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Semantic Audio-Visual Navigation

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Abstract

Recent work on audio-visual navigation assumes a constantly-sounding target and restricts the role of audio to signaling the target's position. We introduce semantic audio-visual navigation*, where objects in the environment make sounds consistent with their semantic meaning (e.g., toilet flushing, door creaking) and acoustic events are sporadic or short in duration. We propose a transformer-based model to tackle this new semantic AudioGoal task, incorporating an inferred goal descriptor that captures both spatial and semantic properties of the target. Our model's persistent multimodal memory enables it to reach the goal even long after the acoustic event stops. In support of the new task, we also expand the SoundSpaces audio simulations to provide semantically grounded sounds for an array of objects in Matterport3D. Our method strongly outperforms existing audio-visual navigation methods by learning to associate semantic, acoustic, and visual cues.*[1]

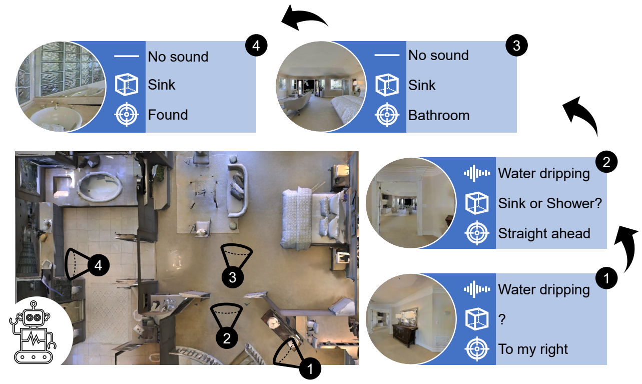

Figure 1: Semantic audio-visual navigation in 3D environments: an agent must navigate to a sounding object. Since the sound may stop while the agent searches for the object, the agent is incentivized to learn the association between how objects look and sound, and to build contextual models for where different semantic sounds are more likely to occur (e.g., water dripping in the bathroom).

1. Introduction

An autonomous agent interacts with its environment in a continuous loop of action and perception. The agent needs to reason intelligently about all the senses available to it (sight, hearing, proprioception, touch) to select the proper sequence of actions in order to achieve its task. For example, a service robot of the future may need to locate and fetch an object for a user, go empty the dishwasher when it stops running, or travel to the front hall upon hearing a guest begin speaking there.

Towards such applications, recent progress in visual navigation builds agents that use egocentric vision to travel to a designated point in an unfamiliar environment [23, 38, 42, 10], search for a specified object [44, 9, 37, 8], or explore and map a new space [35, 34, 13, 10, 15, 10, 36]. Limited new work further explores expanding the sensory suite of the navigating agent to include hearing as well. In particular, the AudioGoal challenge [11] requires an agent to navigate to a sounding target (e.g., a ringing phone) using audio for key directional and distance cues [11, 19, 12].

While exciting first steps, existing audio-visual navigation work has two key limitations. First, prior work assumes the target object constantly makes a steady repeating sound (e.g., alarm chirping, phone ringing). While important, this corresponds to a narrow set of targets; in real-world scenarios, an object may emit a sound only briefly or start and stop dynamically. Second, in current models explored in realistic 3D environment simulators, the sound emitting target has neither a visual embodiment nor any semantic context. Rather, target sound sources are placed arbitrarily in the environment and without relation to the semantics of the scene and objects. As a result, the role of audio is limited to providing a beacon of sound announcing where the object is.

In light of these limitations, we introduce a novel task: *semantic audio-visual navigation*. In this task, the agent must navigate to an object situated contextually in an environment that only makes sound for a certain period of time. Semantic audio-visual navigation widens the set of real-world scenarios to include acoustic events of short temporal duration that are semantically grounded in the environment. It offers new learning challenges. The agent must learn not only how to associate sounds with visual objects, but also

[1]Project page: http://vision.cs.utexas.edu/projects/semantic-audio-visual-navigation

how to leverage the semantic priors of objects (along with any acoustic cues) to reason about where the object is likely located in the scene. For example, hearing the dishwasher stop running and issue its end of cycle chime should suggest both what visual object to search for as well as the likely paths for finding it, i.e., towards the kitchen rather than the bedroom. Notably, in the proposed task, the agent is not given any external information about the goal (such as a displacement vector or name of the object to search for). Hence the agent must learn to leverage sporadic acoustic cues that may stop at any time as it searches for the source, inferring what visual object likely emitted the sound even after it is silent. See Figure 1.

To tackle semantic AudioGoal, we introduce a deep reinforcement learning model that learns the association between how objects look and how they sound. We develop a *goal descriptor* module that allows the agent to hypothesize the goal properties (i.e., location and object category) from the received acoustic cues before seeing the target object. Coupled with a transformer, it learns to attend to the previous visual and acoustic observations in its memory—conditioned on the predicted goal descriptor—to navigate to the audio source. Furthermore, to support this line of research, we instrument audio-visual simulations for real scanned environments such that semantically relevant sounds are attached to semantically relevant objects.

