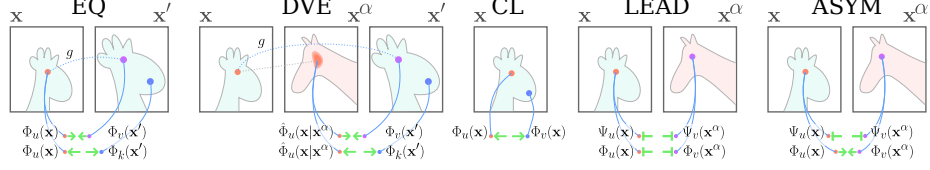
Fig. 1: Unsupervised approaches for semantic correspondence estimation. $\mathbf{x}'$ is a synthetically augmented version of image $\mathbf{x}$, and $\mathbf{x}^\alpha$ is a different image of the same semantic category. EQ [62] minimizes the distance between embeddings of point pairs with known geometric transformations g. DVE [61] builds on EQ by using an additional auxiliary image. CL [11] maximizes distance between embeddings of points within an image. LEAD [29] enforces the same distance between pre-trained and projected embeddings. Our ASYM method extends LEAD by enforcing projected embeddings to be closer in the feature space.

3.2   Unsupervised Semantic Correspondence Learning

EQ [62] proposed an unsupervised method that utilizes the equivariance principle to learn dense matchable features. During training, their model takes an image $\mathbf{x}$ along with an augmented version of it $\mathbf{x}'$ and tries to minimize feature similarity of known corresponding pixel locations u and v. Here, $\mathbf{x}'$ is derived from $\mathbf{x}$ using artificial spatial and appearance-based augmentations and the pixel coordinates u and v are locations from the two images which are related by a known transformation g, such that $v = gu$. They minimize the following loss,

$$\mathcal{L}_{eq} = \frac{1}{|\Omega|^2} \sum_{u \in \Omega} \sum_{v \in \Omega} \|gu - v\| \ p(v|u; \Phi, \mathbf{x}, \mathbf{x}', \tau), \tag{1}$$

$$p(v|u; \Phi, \mathbf{x}, \mathbf{x}', \tau) = \frac{\exp(\langle \Phi_u(\mathbf{x}), \Phi_v(\mathbf{x}') \rangle / \tau)}{\sum_{k \in \Omega} \exp(\langle \Phi_u(\mathbf{x}), \Phi_k(\mathbf{x}') \rangle / \tau)}, \tag{2}$$

where τ is temperature parameter for the softmax function and Ω is the set of possible pixel locations on the image grid. In essence, the model aims to embed corresponding points nearby in the learned embedding space, while also pushing other points further away.

EQ uses artificially augmented image pairs and can thus only learn invariances up to those expressible by these augmentations. Subsequently, DVE [61] extended EQ using an auxiliary image, $\mathbf{x}^\alpha$, to calculate correspondence from $\mathbf{x} \to \mathbf{x}^\alpha$ and then $\mathbf{x}^\alpha \to \mathbf{x}'$. This is achieved by replacing the $\Phi_u(\mathbf{x})$ term in Eqn. 2 with $\hat{\Phi}_u(\mathbf{x}|\mathbf{x}^\alpha) = \sum_w \Phi_u(\mathbf{x}^\alpha) p(w|u; \Phi, \mathbf{x}, \mathbf{x}^\alpha, \tau)$. Importantly, the ground truth correspondence to the auxiliary image does not need to be known as the mapping from $\mathbf{x} \to \mathbf{x}'$ is available.

Recently, two stage methods for learning dense embeddings have been proposed [11, 29]. In these approaches, the first stage makes use of an image-level self-supervised training objective (e.g. [21, 18]) in order to train the feature encoder. Then the projection head is tuned to refine the representation so that

it is better for matching. Like EQ, CL [11] also aims to make features distinct within the image. However, in contrast to EQ, the dense D dimensional feature vectors from $\Psi(\mathbf{x})$ are linearly projected to a lower dimension D' using a linear projection with weights $\mathbf{w} \in \mathbb{R}^{D \times D'}$. They use the same loss as Eqn. 1, but simply use $\mathbf{x}$ instead of $\mathbf{x}'$, i.e. they do *not* use a pair of augmented images.

