



# Multiple Sound Sources Localization from Coarse to Fine

Rui Qian<sup>1</sup>, Di Hu<sup>2</sup>, Heinrich Dinkel<sup>1</sup>, Mengyue Wu<sup>1</sup>, Ning Xu<sup>3</sup>,  
and Weiyao Lin<sup>1</sup>✉

<sup>1</sup> Shanghai Jiao Tong University, Shanghai, China  
{qrui9911, richman, mengyuewu, wylin}@sjtu.edu.cn

<sup>2</sup> Baidu Research, Beijing, China  
hudi04@baidu.com

<sup>3</sup> Adobe Research, San Jose, USA  
nxu@adobe.com

**Abstract.** How to visually localize multiple sound sources in unconstrained videos is a formidable problem, especially when lack of the pairwise sound-object annotations. To solve this problem, we develop a two-stage audiovisual learning framework that disentangles audio and visual representations of different categories from complex scenes, then performs cross-modal feature alignment in a coarse-to-fine manner. Our model achieves state-of-the-art results on public dataset of localization, as well as considerable performance on multi-source sound localization in complex scenes. We then employ the localization results for sound separation and obtain comparable performance to existing methods. These outcomes demonstrate our model's ability in effectively aligning sounds with specific visual sources. Code is available at <https://github.com/shvdiwnkozbw/Multi-Source-Sound-Localization>.

**Keywords:** Sound localization · Audiovisual alignment · Complex scene

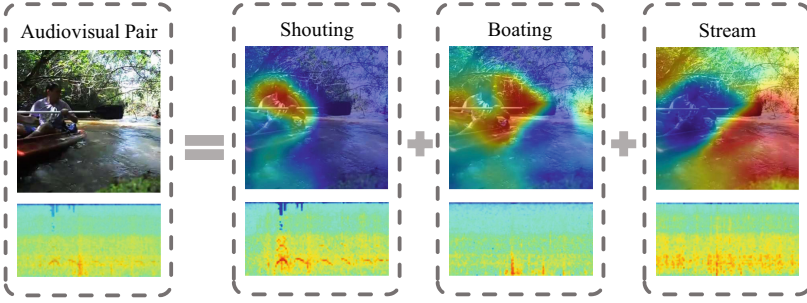
## 1 Introduction

Humans usually perceive the world through information in different modalities, e.g., vision and hearing. By leveraging the relevance and complementary between audio and vision, humans can clearly distinguish different sound sources and infer which object is making sound. In contrast, machines have been proven capable of separately processing audio and visual information using deep neural networks. But can they benefit from joint audiovisual learning?

Works in recent years mainly focus on establishing multi-modal relationship based on temporally synchronized audio and visual signals [1, 3, 17, 19]. This synchronization in video-level becomes the correspondence that is whether audio

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**Fig. 1.** Our model separates a complex audiovisual scene into several simple scenes. The figure shows the input audiovisual pair majorly consists of three elements: a man shouting, sound of boating from the boat and paddle, sound of a water stream. This disentanglement simplifies a complex scenario and generates several one-to-one audiovisual associations.

and visual signals originate from the same video, which works effectively for simple scenes [2, 18], i.e., the single-source conditions. However, in unconstrained videos, various sounds are usually mixed, where the video-level supervision is too coarse to provide the precise alignment between each sound and visual source pair. To tackle this problem, [15, 16] establish audiovisual clusters to associate sound-object pairs, but require to pre-determine the number of clusters, which becomes difficult in an unconstrained scenario, thus greatly affects alignment performance.

Some works further apply audiovisual learning into a series of downstream tasks (e.g., sound localization, sound separation) and exhibit promising performance [10, 16, 18, 22, 24, 29, 31]. Regarding previous works on sound localization, [2, 18, 24] mainly focus on simple scenes, usually unable to find source-specific objects from mixed audio, while [6, 7, 9] employ stereo audio as prior, which contains location information but is difficult to obtain. Additionally, existing evaluation pipelines also lack the ability to measure sound localization performance in multi-source scenarios. For sound separation, [29] uses the entire coarse visual scene as guidance, while [5, 10, 28] rely on extra motion or detection results to improve performance.

To sum up, existing dominant methods mostly lack the ability to analyze complex audiovisual scenes, and fail to effectively utilize the latent alignment between sound and visual source pairs in unconstrained videos. This is because there are majorly two challenges in complex audiovisual scene analysis: one is how to distinguish different sound-sources, the other is how to ensure the established sound-object alignment is fairly satisfactory without one-to-one annotations. To address these challenges, we develop a two-stage audiovisual learning framework. At the first stage, we employ a multi-task framework consisting of classification and audiovisual correspondence to provide the reference of audiovisual content for the second stage. At the second stage, based on the classification predictions, we use the operation of *Class Activation Mapping* (CAM) [4, 23, 30]

to extract class-specific feature representations as the potential sound-object pairs (Fig. 1), then perform alignment in a coarse-to-fine manner, where the coarse correspondence based on category is evolved into the fine-grained matching in both video- and category-level.

Our main contributions can be summarized as follows: (1) We develop a two-stage audiovisual learning framework. At the first stage, we employ multi-task framework for classification and correspondence learning. At the second stage, we employ the CAM technique to disentangle the elements of different categories from complex scenes for alignment. (2) We propose to establish audiovisual alignment in a coarse-to-fine manner. The coarse-grained step ensures correctness of correspondence in category level, while the fine-grained one establishes video- and category-based sound-object association. (3) We achieve state-of-the-art results on public sound localization dataset. In the multi-source conditions, according to our proposed class-specific localization metric, our method shows considerable performance compared with several baselines. Besides, the object representation obtained from localization provides valuable visual reference for sound separation.