We evaluate our model on 85 large-scale real-world environments with a variety of semantic objects and their sounds. Our approach outperforms state-of-the-art models in audio-visual navigation with up to an absolute 8.9% improvement in SPL. Furthermore, our model is robust in handling short acoustic signals emitted by the goal with varying temporal duration, and compared to the competitors, it more often reaches the goal after the acoustic observations end. In addition, our model maintains good performance in the presence of environment noise (distractor sounds) compared to baseline models. Overall, this work shows the potential for embodied agents to learn about how objects look and sound through interactions with a 3D environment.

2. Related work

Visual navigation. To navigate autonomously, traditionally a robot builds a map via 3D reconstruction (i.e., SLAM) and then plans a path using the map [17]. Recent work instead learns navigation policies directly from egocentric observations [23, 37, 29]. A popular task is PointGoal navigation, where the goal position is given to the agent [23, 29, 38, 42]. Alternatively, in the ObjectGoal setting, the agent is given an object label rather than the goal location, and must navigate to the nearest instance of that category (e.g., go to a table) [44, 4, 9]. In contrast to both PointGoal and ObjectGoal, in the proposed setting the agent is not given specific goal information. Instead, it needs to react to an acoustic event to determine what kind of object is sounding and navigate to it. Furthermore, unlike ObjectGoal, the agent needs to navigate to the specific object instance that emitted the sound rather than any instance of that category. Our task represents real-world scenarios where dynamic objects draw the attention of an agent and call it to action (e.g., the sound of a heavy object falling upstairs).

Audio-visual navigation. Recent work leverages audio for the AudioGoal navigation task [11, 19]. In that setup, the agent navigates to a sound-emitting goal using both visual and acoustic observations [11, 19, 12]. As discussed above, prior methods assume the goal is sounding continuously through the episode and that it does not have a visual embodiment. While suitable for certain events like *fire alarm*, many acoustic events are short and infrequent (e.g., glass breaking, door slamming, a person calling for help). We consider a generalized setting where the audio signal is only available for a limited period of time and the agent must find the sounding object using both initial acoustic cues and the goal semantics. In addition, we augment the SoundSpaces audio simulations [11] for Matterport3D [6] to portray semantically relevant object-level sounds, an advance over the simulations used in prior work [11, 19, 12], which inserted a small set of sounds randomly in the environments without any visual embodiment.

Memory models for 3D environments. While it is common to use an implicit memory representation in navigation to aggregate observations, e.g., a recurrent network [28, 38, 11, 27, 3, 30], other methods leverage explicit map-based memories to record occupancy [23, 13, 34, 10, 12, 33] or object locations [9, 5]. To capture long-term dependencies another promising direction is to use a transformer architecture [41] to record observations and poses [15]. We build in this direction and introduce a scene memory transformer that, unlike prior work, 1) is multimodal and 2) leverages an explicit learned *goal descriptor* to attend to the memory. Our memory model learns audio-visual associations between the goal and the observations from the scene, a crucial functionality as we demonstrate in experiments.

Audio-visual learning in video. Work in passive (non-embodied) video analysis also explores the link between object appearance and sound. This includes audio source separation methods that disentangle sounds based on object appearance [20, 14, 31, 1, 43, 21, 22] as well as self-supervised video representation learning methods [26, 32, 16, 18]. Our approach also learns how to associate objects with their sounds. However, in contrast to previous video approaches, our approach learns in the context of an agent's interaction with a 3D environment. Namely, our agent learns to associate an object category inferred from audio with its visual representation and contextual scene cues at the same time it learns to navigate efficiently.

3. Semantic Audio-Visual Navigation

We introduce the novel task of semantic audio-visual navigation. In this task, the agent is required to navigate in a complex, unmapped environment to find a semantic sounding object—semantic AudioGoal for short. Different from AudioGoal [11, 19], the goal sound *need not be periodic*, has *variable duration*, and is associated with a meaningful *semantic object* (e.g., the door creaking is associated with the apartment's door). This setting represents common real world events, and as discussed above, poses new challenges for embodied learning. Relying on audio perception solely to produce step-by-step actions is not sufficient, since the audio event is relatively short. Instead, the agent needs to reason about the category of the sounding object and use both visual and audio perception to predict its location.

3D environments and simulator. Consistent with the active body of computer vision work on embodied AI done in simulation, and to facilitate reproducibility of our work, we rely on a visually and acoustically realistic simulation platform to model an agent moving in complex 3D environments. We use SoundSpaces [11], which enables realistic audio rendering of arbitrary sounds for the real-world environment scans in Replica [40] and Matterport3D [6]. We use the Matterport environments due to their greater scale and complexity. SoundSpaces is Habitat-compatible [38] and allows rendering arbitrary sounds at any pair of source and receiver (agent) locations on a uniform grid of nodes spaced by 1 m. Next we explain how we extend this audio data to provide semantically meaningful sounds.