LEAD [29] also employs a two stage approach, but aims to maximize the similarity between feature correlation maps calculated using the original self-supervised features $\Psi(\mathbf{x})$ and the projected features $\Phi(\mathbf{x})$. The first term in their loss represents the probability that point u from image $\mathbf{x}$ is matched with point v in image $\mathbf{x}^\alpha$ using embeddings from the feature encoder Ψ. In the second term, embeddings are projected to a lower dimensional space using the combined encoder and projection head,

$$\mathcal{L}_{lead} = \frac{1}{|\Omega|^2} \sum_{u \in \Omega} \sum_{v \in \Omega} \; -p(v|u; \Psi, \mathbf{x}, \mathbf{x}^\alpha, \tau) \log p(v|u; \Phi, \mathbf{x}, \mathbf{x}^\alpha, \tau). \qquad (3)$$

LEAD uses 'real' image pairs, as opposed to augmented images, i.e. $\mathbf{x}^\alpha$ is not a synthetically augmented version of $\mathbf{x}$, but instead it is an auxiliary real image depicting the same object class. This is possible as their formulation does not require any ground truth correspondence during training. In essence, LEAD implements a form of learned dimensionality reduction, which can be effective if the pre-trained features already contain useful information for matching.

EQ and DVE were originally designed such that their embedding network Φ was trained in an end-to-end manner, while CL and LEAD separately trained the encoder network Ψ, followed by the learned projection function ρ. Existing methods often use different network architectures for the encoder and decoder which makes it challenging to compare the objective functions directly. To fairly evaluate these approaches, in our experiments we use frozen pre-trained networks as the encoder Ψ, and train a separate linear projection head ρ, i.e. $\Phi(\mathbf{x}) = \rho(\Psi(\mathbf{x}))$, for each of the losses.

3.3   Unsupervised Asymmetric Correspondence Loss

The LEAD objective aims to preserve distances between features before and after they have been projected into a lower dimensional feature space. Given two points, u and v, from different images, the loss term effectively tries to enforce $f(\Psi_u(\mathbf{x}), \Psi_v(\mathbf{x}^\alpha))$ and $f(\Phi_u(\mathbf{x}), \Phi_v(\mathbf{x}^\alpha))$ to be as close as possible. The projection tries to maintain both what is similar and not similar between point pairs by preserving their distance. However, the structure of the embedding space does *not* change after this projection step which means that performance is bounded by the quality of the features in the original feature space.

We make a conceptually simple change to the LEAD objective in order to provide the flexibility to allow the model to change distances in the projected feature space. Unlike LEAD, instead of using the same temperature value in the softmax function for both feature spaces, we utilize a different temperature when we calculate the similarity between point embeddings. Specially, we use

a smaller temperature for the original feature space and a larger one for the projected feature space, i.e. $\tau_1 < \tau_2$, resulting in the following loss,

$$\mathcal{L}_{asym} = \frac{1}{|\Omega|^2} \sum_{u \in \Omega} \sum_{v \in \Omega} || \; p(v|u; \Psi, \mathbf{x}, \mathbf{x}^\alpha, \tau_1) - p(v|u; \Phi, \mathbf{x}, \mathbf{x}^\alpha, \tau_2)||. \qquad (4)$$

A smaller temperature makes the distance between closer points smaller and far away points larger. To match these same distance scores, the projection needs to make embeddings of closer points closer and vice versa. Moreover, the objective also preserves the order of distances of point pairs, i.e. close points remain closer compared to further away ones. As a result, the projection needs to capture what is common between already matching point pairs in order to optimize the loss which leads to better embeddings for matching. While this is a relatively small change in the loss formulation, it results in a significant improvement in the performance. As we use different temperature parameters, we refer to our asymmetric projection loss as ASYM. The other difference between ASYM and LEAD is that we make use of Euclidean distance instead of cross entropy as we found this to be more effective. We compare the impact of these design choices via detailed ablation experiments in our supplementary material.

4   Evaluation Protocol

4.1   Evaluation Metrics

There are two dominant approaches for benchmarking the performance of unsupervised correspondence estimation methods: (i) landmark regression and (ii) feature matching. For landmark regression, an additional supervised regression head is trained for each of the landmarks of interest (e.g. the keypoints of a human face) on top of the representation learned by the correspondence network. For matching, one simply computes the distance in feature space to all the points in the second image for a given point of interest in a source image and then selects the closest match as the corresponding point.