## 2 Related Work

**Audiovisual Correspondence.** Although most audiovisual datasets consist of unlabelled videos, the natural correspondence between sound and vision provides essential supervision for audiovisual learning [1–3, 18, 19]. [3, 19] introduced a method to learn feature representation of one modality with supervision from the other in a teacher-student manner. Arandjelovic and Zisserman [1] viewed audiovisual correspondence (AVC) as the supervision for audiovisual representation learning. [18] adopted temporal synchronization as self-supervision signal to correlate audiovisual content. But these methods mostly fail to process complex scene with multiple sound sources. Hu et al. [15, 16] used clustering to associate latent sound-object pairs, but its performance greatly relies on pre-defined number of clusterings. Our multi-task framework simultaneously treats unimodal content label and audiovisual correspondence as supervision, then performs class-specific audiovisual alignment under complex scenes.

**Sound Localization in Visual Scenes.** Recent methods for localizing sound in visual context mainly focus on joint modeling of audio and visual modalities [2, 15, 18, 24, 27–29]. In [2, 18], authors performed sound localization through audiovisual correspondences. [24] proposed an attention mechanism to capture primary areas in a semi-supervised or unsupervised setting. Tian et al. [27] leveraged audio-guided visual attention and temporal alignment to find semantic regions corresponding to sound sources. Hu et al. [15, 16] established audiovisual clustering to localize sound makers. Zhao et al. [28, 29] employed a self-supervised framework to simultaneously achieve sound separation and visual grounding. Although [28, 29] can separate sound given visual sound source, they require single-source samples to achieve mix-and-separate training. In contrast,

our model is directly trained on unconstrained videos, and can precisely localize visual source of different sounds in complex scenes.

**CAM for Weakly-Supervised Localization.** CAM was proposed by Zhou et al. [30] to localize objects with only holistic image labels. This approach employs a weighted sum of the global average pooled features at the last convolutional layer to generate class-specific saliency maps, but can only be applied to fully-convolutional networks due to modification of network architectures. To generalize CAM and improve visual explanations for convolutional networks, Grad-CAM [23] and Grad-CAM++ [4] were proposed. These two gradient-based methods can achieve weakly-supervised localization with arbitrary off-the-shelf CNN architectures and require no re-training.

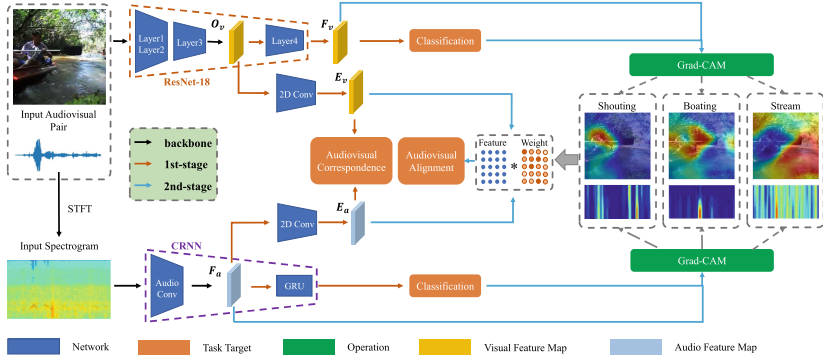
Some previous works on audiovisual learning have adopted CAM or similar methods to localize sound producers [2, 18, 29]. Arandjelovic et al. [2] performed max pooling on predicted score map over all spatial grids, and used obtained correspondence score for training on AVC task. Owens et al. [18] adopted audiovisual synchronization as training supervision, and employed CAM to measure the likelihood of a patch to be sound source. However, they only use CAM at the final step to measure the relationship between two modalities. Our method employs CAM to disentangle audio and visual features of different sounding objects, achieving fine-grained audiovisual alignment.

### 3 Approach

Our two-stage framework is illustrated in Fig. 2. At the first stage, we employ multi-task learning for classification and video-level audiovisual correspondence. At the second stage, the audiovisual feature maps and classification predictions are fed into Grad-CAM [23] module to disentangle class-specific features on both modalities, based on which we employ valid representations to perform fine-grained audiovisual alignment.

#### 3.1 Multi-task Training Framework

Given audio and visual (image) messages  $\{a_i, v_i\}$  from  $i$ -th video, we can obtain the category labels from annotated video tags or predictions of pretrained models, as well as the natural audiovisual correspondence. To leverage these two types of supervision, we employ a multi-task learning model. This model consists of audio and visual learning backbones, classification network and an audiovisual correspondence network, as shown in Fig. 2. Specifically, we adopt CRNN [25], composed of 2D convolutions and a GRU, to process audio spectrograms, and use ResNet-18 [13] to extract deep features from video frames.



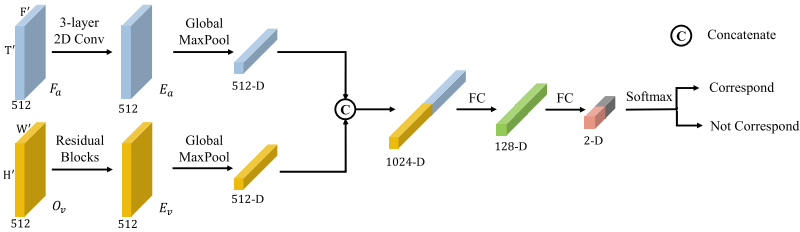
**Fig. 2.** An overview of our two-stage audiovisual learning framework. At the first stage, our model extracts deep features from the audio and visual streams, then performs classification and video-level correspondence. At the second stage, our model disentangles representations of different classes and implements a fine-grained audiovisual alignment.