Semantic sounds data collection. We use the 21 object categories defined in the ObjectGoal navigation challenge [4] for Matterport3D environments: chair, table, picture, cabinet, cushion, sofa, bed, chest of drawers, plant, sink, toilet, stool, towel, tv monitor, shower, bathtub, counter, fireplace, gym equipment, seating, and clothes. All of these categories have objects that are visually present in Matterport environments. By rendering object-specific sounds at the locations of the Matterport objects, we obtain semantically meaningful and contextual sounds. For example, the water flush sound will be associated with the toilet in the bathroom, and the crackling fire sound with the fireplace in the living room or the bedroom. We filter out object instances that are not reachable by the navigability graph. The number of object instances for train/val/test is 303/46/80 on average for each object category.

We consider two types of sound events: object-emitted and object-related. Object-emitted sounds are generated by the object, e.g., a toilet flushing, whereas object-related sounds are caused by people's interactions with the object, e.g., food being chopped on the counter. To provide a variety of sounds, we search a public database `freesound.org` by the 21 object names to get long copyright-free audio clips per object. We split the original clips (average length 81s) evenly into train/val/test clips. These splits allow the characteristics of the unheard sounds (i.e., waveforms not heard during training) to be related to those in the training set, while still preserving natural variations.[2] The duration of the acoustic phase in each episode is randomly sampled from a Gaussian of mean 15s and deviation 9s, clipped for a minimum 5s and maximum 500s. If the sampled duration is longer than the length of the audio clip, we replay the clip. See the Supp. video for examples.

Action space and sensors. The agent's action space is *MoveForward*, *TurnLeft*, *TurnRight*, and *Stop*. The last three actions are always valid, while *MoveForward* only takes effect when the node in front of the agent is reachable from that position (no collision). The sensory inputs are egocentric binaural sound (two-channel audio waveforms), RGB, depth, and the agent's current pose.

Episode specification and success criterion. An episode of semantic AudioGoal is defined by 1) the scene, 2) the agent start location and rotation, 3) the goal location, 4) the goal (object) category and 5) the duration of the audio event. In each episode in a given scene, we choose a random object category and a random instance of that category as the goal. The agent's start pose is also randomly positioned in the scene. In semantic AudioGoal, the agent has to stop near the particular sounding object instance, not simply any instance of the class. This is a stricter success criterion than ObjectGoal [4], which judges an episode as successful if the agent stops near any instance of that category. We define a set of viewpoints around each object within 1 m of the object's boundary; issuing the *Stop* action at any of these viewpoints is considered a successful termination of the episode.

4. Approach

We propose SAVi, a novel model for the **s**emantic **a**udio-**v**isual **n**av**i**gation task. SAVi uses a persistent multimodal memory along with a transformer model, which, unlike RNN-based architectures (e.g., [11]) or reactive ones (e.g., [19]), can directly attend to observations with various temporal distances from the current step to locate the goal efficiently. Furthermore, our model learns to capture goal information from acoustic events in an explicit descriptor and uses it to attend to its memory, thus enabling the agent to discover any spatial and semantic cues that may help it reach the target faster.

Our approach has three main components (Figure 2): 1) an Observation Encoder that maps the egocentric visual and acoustic observations received by the agent at each step to an embedding space; 2) a Goal Descriptor Network that

[2] Note that even the same waveform will sound different when rendered in a new environment; the sound received by the agent is a function of not only that waveform but also the environment geometry and the agent's position relative to the source.