 We argue that matching is a better task for evaluating the power of learned feature embeddings as regression requires ground truth supervision to train the additional parameters. As matching uses raw feature embeddings it cannot incorporate biases from datasets, e.g. exploiting the average locations of keypoints. While current literature tends to focus on regression evaluation, there are some exceptions to this. However, by and large, matching results are only presented for comparably easier datasets. For example, [61, 11, 29] only present matching results on the MAFL dataset [75]. MAFL contains cropped and aligned images of human faces, and current methods perform very well on it, with matching errors close to two pixels on average.

Percentage of Correct Keypoints (PCK). Traditionally, matching performance is measured using the PCK metric. Given a set of ground truth keypoints $\mathcal{P} = \{\mathbf{p}_m\}_{m=1}^M$ and predictions $\hat{\mathcal{P}} = \{\hat{\mathbf{p}}_m\}_{m=1}^M$, PCK is calculated as

| (a) Source | (b) Match | (c) Miss | (d) Jitter | (e) Swap |

Fig. 2: For the keypoint denoted in red in the source image (a), we see the correct match in (b). If the point matches with the background it is a miss (c), if it is close to the correct location it is a jitter (d). If the match is in the correct vicinity but closer to another semantic part, it is a swap error (e).

$PCK(\mathcal{P}, \hat{\mathcal{P}}) = \frac{1}{M} \sum_{m=1}^{M} \mathbb{1}[\|\hat{\mathbf{p}}_m - \mathbf{p}_m\| \leq d]$. Here, $d = \alpha \max(W^b, H^b)$ is a distance threshold, chosen as a proportion (e.g. $\alpha = 0.1$ of the maximum side length) of the object bounding box (with width W^b and height H^b) size. A prediction is counted as correct if it is inside of the target keypoint area.

Detailed Error Evaluation. Inspired by [55], we define additional error metrics to analyze performance of different methods in more detail. A visual overview is illustrated in Fig. 2. If a point is matched with a point that not is close to any of the keypoints in the target image, we denote this error as a 'miss'. This error generally occurs when a point is matched with the image background: $E_{miss} = \mathbb{1}[d < \min\{\|\hat{\mathbf{p}}_m - \mathbf{p}\| \mid \mathbf{p} \in \mathcal{P}\}]$. If a prediction is in the correct vicinity, but outside of the defined distance threshold, we denote this a 'jitter', $E_{jitter} = \mathbb{1}[d < \|\hat{\mathbf{p}}_m - \mathbf{p}_m\| < 2d]$. The last error type is a 'swap' which occurs when a point matches in an area that is closer to a different keypoint, $E_{swap} = \mathbb{1}[\delta \neq \|\hat{\mathbf{p}}_m - \mathbf{p}_m\| \wedge d > \delta]$, where $\delta = \min\{\|\hat{\mathbf{p}}_m - \mathbf{p}\| \mid \mathbf{p} \in P\}$.

The miss and jitter errors are also counted as incorrect by the PCK metric, but swaps may still be counted as correct. For instance, a prediction which is in the middle of a pair of eyes might still be counted as correct according to PCK even if it closer to the wrong eye since it could be still within the distance threshold. As our goal is to estimate semantic correspondence, we should aim to match with the *correct* semantic part. As a result, we propose a new version of PCK which penalizes these swaps. Under this metric, to make a correct prediction, a point needs to both match close to the corresponding keypoint *and* the closest keypoint should be the same semantic keypoint,

$$PCK^{\dagger}(\mathcal{P}, \hat{\mathcal{P}}) = \frac{1}{M} \sum_{m=1}^{M} \mathbb{1}[\|\hat{\mathbf{p}}_m - \mathbf{p}_m\| \leq d \ \wedge \ \delta = \|\hat{\mathbf{p}}_m - \mathbf{p}_m\|]. \qquad (5)$$

4.2   Evaluation Datasets

In order to evaluate semantic correspondence performance we perform experiments on five different datasets: AFLW [34], Spair-71k [46], CUB-200-2011 (CUB) [66], Stanford Dogs Extra (SDog) [30, 5], and Awa-Pose [71, 4]. These

Table 1: Summary of the different datasets that we use for evaluating semantic correspondence performance. We also report the metadata that is provided with each dataset: KP (keypoints/landmarks) and Bbox (bounding boxes). With the exception of Spair-71k, there is no pre-defined evaluation pairs for the datasets.