**Classification on Two Modalities.** To perform classification with audio and visual messages  $\{a_i, v_i\}$ , we adopt video tags or predicted pseudo labels from pretrained models as supervision. Considering the sound-object alignment to be established, we employ the same categories for both modalities. We denote  $C$  as the number of class and  $c$  as the  $c$ -th class.

Considering there are multiple sound sources contained in the video, multi-label binary cross entropy loss is considered for classification:

$$L_{cls} = \mathcal{H}_{bce}(\mathbf{y}_{a_i}, \mathbf{p}_{a_i}) + \mathcal{H}_{bce}(\mathbf{y}_{v_i}, \mathbf{p}_{v_i}), \tag{1}$$

where  $\mathcal{H}_{bce}$  is the binary cross-entropy loss for multi-label classification,  $\mathbf{y}$  and  $\mathbf{p}$  are the annotated class labels and corresponding predicted probability respectively,  $\mathbf{y} \in \{0, 1\}^C$ ,  $\mathbf{p} \in [0, 1]^C$ .



**Fig. 3.** Details for audiovisual correspondence learning network. For audio stream, the 3-layer 2D convolutions are listed as: (1)  $3 \times 1 \times 512$ , with dilation 2 on time dimension, (2)  $1 \times 2 \times 512$ , with stride 2 on frequency dimension, (3)  $3 \times 1 \times 512$ , each followed with a batch normalization layer and ReLU activation. For visual stream, the layer settings for residual blocks are the same as layer4 in ResNet-18, but the weights are not shared.

**Audiovisual Correspondence Learning.** Similar to [1], audiovisual correspondence learning is viewed as a two-class classification problem, i.e., corresponding or not. And the network shown in Fig. 3 is employed for achieving this learning task. Specifically, we take audio features before GRU in CRNN and visual outputs from layer3 of ResNet-18 as inputs<sup>1</sup>, i.e.,  $F_a$  and  $O_v$  in Fig. 2. Through a series of convolution and pooling operation in Fig. 3, we can get 512-D audio and visual features. Then, these two 512-D features are concatenated into one 1024-D vector and passed through two fully-connected layers of 1024-128-2. The 2-D output with softmax regression aims to determine whether audio and vision correspond.

$\{a_i, v_i\}$  from  $i$ -th video are viewed as corresponding pair, then we random select a different video  $j$  and use its image  $v_j$  to construct mis-corresponding pair  $\{a_i, v_j\}$ . The learning objective can be written as:

$$L_{avc} = \mathcal{H}_{cce}(\boldsymbol{\delta}, \mathbf{q}), \quad (2)$$

where  $\mathcal{H}_{cce}$  is the categorical cross entropy loss,  $\mathbf{q} \in [0, 1]^2$  is the predicted output,  $\boldsymbol{\delta} = (0, 1)$  for correspondence while  $\boldsymbol{\delta} = (1, 0)$  for not. For multi-task learning, we take  $L_{mul}$  as final loss function,  $\lambda$  is the hyperparameter of weighting:

$$L_{mul} = L_{cls} + \lambda L_{avc}. \quad (3)$$

After training with multi-task objective, we could achieve coarse-grained audiovisual correspondence in the category level.

### 3.2 Audiovisual Feature Alignment

In this section, we propose to disentangle feature representations of different categories based on the classification predictions and implement fine-grained audiovisual alignment with the video- and category-based sound-object association.

**Disentangle Features by Grad-CAM.** Inspired by [4, 23, 30], CAM method can generate class-specific localization maps, which measures the importance of each spatial grid on the feature map to specific categories, through classification task. Hence, it is feasible for us to disentangle feature representations of different classes based on the predictions in Sect. 3.1.

Specifically, we leverage the operation of Grad-CAM [23] to perform disentanglement. For simplicity, we use  $r \in \{a, v\}$  to represent audio or visual modality. Given the feature map activations of the last convolutional layer,  $F_r$ , and the

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<sup>1</sup> We choose  $F_a$  and  $O_v$  for two reasons: we can obtain more fine-grained local features and achieve easier training process.

output of classification branch without activation for class  $c$ ,  $\hat{p}_r^c$ , we calculate the class-specific map  $W_r^c$ , i.e.,

$$W_r^c = \text{Grad-CAM}(F_r, \hat{p}_r^c). \quad (4)$$

Then we take class-specific map  $W_r^c$ , i.e., the visualized heatmap in Fig. 2, as weights to perform weighted global pooling over the feature map  $E_r(u, v)$  to obtain class-aware representation<sup>2</sup>, where  $u$  and  $v$  are the map entries. That is:

$$f_r^c = \frac{\sum_{u,v} E_r(u, v) W_r^c(u, v)}{\sum_{u,v} W_r^c(u, v)}. \quad (5)$$

Finally, we get  $C$  512-D vectors as the feature representation of all the categories. And  $\{f_{a_i}^m | m = 1, 2, \dots, C\}$  and  $\{f_{v_i}^n | n = 1, 2, \dots, C\}$  are as the set of audio and visual class-specific feature representations for  $i$ -th video. We use them for fine-grained feature alignment in next step.

**Fine-Grained Audiovisual Alignment.** To effectively establish audiovisual alignment with disentangled features, there are potentially two ways. One is to treat all audio and visual features of the same class in a batch as positive pairs for alignment, the other is to only take pairs of the same class from the same video as positive. As each category contains various entities (e.g., the human category contains audio and visual patterns of baby, sportsman, old man etc.), in order to reduce the interference among different entities, we choose the latter one to acquire the positive pairs with higher quality.