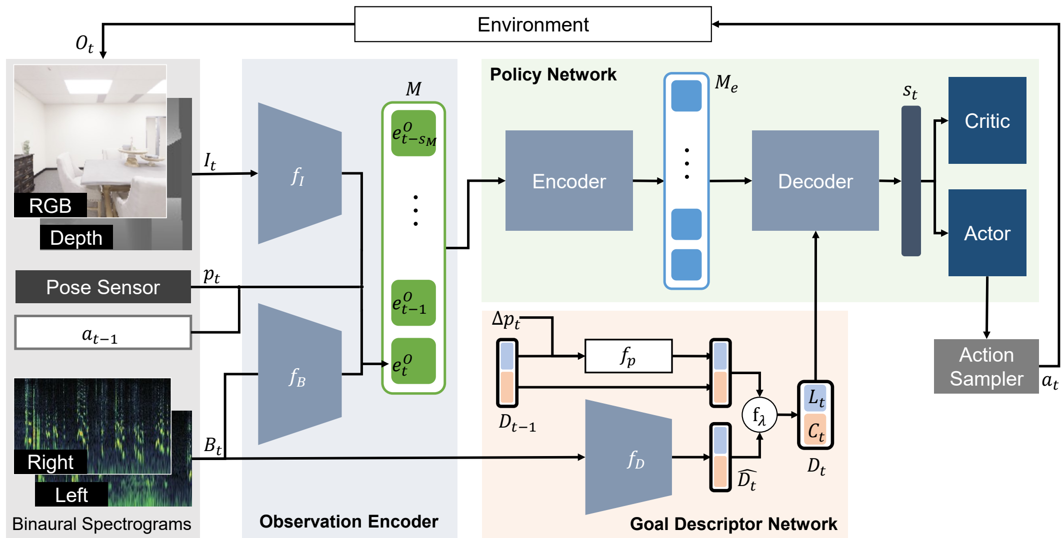

Figure 2: In our model, the agent first encodes input observations and stores their features in memory M. Then our goal descriptor network leverages the acoustic cues to dynamically infer and update a *goal descriptor* D_t of the target object, which contains both location L_t and object category C_t information about the goal. By conditioning the agent's scene memory on the goal descriptor, the learned state representation s_t preserves information most relevant to the goal. Our transformer-based policy network attends to the encoded observations in M with self-attention to reason about the 3D environment seen so far, and it attends to M_e with D_t to capture possible associations between the hypothesized goal and the visual and acoustic observations to predict the state s_t. Then, s_t is fed to an actor-critic network, which predicts the next action a_t. The agent receives its reward from the environment based on how close to the goal it moves and whether it succeeds in reaching it.

produces a goal descriptor based on the encoded observations; and 3) a Policy Network that given the encoded observations and the predicted goal descriptor, extracts a descriptor-conditioned state representation and outputs the action distribution. Next, we describe each module. We defer CNN architecture details to Sec. 4.4.

4.1. Observation Encoder

At each time step t, the agent receives an observation $O_t = (I_t, B_t, p_t, a_{t-1})$, where I is the egocentric visual observation consisting of an RGB and depth image; B is the received binaural audio waveform represented as a two-channel spectrogram; p is the agent pose defined by its location and orientation (x, y, θ) with respect to its starting pose p_0 in the current episode; and a_{t-1} is the action taken at the previous time step.

Our model encodes each visual and audio observation with a CNN, $e^I_t = f_I(I_t)$ and $e^B_t = f_B(B_t)$. Then, the observation O_t encoding is $e^O_t = [e^I_t, e^B_t, p_t, a_{t-1}]$. The model stores the encoding of the observations up to time t in memory $M = \{e^O_i : i = \max\{0, t - s_M\}, \dots, t\}$ (see Figure 2 second column), where s_M is the memory size.

4.2. Goal Descriptor Network

As described in Sec. 3, the agent does not receive direct information about the goal; rather, it needs to rely solely on its observations to set its own target. Audio carries rich cues about the target—not only its relative direction and distance from the agent, but also the type of object that may have produced the acoustic event. Hence, we leverage the acoustic signal to predict the goal properties, namely its location (spatial) and object category (semantics). Both properties are crucial for successful navigation. The estimated goal location gives the agent an idea of where to find the goal. However, since the acoustic event may be short-lived, and the estimate may be inaccurate, the agent cannot solely rely on this initial estimate. Our model thus aims to also leverage the goal semantics in terms of both the object's likely appearance and the scene's visual context.

The goal descriptor network is a CNN f_D such that $\hat{D}_t = f_D(B_t)$, where $\hat{D}_t$ is the step-wise estimate of the descriptor and it consists of two parts: the current estimate of the goal location $\hat{L}_t = (\Delta x, \Delta y)$ relative to the agent's current pose p_t, and its predicted object label $\hat{C}_t$. To reduce the impact of noise from a single prediction, the agent aggregates the current estimate with the previous goal descriptor $D_t = f_\lambda(\hat{D}_t, D_{t-1}, \Delta p_t) = (1 - \lambda)\hat{D}_t + \lambda f_p(D_{t-1}, \Delta p_t)$, where $f_p(\cdot)$ transforms the previous goal location $\hat{L}_{t-1}$ based on the last pose change Δp_t (the goal label is unaffected by this transformation), and λ is the weighting factor, which is set to 0.5 based on validation. When sound stops (i.e., the sound intensity becomes zero), the agent maintains its latest estimate D_t by simply transforming the previous descriptor based on the pose change Δp_t to obtain the current descriptor $D_t = f_p(D_{t-1}, \Delta p_t)$.