Dataset Name	# Images	# Pairs	# Classes	Annotations	Matching Diversity
SPair-71k [46]	2k	70k	18	KP (3-30), Bbox	Med
Stanford Dogs (SDog) [5]	10k	10k	120	KP (24), Bbox	Med
CUB-200-2011 (CUB) [66]	11k	10k	200	KP(15), Bbox	Med
AFLW [34]	13k	10k	-	KP(5)	Low
Awa-Pose [4]	10k	10k	36	KP (30-40), Bbox	High

datasets were chosen as they span a range of object category types (e.g. from man made to natural world classes) and exhibit different levels of difficulty (e.g. from topologically simply human faces to deformable animals). AFLW [34] contains images of human faces with various backgrounds from different view points. However, due to structured nature of faces, the visual difference between images are limited and thus the task is relatively easy compared to the other datasets. SDog [30, 5] and CUB [66] contain images of fine-grained visual categories (dogs and birds respectively) and include highly varying appearance, diverse backgrounds, and non-rigid poses which results in a challenging matching task. Awa-Pose [71, 4] contains images from 35 different animal species and allows us to asses inter-class correspondence as the keypoints are shared across the species. SPair-71k [46] contains scenes with multiple man made objects present with complex backgrounds, but the pairs come from same class and the size of the datasets is relatively small. An overview can be found in Table 1.

Only the annotations in SPair-71K were explicitly collected with a focus on semantic correspondence evaluation. For the other datasets there are no predefined image pairs or standardized correspondence evaluation splits. In the existing literature random image pairs are selected that makes direct comparison between alternative methods challenging [76, 39, 14]. As the keypoint annotations are semantically consistent across instances in these datasets, we create splits for each dataset, where random image pairs are selected from test splits of the datasets. We will publish these splits in order to aid future evaluation.

4.3   Implementation Details

We perform experiments with two different types of backbones models for our feature encoder Ψ. For the CNN, unless otherwise specified, we extract features from images resized to 384×384, and use the 1024 dimensional features from the conv3 layer of a ResNet-50 [22]. For the Transformer, 8×8 patches from 224×224 images with stride 8 are used as input (similar to [2]) and we extract 736 dimensional features from 9th layer. We also investigate supervised and self-supervised trained backbones. The supervised and self-supervised CNNs are from [22] and [10] and the Transformer models are from [35] and [7] respectively. Unless stated otherwise, we report results using the standard PCK metric with

$\alpha = 0.1$ for direct comparison to other methods. We set the temperature τ_1 to 0.2 and τ_2 to 0.4 for ASYM. We provide an evaluation of different temperature values and additional implementation details in the supplementary material.

5 Experiments

In our experiments, we attempt to answer the following questions: i) how well do current unsupervised correspondence methods perform on challenging datasets, ii) how does the choice of backbone architecture and pre-training objective impact performance, iii) how does the pre-training data source impact performance, iv) how does the data source used for finetuning the correspondence model impact performance, and finally, v) what are the current source of errors, and thus what needs to be done to close the gap between current state-of-the art supervised and unsupervised methods.

5.1   Impact of Unsupervised Correspondence Objective

To evaluate the unsupervised correspondence methods outlined in Sec. 3, in Table 2 we train a linear projection head ρ on top of the embeddings from a frozen pre-trained backbone Ψ. Additional baselines are also presented, including: pre-trained features directly from the backbone models with no projection (None), Non-Negative Matrix Factorization (NMF), Principal Component Analysis (PCA), projection using a Random weight matrix, and Supervised projection where we optimize the objective in Eqn. 1 using ground truth keypoint pairs. We explore CNNs and Transformers as backbones that are pre-trained either in a supervised or self-supervised fashion.

Overall, our proposed ASYM approach obtains better scores than other unsupervised methods on all datasets, independent of the choice of backbone or pre-training method, with the exception of the AFLW face dataset. Compared to LEAD, our proposed adaptation improves performance on datasets where the visual diversity is high (i.e. non-face datasets). EQ and DVE perform poorly on the datasets where the visual appearance is high across instances, but it is worth noting that these methods were originally designed for the end-to-end trained setting. CL obtains good performance in some cases and is the best on AFLW. However, our ASYM method is still consistently strong. Perhaps somewhat surprisingly, PCA based projection performs better than most of the baselines, while NMF did not perform well. PCA's performance can be partially explained by the strength of the original features (i.e. None). Although the performance of unsupervised methods differs across different backbones, the relative ordering stays the same – Sup, ASYM, CL, PCA, NONE, LEAD, NMF, EQ, and DVE.