To effectively compare the class-specific audio and visual representation, i.e.,  $f_{a_i}^m$  and  $f_{v_j}^n$ , we project them into a shared embedding space via two fully-connected layers of 512-1024-128 followed with  $L2$  normalization, respectively. Then we compare the projected features with Euclidean distance,

$$D(f_{a_i}^m, f_{v_j}^n) = \|g_a(f_{a_i}^m) - g_v(f_{v_j}^n)\|_2, \quad (6)$$

where  $g_a$  and  $g_v$  are the fully-connected layers for audio and visual modalities, respectively. We then adopt contrastive loss [12] to implement sound-object alignment. The loss function is written as<sup>3</sup>

$$L_{ava} = \sum_{i,j=1}^N \sum_m \sum_n (\delta_{i=j}^{m=n} D^2(f_{a_i}^m, f_{v_j}^n) + (1 - \delta_{i=j}^{m=n}) \max(\Delta - D(f_{a_i}^m, f_{v_j}^n), 0)^2), \quad (7)$$

where  $\delta_{i=j}^{m=n}$  indicates whether the audiovisual pair is positive, i.e.,  $\delta_{i=j}^{m=n} = 1$  when  $i = j$  and  $m = n$ , otherwise 0.  $\Delta$  is a margin hyper-parameter.

<sup>2</sup> We find that directly using  $F_r$  with the weights  $W_r^c$  is difficult to perform alignment objective, but by performing weighted pooling on  $E_r$ , we achieve easier training and faster convergence.

<sup>3</sup> In practice, a threshold over all the class predictions is considered to select valid categories.

### 3.3 Sound Localization and Its Application in Separation

In this section, we use our method to visually localize sounds, and adopt localization results as object representation to guide sound separation.

**Visual Localization of Sounds.** In this task, we aim to visually localize sounds by generating source-aware localization maps. To leverage the established alignment to associate sounds with objects, the visual feature map  $E_{v_i}$  of testing image is firstly projected into the shared embedding space via  $g_v$  in Eq. 6, then compared with the disentangled  $c$ -th class audio features  $f_{a_i}^c$  through Eq. 8,

$$K_i^c(u, v) = -\|g_a(f_{a_i}^c) - g_v(E_{v_i})(u, v)\|_2. \quad (8)$$

Note that  $g_v$  in Eq. 8 is transformed into  $1 \times 1$  convolutions with parameters unchanged. The obtained  $K_i^c \in \mathbb{R}^{U \times V}$  reveals how likely a specific region in the visual scene  $v_i$  is the  $c$ -th visual source of sound  $a_i$ . Then,  $K_i^c$  is normalized and resized to the original image size to be the final localization maps for sound source in the  $c$ -th class. Further, the localization results with class label can be used to evaluate sound localization performance in multi-source conditions.

**Sound Source Separation.** To evaluate the effectiveness of our sound localization results, we use localized objects to guide sound separation. To generate the visual source guidance for the sound belonging to  $c$ -th class, we perform weighted global pooling over the feature map  $E_{v_i}$  w.r.t. the localized visual source  $K_i^c$ , similar to Eq. 5. Then, following [29], we adopt the same mix-and-separate learning framework, and take U-Net [21] to process mixed audio spectrogram, where the visual representation of object in [29] is replaced by our automatically determined visual source guidance. Finally, the output of masked spectrogram w.r.t. the visual source is converted into audio waveform via inverse short-time Fourier transform. More details about the processing can be found in [29].

## 4 Experiments

### 4.1 Datasets

**SoundNet-Flickr.** This dataset was proposed in [3], containing over 2 million unconstrained videos from Flickr. Following [1, 24], we adopt one 5-s audio clip and its corresponding image as an audiovisual pair, and no extra supervision is used for training. For quantitative evaluation of sound localization, the human-annotated subset of SoundNet-Flickr [24] is adopted. In our setting, a random subset of 10k pairs is used for training, and 250 annotated pairs for testing.



**AudioSet.** AudioSet consists of mainly 10-s video clips, many containing multiple sound sources, divided into 632 event categories. Following [8, 10], we only consider sounds from 15 musical instruments extracted from the “unbalanced” split for training and from the “balanced” split for testing. Since this subset provides musical scenes with multiple sound sources, some of poor quality, it is proper and also challenging for multi-source sound localization evaluation. We extract video frames at 1 fps, and employ the well-trained Faster RCNN detector w.r.t. these 15 instruments [10] to provide object locations (bounding boxes), which is then used as the evaluation reference for the sound localization. Finally, we get 96,414 10-s clips for training, and 4503 ones for testing<sup>4</sup>.

**MUSIC.** MUSIC dataset consists of 685 untrimmed videos, with 536 musical solo and 149 duet, containing 11 categories of musical instrument. Since this dataset contains less noise and cleaner than AudioSet, it is more proper to train sound separation models. Following [29], we set the first/second video of each category as validation/test set, and use the rest for training. But some videos have been removed on YouTube, we finally get 474 solo and 105 duet videos in total.

## 4.2 Implementation Details

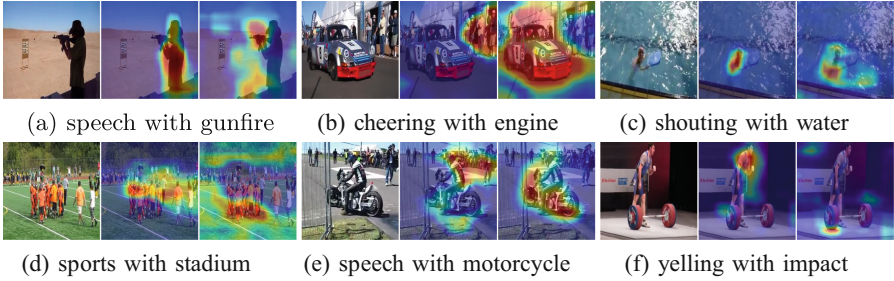
Our audiovisual learning model is implemented in PyTorch. We pretrain CRNN [25] and ResNet-18 [13] model as audio and visual feature extractors. The CRNN is pretrained on a subset of the unbalanced AudioSet corpus, encompassing 700k audio-clips out of the available 2 Million. The ResNet-18 is pretrained on ImageNet.