4.3. Policy Network

Our reinforcement learning policy network is based on a transformer architecture. Using the memory M collected so far in the episode, the transformer proceeds by encoding these observation embeddings with a self-attention mechanism to capture any possible relations among the inputs, yielding the encoded memory $M_e = \text{Encoder}(M)$. Then, using the predicted goal descriptor D_t, a decoder network attends to all cells in the encoded memory M_e to calculate the state representation $s_t = \text{Decoder}(M_e, D_t)$. An actor-critic network uses s_t to predict the action distribution and value of the state. The actor and the critic are each modelled by single linear layer neural network. Finally, an action sampler samples the next action a_t from this action distribution, determining the agent's next motion in the 3D scene.

4.4. Training

To train the goal descriptor network, we generate pairs of ground truth locations and categories from the simulator for the array of training sounds, and train the prediction network in a supervised fashion. For the category prediction portion, we find off-policy training gives good accuracy; hence we pre-train the classifier on 3.5M collected spectrogram-category pairs at a variety of positions in the training environments and freeze it during policy training. In contrast, location prediction is learned better on-policy. Training the L_t predictor on-policy has the benefit of matching the training data distribution with policy behavior, leading to higher accuracy (see Supp.). We use the same experience collected for policy training to train the location predictor and update them at the same frequency. We use the mean squared error loss for the location predictor and the cross entropy loss for the goal object label predictor.

For policy training, we follow a two-stage training paradigm (as shown to be effective for transformer-based models [15]) using decentralized distributed proximal policy optimization (DD-PPO) [42]. In the first stage, we set the memory size $s_M = 1$ (the most recent observation) to train the observation encoder without attention. Then, in the second stage, we freeze the observation encoder and train the rest of the model with the full memory size ($s_M = 150$). In both stages, the loss consists of a value network loss to reduce the error of state-value prediction, a policy network loss to produce better action distributions, and an entropy loss to encourage exploration. We refer readers to PPO [39] for more details. To train the policy, we reward the agent with $+10$ if it reaches the goal successfully and issue an intermediate reward of $+1$ for reducing the geodesic distance to the goal, and an equivalent penalty for increasing it. We also issue a time penalty of -0.01 per time step to encourage efficiency.

To avoid sampling easy episodes (e.g., short or straight-line paths), we require the geodesic distance from the start pose to the goal to be greater than 4 m and the ratio of Euclidean distance to geodesic distance to be greater than 1.1. We collect 0.5M/500/1000 episodes for train/val/test splits for all 85 Matterport3D SoundSpaces environments.

We train our model with Adam [25] with a learning rate of 2.5×10^{-4} for the policy network and 1×10^{-3} for the descriptor network. We roll out policies for 150 steps, update them with collected experiences for two epochs, and repeat this procedure until convergence. We train all methods, both ours and the baselines, for 300M steps for them to fully converge.

At each time step, the agent receives a binaural audio clip of 1s, represented as two 65×26 spectrograms. The audio is computed by convolving the appropriate impulse response from SoundSpaces with the source audio waveform, thereby generating the sound the agent would hear in that environment at its current position relative to the source. The RGB and depth images are center cropped to 64×64. Both the observation encoder CNNs f_B and f_I and the descriptor network f_D use a simplified ResNet-18 [24] that is trained from scratch. For the transformer model, we use one encoder layer and one decoder layer, which employ multi-attention with 8 heads. The hidden state size is 256 and the memory size s_M is 150, matching the frequency of policy updates.

5. Experiments

Baselines. We compare our model to the following baselines and existing work:

1. **Random**: A random baseline that uniformly samples one of three actions and executes *Stop* automatically when it reaches the goal (perfect stopping).
2. **ObjectGoal RL**: An end-to-end RL policy with a GRU encoder and RGB-D inputs (no audio). It is given the one-hot encoding of the true category label as an additional input to search for the goal object instance. This baseline is widely used in ObjectGoal tasks [23, 9, 30, 7]. We train this method for 800M steps with perfect stopping. Details in Supp.
3. **Gan et al. [19]**: A modular audio-visual model that trains a goal location predictor offline and uses a geometric planner for planning. Since the original model can not handle sporadic audio events, we improve its goal location predictor with our update operation f_λ.
4. **Chen et al. [11]**: An end-to-end RL policy that encodes past memory with a GRU RNN and is trained to reach the goal using audio and visual observations.