5.2   Impact of Backbone Model and Pre-training Objective

While [12] claims that the choice of CNNs or Transformers as the backbone model does not affect the performance, recently [2] presented impressive correspondence results using a Transformer-based model. In order to explore further,

Table 2: Comparison of different unsupervised semantic correspondence methods. Here we vary the backbone models and pre-training strategies. The unsupervised correspondence methods are trained on the respective evaluation datasets.

(a) Ψ = Sup. pre-trained - CNN

Projection(ρ)	Spair-71K	SDogs	CUB	AFLW	Awa
None	31.8	34.9	51.3	57.4	28.8
NMF	27.4	33.9	49.6	53.6	28.0
PCA	32.2	35.5	53.1	57.8	29.7
Random	26.9	30.5	43.1	54.9	23.4
Supervised	38.7	53.2	72.7	80.8	46.1
EQ[62]	16.4	21.2	28.1	48.5	15.6
DVE[61]	16.3	20.5	27.7	58.7	15.4
CL[11]	30.8	37.0	54.5	**67.3**	31.7
LEAD[29]	31.7	35.1	51.5	58.0	29.1
ASYM (Ours)	**34.0**	**40.4**	**60.8**	63.6	**34.1**

(b) Ψ = Unsup. pre-trained - CNN

Projection(ρ)	Spair-71K	SDogs	CUB	AFLW	Awa
None	30.7	34.3	47.5	64.3	27.6
NMF	20.6	19.9	44.0	40.8	15.6
PCA	27.4	29.8	50.7	51.0	24.1
Random	26.6	31.5	40.0	60.2	23.3
Supervised	39.5	54.0	73.4	83.8	48.2
EQ[62]	14.3	20.5	26.4	62.8	15.5
DVE[61]	15.0	19.4	28.7	60.6	14.7
CL[11]	29.7	37.9	54.1	**77.1**	**33.4**
LEAD[29]	30.5	34.4	48.3	64.9	28.1
ASYM (Ours)	**33.2**	**38.2**	**54.4**	69.7	32.1

(c) Ψ = Sup. pre-trained - Transformer

Projection(ρ)	Spair-71K	SDogs	CUB	AFLW	Awa
None	**33.5**	38.0	66.3	54.1	34.1
NMF	23.3	29.2	55.5	51.5	24.7
PCA	33.0	38.1	66.4	53.9	34.1
Random	31.9	36.9	63.3	52.9	31.8
Supervised	38.5	48.2	78.2	70.5	47.9
EQ[62]	15.5	15.9	24.0	60.2	11.7
DVE[61]	15.4	17.5	23.8	55.6	11.8
CL[11]	30.5	35.8	67.1	**68.4**	31.0
LEAD[29]	32.7	37.6	65.8	53.8	33.9
ASYM (Ours)	33.2	**41.7**	**72.2**	54.2	**38.5**

(d) Ψ = Unsup. pre-trained - Transformer

Projection(ρ)	Spair-71K	SDogs	CUB	AFLW	Awa
None	**34.1**	42.7	61.0	64.2	36.1
NMF	26.3	39.0	51.9	61.0	32.9
PCA	34.0	42.7	61.0	64.2	36.1
Random	32.3	42.1	59.6	61.9	34.6
Supervised	38.1	52.7	72.9	92.0	47.4
EQ[62]	9.0	12.5	15.0	62.5	8.8
DVE[61]	8.5	13.1	14.1	60.6	9.0
CL[11]	25.8	32.3	54.1	**81.8**	25.0
LEAD[29]	33.6	42.5	60.8	64.2	35.8
ASYM (Ours)	32.9	**45.2**	**65.2**	65.9	**39.9**

we compared features from models pre-trained on Imagenet with either supervised (Sup.) or unsupervised (Unsup.) objectives.