For all experiments, if not specially mentioned, we sample the audio at 22.05 kHz and convert it to log-mel spectrogram (LMS) [14], obtaining 64 frequency bins from a window of 40 ms every 20 ms using the librosa framework. Regarding visual input, we resize the image to  $256 \times 256 \times 3$ . Our model is optimized in a two-stage manner. First, we set  $\lambda$  to 1 and train the multi-task model w.r.t. Eq. 3 in Sect. 3.1. Then, we jointly optimize the entire network w.r.t. Eq. 3 and Eq. 7. The model is trained by SGD optimizer with momentum 0.9 and starting learning rate  $1 \times 10^{-3}$ . We set learning rate for two backbones to  $1 \times 10^{-4}$ . The learning rate is decreased by 0.1 every 20 epochs.

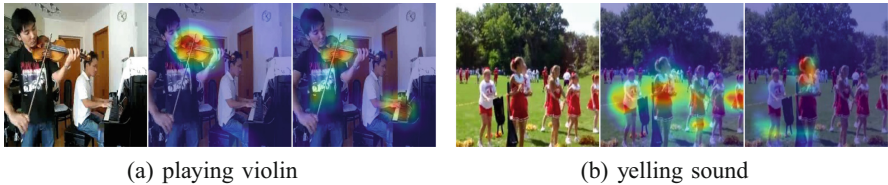
## 4.3 Sound Localization

**Sound Localization on SoundNet-Flickr.** In this section, we adopt audio-visual pairs from SoundNet-Flickr [3] for training and evaluation. The videos in this dataset are completely unconstrained and noisy, thus very challenging to localize sound sources. As there are no video tags available, we adopt the

<sup>4</sup> Since AudioSet only provides clip-level audio labels, we can only ensure that labelled sounds appear in the clip. Thus we adopt the whole 10-s audio clip with one randomly selected frame from video as a pair.



**Fig. 4.** We visualize the localization maps corresponding to different elements contained in the mixed sounds of two sources. The results qualitatively demonstrate our model’s performance in multi-source sound localization.



**Fig. 5.** We compare violin and human yelling sound localization results of our model and CAM output of corresponding category, images in each subfigure are listed as: original image, localization result of our method, and result of CAM.

first-level labels in AudioSet [11] of 7 categories (human sounds, music, animal, sounds of things, natural sounds, source-ambiguous sounds, and environment) as final classification target. We correlate ImageNet labels with these 7 categories by using the similarity of word embeddings [20] and conditional probabilities between labels of these two datasets, more details on this are in the supplemental materials. The pseudo labels are generated based on the prediction of pretrained CRNN and ResNet-18 model. For evaluation, we disentangle class-specific features on audio stream and localize corresponding sound source on each spatial grid of visual feature maps.

To effectively present our model’s ability of category-level disentanglement and fine-grained alignment, we visualize video frames with localization maps in Fig. 4. Unlike [24] which inputs different types of audio to demonstrate interactive sound localization, we input a mixed audio containing multiple sources to generate class-specific localization responses. For example, in Fig. 4(a), when input audio clip contains human speaking and sound of gunfire, our model automatically separates these two parts and respectively highlights the person and gun area. Besides sounds with clear visual sources, for source-ambiguous sound like impact, our model accurately captures the contact surface as shown in Fig. 4(f). More examples are shown in the supplemental material.

The comparison between our model and CAM is shown in Fig. 5. First, our method can generally associate sounds with specific sources. In Fig. 5(a), the violin is making sound while the piano is silent, and our method accurately distinguishes these two objects that belong to the same category of “music”, which surpasses the category-based localization technique of CAM. Second, compared with CAM, Fig. 5(b) shows that our model can precisely localize the position of human by listening to the yelling sound but CAM somewhat fails to achieve this only with human category information. More comparison examples are shown in the supplemental material.

Further we implement quantitative evaluation on 249 pairs from human annotated subset of SoundNet-Flickr [24]. Consensus Intersection over Union (cIoU) and Area Under Curve (AUC) [24] are employed as evaluation metrics. To evaluate the localization response to the entire audio, we perform weighted summation over valid categories as final localization map, where the weights are the normalized predicted probabilities. Table 1 shows the results for different methods, all of which are trained in an unsupervised manner. Despite that most audiovisual pairs in test set are of single-source, our model still outperforms Attention [24] and DMC [15] by a large margin, and is slightly better than CAVL [16]. But note that CAVL is trained on single-source videos while our model is trained on unconstrained ones, which poses greater challenge in the joint audiovisual learning. This result demonstrates that our fine-grained alignment effectively facilitates audiovisual learning with unconstrained videos. Due to limited computing resources, we did not try very large training data size like 144K as [24], but the result on 20K training data has shown the performance is increased with the number of training data.

**Table 1.** Quantitative localization results on SoundNet-Flickr subset, cIoU and AUC are reported (results of other methods are directly reported from [16]).