	Heard Sounds					*Unheard Sounds*				
	Success ↑	SPL ↑	SNA ↑	DTG ↓	SWS ↑	Success ↑	SPL ↑	SNA ↑	DTG ↓	SWS ↑
Random	1.4	3.5	1.2	17.0	1.4	1.4	3.5	1.2	17.0	1.4
ObjectGoal RL	1.5	0.8	0.6	16.7	1.1	1.5	0.8	0.6	16.7	1.1
Gan et al. [19]	29.3	23.7	**23.0**	11.3	14.4	15.9	12.3	11.6	12.7	8.0
Chen et al. [11]	21.6	15.1	12.1	11.2	10.7	18.0	13.4	12.9	12.9	6.9
AV-WaN [12]	20.9	16.8	16.2	10.3	8.3	17.2	13.2	12.7	11.0	6.9
SMT [15] + Audio	22.0	16.8	16.0	12.4	8.7	16.7	11.9	10.0	12.1	8.5
SAVi (**Ours**)	**33.9**	**24.0**	18.3	**8.8**	**21.5**	**24.8**	**17.2**	**13.2**	**9.9**	**14.7**

Table 1: Navigation performance on the SoundSpaces Matterport3D dataset [11]. Our SAVi model has higher success rates and follows a shorter trajectory (SPL) to the goal compared to the state-of-the-art. Equipped with its explicit goal descriptor and having learned semantically grounded object sounds from training environments, our model is able to reach the goal more efficiently—even after it stops sounding—at a significantly higher rate than the closest competitor (see the SWS metric).

5. **AV-WaN [12]**: A hierarchical RL model that records acoustic observations on the ground plane, predicts waypoints, and uses a path planner to move towards these waypoints using a sequence of navigation actions.
6. **SMT [15] + Audio**: We adapt the scene memory transformer (SMT) model [15] to our task by also encoding the audio observation in its memory. Unlike our model, it does not explicitly predict the goal description and relies only on the cues available in memory to reach the goal. The latest observation embedding is used as decoder input to decode M_e and predict the state.

All models use the same reward function and inputs. For all methods, there is no actuation noise since audio rendering is only available at grid points (see [11] for details).

Metrics. We evaluate the following navigation metrics: 1) success rate: the fraction of successful episodes; 2) success weighted by inverse path length (SPL): the standard metric [2] that weighs successes by their adherence to the shortest path; 3) success weighted by inverse number of actions (SNA) [12]: this penalizes collisions and in-place rotations by counting number of actions instead of path lengths; 4) average distance to goal (DTG): the agent's distance to the goal when episodes are finished; 5) success when silent (SWS): the fraction of successful episodes when the agent reaches the goal after the end of the acoustic event.

Navigation results. Following standard protocol [11] we evaluate all models in two settings: 1) *heard sounds*—train and test on the same sound 2) *unheard sounds*—train and test on disjoint sounds. In both cases, the test environments are always unseen, hence both require generalization. All results are averaged over 1,000 test episodes.

Table 1 shows the results. Our SAVi approach outperforms all other models by a large margin on all metrics—with 0.3%, 8.9%, 7.2%, 7.2% absolute gains in SPL on *heard sounds* and 4.9%, 3.8%, 4%, 5.3% absolute SPL gains on *unheard sounds* compared to Gan et al. [19], Chen et al. [11], AV-WaN [12], and SMT [15], respectively. This shows our model leverages audio-visual cues intelligently and navigates to goals more efficiently. AV-WaN represents the state-of-the-art for AudioGoal audio-visual navigation. Our SAVi model's gains over AV-WaN show both 1) the distinct new challenges offered by the semantic AudioGoal task, and 2) our model's design effectively handles them.[3]

In addition, our model improves the success-when-silent (SWS) metric by a large margin compared to the closest competitor. This emphasizes the advantage of our goal descriptor module. The explicit and persistent descriptor for the goal in our model helps to maintain the agent's focus on the target even after it stops emitting a sound. Although the SMT+Audio [15] model also has access to a large memory pool and can leverage implicit goal information from old observations, lacking our goal descriptor and the accompanying goal-driven attention, it underperforms our model by a sizeable margin.

As expected, Random does poorly on this task due to the challenging complex environments. Although ObjectGoal RL has the goal's ground truth category label as input, it fails in most cases. This shows that knowing the category label by itself is insufficient to succeed in this task; the agent needs to locate the specific instance of that category, which is difficult without the acoustic cues.

Navigation trajectories. Figure 3 shows test episodes for our SAVi model. The agent uses its acoustic-visual perception and memory along with the spatial and semantic cues from the acoustic event, whether from a long event (water dripping sound) or a short one (opening and closing a door

[3] While AV-WaN [12] reports large performance improvements over Chen et al. [11] on the standard AudioGoal task, we do not observe similar margins between the two models here. We attribute this to temporal gaps in the memory caused by AV-WaN's waypoint formulation—which are not damaging for constantly sounding targets, but do cause problems for semantic AudioGoal (see Supp. for details).