When a projection layer is trained with keypoint supervision, the performance difference between architectures diminishes, as can be observed by comparing the supervised baseline to original embeddings (None) in Table 2. However, when the projection layer is trained using no supervision, the best results are obtained in the cases where the initial embeddings were the best on a given dataset. For instance, the unsupervised pre-trained Transformer obtains the best results with no projection on the SDog and Awa datasets compared to other backbone models. Training the unsupervised methods from these embeddings also results in the best performance compared to other pre-trained backbones. In summary, if keypoint supervision is available, the choice of backbone does not significantly impact the end result. However, in the unsupervised case, starting with good performing embeddings is important. Furthermore, the pre-training strategy does not affect the performance of CNNs, while unsupervised Transformers generally performs better than supervised one (see Table 2).
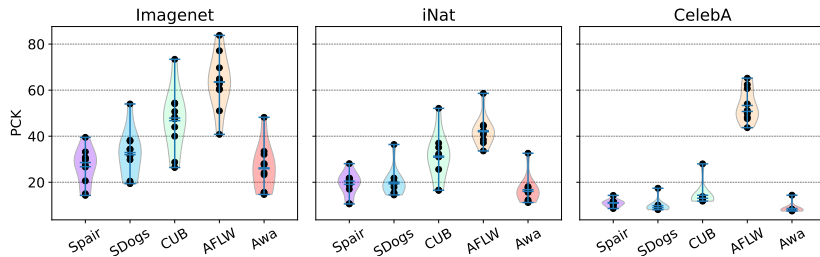
Fig. 3: Impact of different pre-training datasets used to train a CNN feature encoder using self-supervised training. For each of the three datasets we report the performance of different methods shown as individual dots.

5.3 Impact of Pre-training Dataset

Here we explore the impact of the pre-training data source used to train the feature encoder. We train correspondence losses using embeddings from a CNN trained via contrastive self-supervision on either Imagenet [57] (various categories), iNat2021 [65] (natural world categories), or Celeb-A [42] (human faces). Specifically, we use MoCov3 from [10] for Imagenet, MoCov2 [9] for iNat from [65], and MoCov2 from [11] for CelebA. These results are presented in Fig. 3.

It is clear that the choice of pre-training data has an impact on all unsupervised methods, with Imagenet outperforming other sources. The CelebA model performs poorly on all tasks with the exception of AFLW, as the features likely only contain information about faces. iNat2021 does not contain any man-made objects or dog categories, and as a result, models trained on it perform worse on SDog and Spair. While iNat2021 contains many bird images, it contains an order of magnitude less mammals making it less effective on Awa-Pose.

5.4 Impact of Finetuning Correspondence Dataset

Next we explore how transferable are the embeddings trained on one dataset and evaluated on another. For instance, what happens if the linear projection is trained on dog images and then tested on birds, or in an extreme case, trained on human faces and tested on animal categories. The correspondence losses are trained on top of the sup. CNN from Table 2. The results are outlined in Fig. 4.

The generalization performance across other datasets is poor for supervised losses compared to the unsupervised ones. The performance drop is largest for models trained on faces, but when training on other data and tested on faces, the performance does not drop significantly. Models trained on Spair-71k generally perform reasonably well on other datasets.

5.5 Detailed Error Analysis

Here we break down the different error types in order to better understand where the different methods fail and thus require improvement. We compare

Fig. 4: Cross dataset evaluation results. Each row represents the test source data, and each column is the dataset that a given correspondence loss is trained on. Note that the colormaps are row normalized. These results use the same initial encoder as the 'Sup. pre-trained - CNN' results in Table 2.

unsupervised correspondence losses and supervised projection to the current best performing methods CATs [12], CHM [44], and MMNet [76] on Spair-71K. Results are presented in Table 3.

For the supervised methods, MMNet has significantly lower miss errors compared to all other methods, although it results in a lot of swaps. As this method combines correlation maps from different layers, it is able to capture more global context, which helps reduce misses. However, while CATs and CHM produce more misses compared to MMNet, swaps are reduced, as they use more sophisticated aggregation methods (6D convolution and attention) to resolve ambiguities during matching. Moreover, as these two lines of work complement each other in the error types, they could potentially be combined to obtain better results.