Methods	cIoU@0.5	AUC
Random	7.2	30.7
Attention 10K [24]	43.6	44.9
DMC AudioSet [15]	41.6	45.2
CAVL AudioSet [16]	50.0	49.2
Ours 10K	<b>52.2</b>	<b>49.6</b>
Ours 20K	53.8	50.6

**Multi-source Localization on AudioSet.** Since existing methods of sound localization evaluation are mainly for single-source scenes, We propose a quantitative evaluation pipeline for multi-source sound localization in complex scenes. We adopt a subset of AudioSet covering 15 musical instruments for training and testing.

To evaluate the model’s ability of separating sounds of different instruments and aligning them with corresponding visual sources, we use cIoU and AUC metric in a class-aware manner. Different from class-agnostic score map used in [24], our method uses the detected bounding boxes of Faster RCNN to indicate the localization of sounding objects<sup>5</sup>, each box is labelled as one specific category of music instruments, i.e.,  $C = 15$  on this dataset. Next, we calculate cIoU scores (e.g., with threshold 0.5) on each valid sound source and take an average. Final cIoU\_class on each frame can be calculated by

$$\text{cIoU\_class} = \frac{\sum_{c=1}^C \theta_c \text{cIoU}_c}{\sum_{c=1}^C \theta_c}, \quad (9)$$

where  $c$  indicates the class index of instruments,  $\theta_c = 1$  if instrument of class  $c$  makes sounds, otherwise 0. In this way, only when the model is able to establish class-specific association between sounds and objects, the evaluation score of cIoU\_class will become high.

**Table 2.** Quantitative localization results on AudioSet of different difficulty levels. The cIoU\_class threshold is 0.5 for level-1 and level-2, but 0.3 for level-3. Note that †AVC method is evaluated in a class-agnostic way.

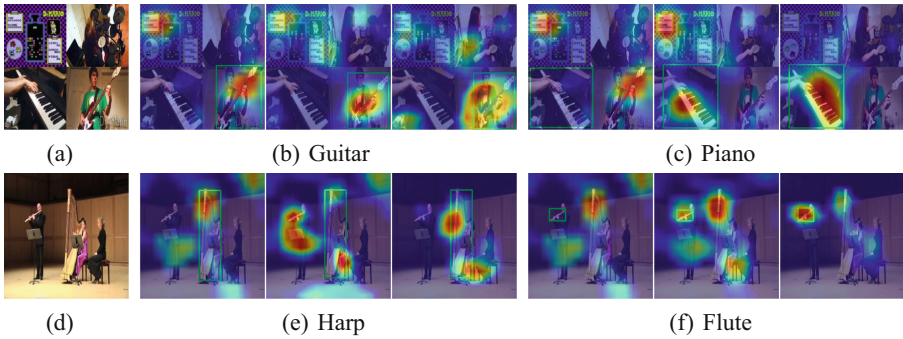
Methods	level-1		level-2		level-3	
	cIoU_class	AUC	cIoU_class	AUC	cIoU_class@0.3	AUC
†AVC	24.8	32.0	4.27	23.6	5.3	14.9
Multi-task	20.6	29.5	2.37	17.4	10.5	17.8
Ours	<b>32.8</b>	<b>38.3</b>	<b>6.16</b>	<b>23.9</b>	<b>21.1</b>	<b>22.0</b>

To clearly present the effectiveness of our audiovisual alignment, we further divide the testing set into different difficulty levels based on the number of categories of sounding instruments, which results in 4,273 pairs of single-source (level-1), 211 pairs of two-source (level-2) and 19 pairs of three-source (level-3). As our model is a two-stage learning method, consisting of multi-task learning and fine-grained alignment, to validate the contribution of each of them, we conduct an ablation study with two baselines. The two baselines are (1) AVC: only using video-level audiovisual correspondence for training and inferring the sound locations in a class-agnostic way. (2) multi-task learning: using both of classification and audiovisual correspondence for training and inferring the sound locations with the coarse-grained audiovisual correspondence. Table 2 shows the localization results on different difficulty levels. Note that, as AVC method is not provided with any category information, we evaluate it in a class-agnostic way. From the results, we have several observations. First, using AVC to localize sound in a class-agnostic way is effective with limited sound sources,

<sup>5</sup> We have filtered out those silent detected objects.

but fails when more objects make sounds. This is because the video-level correspondence is too coarse to provide sound-object association in complex scenes. Second, although AVC takes a much looser evaluation metric of class-agnostic, it is still worse than the multi-task method on level-3, which reveals introduced classification helps to distinguish sounds of different sources. Third, our method with audiovisual alignment significantly outperforms two baselines and is robust on all difficulty levels. It demonstrates that our feature disentanglement and fine-grained alignment is effective to establish one-to-one association in both single-source and multi-source scenes.

We visualize some localization maps for the scenes in level-2 w.r.t. three different methods: AVC, Multi-task and Ours in Fig. 6. It is clear that our method can generally associate sounds with specific instruments. For example, our method precisely focuses on the tiny area where the flute locates, while the other two associate flute sound with visual object of harp.



**Fig. 6.** We visualize some examples in AudioSet level-2. The localization maps in each subfigure are listed from left to right: AVC, Multi-task, Ours. The green boxes are detection results of Faster RCNN. (Color figure online)

#### 4.4 Sound Separation

In this task, we use localized objects as visual guidance to perform sound source separation, and evaluate it on MUSIC dataset. Following [29], we sub-sample it at 11kHz, and randomly crop 6-s clips to generate  $256 \times 256$  spectrograms with log-frequency projection as input, then feed to U-Net. To acquire effective visual guidance of sound source, we use clip-level audio tags for classification and perform audiovisual alignment within the contained 11 instruments. Then the visual representation of sound source is generated to guide source separation.