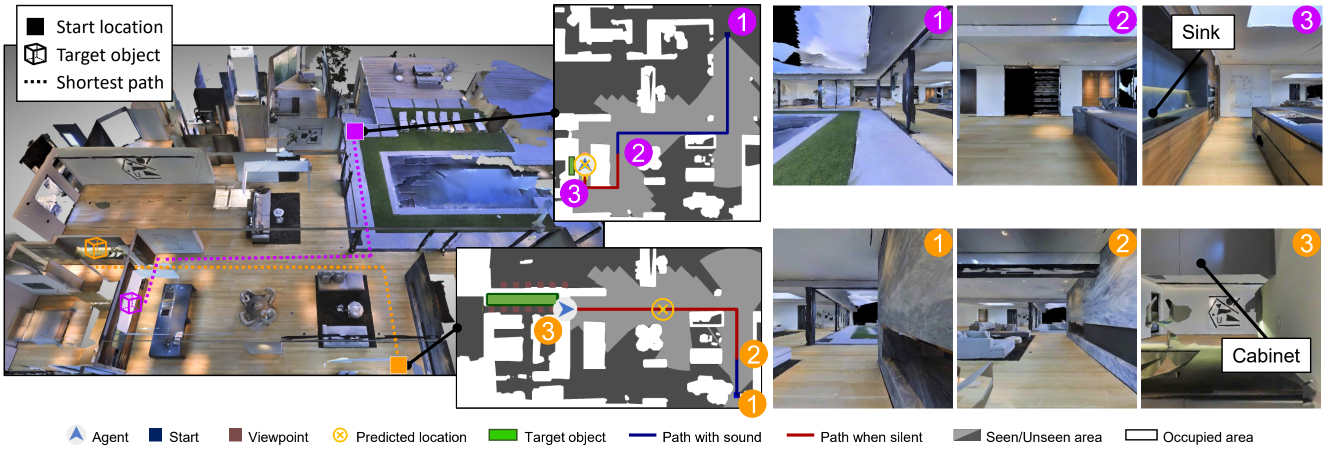

Figure 3: Example SAVi navigation trajectories. In the first episode (top/magenta) the agent hears a water dripping sound and in the second episode (bottom/orange) a sound of opening and closing a door. For each episode, we show three egocentric visual views (right) sampled from the agent's trajectory at the start location ①, when the sound stops ②, and at the end location ③. In the top episode, the acoustic event lasts for two thirds of the trajectory and when the sound stops the agent has an accurate estimate of the object location that helps it find the sounding object (the sink). The second episode (bottom) has a much shorter acoustic event. The agent's estimate of the object location is inaccurate when the sound stops but still helps the agent as a general directional cue. The agent leverages this spatial cue *and* the semantic cue from its estimate of the object category, a cabinet, to attend to its multimodal memory to find the object in the kitchen and end the episode successfully.

sound), to successfully find the target objects (the sink and the cabinet). See the Supp. video for more examples.

Common failure cases are when: 1) the sound stops too early in the episode, and the agent has not accumulated enough spatial or semantic cues about the goal. In this case the agent might either search for the wrong object (noisy semantics) or search for the object in the wrong place (noisy location); 2) the agent issues a premature stop action near the target object but not exactly at the right location.

Distractor sounds. In our tests so far, there is a single acoustic event per episode, whether comprised of a heard or unheard sound (Table 1). Next, we generalize the setting further to include *unheard distractor sounds*—sounds happening simultaneously with the target object. This corresponds to real-world scenarios, for example, where the door slams shut while the AC is humming. For this setting to be well-defined, the agent must know which sound is its target; hence, we input the one-hot encoding of the target object to all models and concatenate it with their state features. For our model, in addition to replacing C_t with this one-hot encoding, we also use it as input to the location prediction network along with B_t. This allows the location prediction network to learn to identify which of the sounds mixed in the input needs to be localized. We use the 102 periodic sounds from SoundSpaces [11] as the set of possible distractor sounds, which are disjoint from the target object sounds curated for this work. We divide these 102 sounds into non-overlapping 73/11/18 splits for train/val/test, and hence the distractor sound at test time is unheard. In each episode, we randomly position one distractor sound in the environment at a location different from the goal.

	Success ↑	SPL ↑	SNA ↑	DTG ↓	SWS ↑
Chen et al. [11]	4.0	2.4	2.0	14.7	2.3
AV-WaN [12]	3.0	2.0	1.8	14.0	1.6
SMT [15]+Audio	4.2	2.9	2.1	14.9	2.8
SAVi (**Ours**)	**11.8**	**7.4**	**5.0**	**13.1**	**8.4**

Table 2: Navigation performance on *unheard sounds* in the presence of unheard distractor sounds.

Table 2 shows the results. While the performance of the baselines suffers from the distracting environment noise, our agent is still able to reach a success rate of 11.8% and SPL of 7.4%, which is 7.6% and 4.5% higher than the best-performing baseline. This shows the proposed inferred goal descriptor helps the agent attend to important observations to capture semantic and spatial cues, making our model more robust to the environment noise. That said, the absolute performance declines for all methods in this hard setting. We plan to investigate ways to explicitly separate the "clutter" sounds in future work.