For the unsupervised methods, we see that the most common error type is miss across all methods. While ASYM reduces misses compared to other unsupervised methods, it is not as good as the supervised approaches. As swaps are instances where a match has occurred, but to the wrong keypoint, methods with high number of misses will not have many swaps by definition. ASYM results in fewer misses, which is desirable, but this increases the chance that swaps can occur. The 'Supervised' baseline reduces misses, but compared to the more sophisticated supervised approaches it generates more swaps. We argue that while more supervision might help to reduce misses, in order to reduce swaps, better matching mechanisms are needed, as in [12, 44].

Finally, we can see that our PCK† metric is reduced by $\sim 20\%$ compared to the original PCK metric in all cases. This indicates that in one in five cases, the source point matches an area closer to another keypoint instead of the correct corresponding point. For some applications these errors might not affect the end performance drastically, while for others, this disparity could be significant. We provide additional analysis and PCK† scores for other datasets in the supplementary material.

5.6   Discussion and Limitations

Our exhaustive experiments show that evaluating with varied challenging datasets is crucial in order to see the benefits of current methods as human face data re-

Table 3: Detailed error types for both unsupervised and supervised correspondence losses on Spair using two different distance thresholds. FT indicates if the backbone was finetuned with keypoint supervision. Our baselines use the 'Sup. pre-trained - CNN' encoder from Table 2, in other cases we use the public models by the authors. All models use a ResNet backbone, except MMNet-FCN[76].

(a) $\alpha = 0.1$

	FT	Method	Miss↓	Jitter↓	Swap↓	PCK↑	PCK†↑
Unsup.		CL	51.5	13.7	24.3	30.8	24.2
		EQ	68.3	15.0	18.9	16.4	12.8
		DVE	67.9	14.9	19.7	16.3	12.4
		LEAD	47.1	13.6	27.4	31.7	25.4
		ASYM	44.1	13.2	28.6	34.0	27.2
Sup.		Supervised	40.2	14.9	29.4	38.7	30.4
		CATs [12]	46.3	21.0	21.9	42.4	31.7
	✓	CATs [12]	40.1	19.1	20.3	49.9	39.6
	✓	CHM [44]	40.3	18.2	23.8	44.2	35.8
	✓	MMNet-FCN[76]	28.5	14.7	28.8	52.2	42.6

(b) $\alpha = 0.05$

	FT	Method	Miss↓	Jitter↓	Swap↓	PCK↑	PCK†↑
Unsup.		CL	71.5	13.2	12.9	17.7	15.6
		EQ	85.1	8.8	8.0	7.6	6.9
		DVE	85.3	9.0	8.3	7.3	6.5
		LEAD	66.9	12.4	15.9	19.3	17.3
		ASYM	63.3	12.6	17.5	21.5	19.2
Sup.		Supervised	61.1	14.6	17.6	24.1	21.3
		CATs [12]	71.0	20.7	10.8	21.6	18.1
	✓	CATs [12]	64.8	22.2	10.7	27.7	24.4
	✓	CHM [44]	64.5	18.7	12.4	25.6	23.1
	✓	MMNet-FCN[76]	51.7	19.0	18.1	33.3	30.2

sults (e.g. AFLW) alone can be misleading (Table 2). While unsupervised performance may not yet be at the level of fully supervised baselines, they are not far off but have the benefit of generalizing better across datasets (Fig. 4). Current performance metrics (i.e. PCK) do not penalize all error types and thus result in overly optimistic performance (Table 3). The choice of pre-training can have a big impact, but in most instances Imagenet pre-training is superior (Fig. 3).

It is not feasible to control all hyper-parameter values as the space too large. As a result, to ensure fair and controlled comparisons, we adopted a two stage pipeline, with frozen backbone models, as advocated in recent start-of-the-art work [11]. We justified the important design choices and provide additional experiments in the supplementary material. Finally, the keypoints used for evaluating correspondence are derived from object landmarks which are detectable and salient by design. In future work, it would be interesting to use additional annotations from other object parts which are not necessarily easily annotated but still have semantically meaningful correspondences across instances.

6   Conclusion

We presented a thorough evaluation of existing unsupervised methods for semantic correspondence estimation and presented a new approach that consistently outperforms existing methods. We showed that while matching performance on human face data is strong, there is still a way to go on more challenging datasets. Our analysis sheds light on some of the reasons for failure as well as providing some further insight into the role of data, models, and losses which we hope will enable others to make further progress on this important task.

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