To precisely evaluate the separation performance, we adopt three metrics of Signal-to-Distortion Ratio (SDR), Signal-to-Interference Ratio (SIR) and Signal-to-Artifact Ratio (SAR), where higher is better for all [10, 29]. Table 3 shows separation results under different training conditions, where Single-Source means

training with only solo videos, while Multi-Source refers to training with both solo and duet videos. We compare three different learning settings, the first is to directly use weights output by Grad-CAM as prediction mask, and the latter two are using audio and visual representation as guidance. The separation performance with Grad-CAM output weight is relatively poor, because it is of very low resolution, far from enough precise for sound separation. As for audio representations, since they are disentangled from mixed spectrogram by weighted pooling (Eq. 5), it is only slightly better than Grad-CAM but still not enough to represent a specific instrument. But when using visual representation as guidance, our model achieves comparable results on all three metrics. It demonstrates that our sound localization results contribute to effective visual representation of specific sound sources. Note that our model is trained with fewer audiovisual pairs compared to other methods, and [10] adopts an additional detector to extract sound source but which is not necessary for our model. To further validate the efficacy of our approach in multi-source scenes, our model is also trained with duet videos. The results reveal that our model can capture useful information in complex scenes to establish cross-modal association.

**Table 3.** Sound source separation results on MUSIC dataset. We report performance when training only on single-source (solo) videos and multi-source (solo+duet) videos as [10]. Note that SAR only captures absence of artifacts, and can be high even if separation of poor quality.

Methods	Single-source			Multi-source		
	SDR	SIR	SAR	SDR	SIR	SAR
NMF-MFCC [26]	0.92	5.68	5.84	0.92	5.68	5.84
AV-Mix-Sep [8]	3.16	6.74	8.89	3.23	7.01	9.14
Sound-of-Pixels [29]	7.30	11.90	11.90	6.05	9.81	12.40
Co-Separation [10]	7.38	13.70	10.80	7.64	13.80	11.30
CAVL [16]	6.59	10.10	12.56	6.78	10.62	12.19
Ours Grad-CAM	-2.78	-0.01	7.79	-2.49	0.08	8.34
Ours Audio	-1.16	0.33	11.11	-0.97	0.43	11.02
Ours Visual	6.53	12.15	11.31	6.57	11.90	10.78

## 5 Conclusions

In this work, we present an audiovisual learning framework which automatically disentangles audio and visual representations of different categories from complex scenes, and performs feature alignment in a coarse-to-fine manner. We further propose a novel evaluation pipeline for multi-source sound localization to

demonstrate the superiority of our model. And our model shows promising performance on sound localization in complex scenes with multiple sound sources, as well as on sound source separation.

In future, to better distinguish different sounds and objects, we would like to introduce more categories into classification task. In this way, we are able to establish more precise sound-object association.

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## References

1. Arandjelovic, R., Zisserman, A.: Look, listen and learn. In: 2017 IEEE International Conference on Computer Vision (ICCV), pp. 609–617, October 2017. <https://doi.org/10.1109/ICCV.2017.73>
2. Arandjelović, R., Zisserman, A.: Objects that sound. In: Ferrari, V., Hebert, M., Sminchisescu, C., Weiss, Y. (eds.) ECCV 2018. LNCS, vol. 11205, pp. 451–466. Springer, Cham (2018). [https://doi.org/10.1007/978-3-030-01246-5\\_27](https://doi.org/10.1007/978-3-030-01246-5_27)
3. Aytar, Y., Vondrick, C., Torralba, A.: SoundNet: learning sound representations from unlabeled video. In: Lee, D.D., Sugiyama, M., Luxburg, U.V., Guyon, I., Garnett, R. (eds.) Advances in Neural Information Processing Systems 29, pp. 892–900. Curran Associates, Inc. (2016). <http://papers.nips.cc/paper/6146-soundnet-learning-sound-representations-from-unlabeled-video.pdf>
4. Chattopadhyay, A., Sarkar, A., Howlader, P., Balasubramanian, V.N.: Grad-CAM++: generalized gradient-based visual explanations for deep convolutional networks. In: 2018 IEEE Winter Conference on Applications of Computer Vision (WACV), pp. 839–847, March 2018. <https://doi.org/10.1109/WACV.2018.00097>
5. Gan, C., Huang, D., Zhao, H., Tenenbaum, J.B., Torralba, A.: Music gesture for visual sound separation. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, pp. 10478–10487 (2020)
6. Gan, C., Zhang, Y., Wu, J., Gong, B., Tenenbaum, J.B.: Look, listen, and act: towards audio-visual embodied navigation. arXiv preprint [arXiv:1912.11684](https://arxiv.org/abs/1912.11684) (2019)
7. Gan, C., Zhao, H., Chen, P., Cox, D., Torralba, A.: Self-supervised moving vehicle tracking with stereo sound. In: Proceedings of the IEEE International Conference on Computer Vision, pp. 7053–7062 (2019)
8. Gao, R., Feris, R., Grauman, K.: Learning to separate object sounds by watching unlabeled video. In: Ferrari, V., Hebert, M., Sminchisescu, C., Weiss, Y. (eds.) ECCV 2018. LNCS, vol. 11207, pp. 36–54. Springer, Cham (2018). [https://doi.org/10.1007/978-3-030-01219-9\\_3](https://doi.org/10.1007/978-3-030-01219-9_3)
9. Gao, R., Grauman, K.: 2.5D visual sound. In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, pp. 324–333 (2019)
10. Gao, R., Grauman, K.: Co-separating sounds of visual objects. In: The IEEE International Conference on Computer Vision (ICCV), October 2019
11. Gemmeke, J.F., et al.: Audio set: an ontology and human-labeled dataset for audio events. In: 2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 776–780, March 2017. <https://doi.org/10.1109/ICASSP.2017.7952261>