Analyzing the goal descriptor. Next we ablate the two main components in the goal descriptor, location and category, to study their relative impact for the *unheard sounds* experiment from Table 1. Table 3 shows that ablating any component results in a performance drop. L_t has a compar-

	Success ↑	SPL ↑	SNA ↑	DTG ↓	SWS ↑
C_t-only	20.5	13.5	11.6	9.8	11.0
L_t-only	23.9	16.2	**13.5**	**9.3**	13.8
w/o aggregation	21.9	14.3	11.1	9.7	13.4
Full model	**24.8**	**17.2**	13.2	9.9	**14.7**

Table 3: Ablation experiment results.

atively larger impact on our model's performance.

Next we analyze the *successful* episodes in the context of L_t and C_t. For 56% of them, our model ends the episode by stopping at its own estimate of the goal location in its descriptor, suggesting that the agent has successfully used its directional sound prediction to guide its movements. On the other hand, for the other 44%, the agent stops at a (correct) location *different* than L_t, suggesting that the agent has relied more on the visual context cues leading to the anticipated object C_t. In fact, if we inject a random category label instead of C_t at the start of the episode, success rates and SPL drop up to 8%. The learned associations between the spatial and semantic cues are important for success; breaking these associations with random category labels forces the agent to attend to contradictory cues about the goal in its memory, thus increasing the chance of failure.

To understand if the performance gain comes from our goal descriptor or the transformer, we further ablate our model by replacing the transformer with an RNN. We find that our goal descriptor network also provides significant improvements when combined with RNNs (see Supp.).

Goal descriptor accuracy and aggregation. The goal descriptor network has two main modules: 1) $f_D(\cdot)$, which produces the current descriptor estimate and 2) an aggregation function $f_\lambda(\cdot)$, which aggregates the current estimate with the previous goal descriptor. Next we evaluate goal prediction accuracy with and without aggregation, as well as how aggregation impacts the navigation performance.

The average location prediction error is 8.1 m and the average category prediction accuracy is 64.5% with aggregation, and 8.4 m, 53.6% without aggregation. Aggregation is important because the source sound is divided into 1s clips for each step, and the characteristics of the sound in some seconds are harder to identify, e.g., the silent moment between pulling and pushing a chest of drawers. Essentially, aggregation stabilizes the goal descriptor prediction. Navigation performance is affected as well: success rate and SPL drop about 3 points without aggregation ("w/o aggregation" ablation in Table 3).

Robustness to silence duration. Figure 4 analyzes how the models perform after the goal sound stops. We plot the cumulative success rate vs. silence ratio, where the latter is the ratio of the minimum number of actions required to

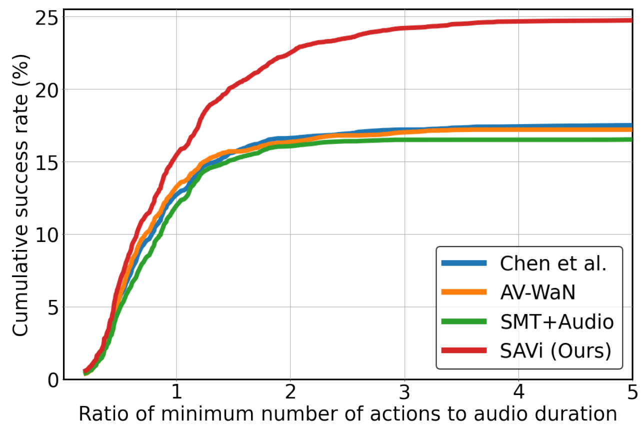

Figure 4: Cumulative success rate vs. silence percentage.

reach the goal to the duration of audio. A point (x, y) on this plot means the fraction of successful episodes with ratios up to x among all episodes is y. When this ratio is greater than 1, no agent can reach the goal before the audio stops. The greater this ratio is, the longer the fraction of silence, and hence the harder the episode. Indeed, we see for all models the success rate accumulates more slowly as the ratio becomes bigger. However, while the success rates of Chen et al. [11], AV-WaN [12], and SMT [15] increase only marginally for ratios greater than 1, our model shows a noticeable increase after the ratios surpass 1 and even 2. This indicates our model is able to cope with long silence to reach goals, thanks to the guidance of our predicted goal descriptor and its attention on the memory.

6. Conclusions

We introduce the task of semantic audio-visual navigation in complex 3D environments. To support this task, we expand an existing audio simulation platform to provide semantically grounded object sounds. We introduce a transformer-based model that learns to predict a goal descriptor capturing both spatial and semantic properties of the target. By encoding the observations conditioned on this goal descriptor, our model learns to associate acoustic events with visual observations. We show that our approach outperforms existing state-of-the-art models. We provide an in-depth analysis of the impact of the goal descriptor and its components, and show that our model is more robust to long silence duration and acoustic distractors. In future work, we are interested in generalizing policies learned in these high quality simulators to test in the real world.

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