12. Hadsell, R., Chopra, S., LeCun, Y.: Dimensionality reduction by learning an invariant mapping. In: 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR 2006), vol. 2, pp. 1735–1742, June 2006. <https://doi.org/10.1109/CVPR.2006.100>
13. He, K., Zhang, X., Ren, S., Sun, J.: Deep residual learning for image recognition. In: The IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2016
14. Hershey, S., et al.: CNN architectures for large-scale audio classification. In: 2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 131–135, March 2017. <https://doi.org/10.1109/ICASSP.2017.7952132>
15. Hu, D., Nie, F., Li, X.: Deep multimodal clustering for unsupervised audiovisual learning. In: The IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2019
16. Hu, D., Wang, Z., Xiong, H., Wang, D., Nie, F., Dou, D.: Curriculum audiovisual learning. arXiv preprint [arXiv:2001.09414](https://arxiv.org/abs/2001.09414) (2020)
17. Korbar, B., Tran, D., Torresani, L.: Co-training of audio and video representations from self-supervised temporal synchronization. [arXiv:1807.00230](https://arxiv.org/abs/1807.00230) (2018)
18. Owens, A., Efros, A.A.: Audio-visual scene analysis with self-supervised multisensory features. In: Ferrari, V., Hebert, M., Sminchisescu, C., Weiss, Y. (eds.) ECCV 2018. LNCS, vol. 11210, pp. 639–658. Springer, Cham (2018). [https://doi.org/10.1007/978-3-030-01231-1\\_39](https://doi.org/10.1007/978-3-030-01231-1_39)
19. Owens, A., Wu, J., McDermott, J.H., Freeman, W.T., Torralba, A.: Ambient sound provides supervision for visual learning. In: Leibe, B., Matas, J., Sebe, N., Welling, M. (eds.) ECCV 2016. LNCS, vol. 9905, pp. 801–816. Springer, Cham (2016). [https://doi.org/10.1007/978-3-319-46448-0\\_48](https://doi.org/10.1007/978-3-319-46448-0_48)
20. Pennington, J., Socher, R., Manning, C.D.: GloVe: global vectors for word representation. In: Empirical Methods in Natural Language Processing (EMNLP), pp. 1532–1543 (2014). <http://www.aclweb.org/anthology/D14-1162>
21. Ronneberger, O., Fischer, P., Brox, T.: U-Net: convolutional networks for biomedical image segmentation. In: Navab, N., Hornegger, J., Wells, W.M., Frangi, A.F. (eds.) MICCAI 2015. LNCS, vol. 9351, pp. 234–241. Springer, Cham (2015). [https://doi.org/10.1007/978-3-319-24574-4\\_28](https://doi.org/10.1007/978-3-319-24574-4_28)
22. Rouditchenko, A., Zhao, H., Gan, C., McDermott, J., Torralba, A.: Self-supervised audio-visual co-segmentation. In: ICASSP 2019–2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 2357–2361. IEEE (2019)
23. Selvaraju, R.R., Cogswell, M., Das, A., Vedantam, R., Parikh, D., Batra, D.: Grad-CAM: visual explanations from deep networks via gradient-based localization. In: The IEEE International Conference on Computer Vision (ICCV), October 2017
24. Senocak, A., Oh, T.H., Kim, J., Yang, M.H., So Kweon, I.: Learning to localize sound source in visual scenes. In: The IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2018
25. Shi, B., Bai, X., Yao, C.: An end-to-end trainable neural network for image-based sequence recognition and its application to scene text recognition. *IEEE Trans. Pattern Anal. Mach. Intell.* **39**(11), 2298–2304 (2017). <https://doi.org/10.1109/TPAMI.2016.2646371>
26. Spiertz, M., Gmann, V.: Source-filter based clustering for monaural blind source separation. In: Proceedings of the 12th International Conference on Digital Audio Effects (2009)



27. Tian, Y., Shi, J., Li, B., Duan, Z., Xu, C.: Audio-visual event localization in unconstrained videos. In: Ferrari, V., Hebert, M., Sminchisescu, C., Weiss, Y. (eds.) ECCV 2018. LNCS, vol. 11206, pp. 252–268. Springer, Cham (2018). [https://doi.org/10.1007/978-3-030-01216-8\\_16](https://doi.org/10.1007/978-3-030-01216-8_16)
28. Zhao, H., Gan, C., Ma, W.C., Torralba, A.: The sound of motions. In: The IEEE International Conference on Computer Vision (ICCV), October 2019
29. Zhao, H., Gan, C., Rouditchenko, A., Vondrick, C., McDermott, J., Torralba, A.: The sound of pixels. In: Ferrari, V., Hebert, M., Sminchisescu, C., Weiss, Y. (eds.) ECCV 2018. LNCS, vol. 11205, pp. 587–604. Springer, Cham (2018). [https://doi.org/10.1007/978-3-030-01246-5\\_35](https://doi.org/10.1007/978-3-030-01246-5_35)
30. Zhou, B., Khosla, A., Lapedriza, A., Oliva, A., Torralba, A.: Learning deep features for discriminative localization. In: The IEEE Conference on Computer Vision and Pattern Recognition (CVPR), June 2016
31. Zhou, H., Xu, X., Lin, D., Wang, X., Liu, Z.: Sep-stereo: visually guided stereophonic audio generation by associating source separation. In: Vedaldi, A., Bischof, H., Brox, T., Frahm, J.-M. (eds.) ECCV 2020. LNCS, vol. 12357, pp. 52–69. Springer, Cham (2020). [https://doi.org/10.1007/978-3-030-58610-2\\_4](https://doi.org/10.1007/978-3-030-58610-2_4)