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HERMES: KV Cache as Hierarchical Memory for Efficient Streaming Video Understanding

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Abstract

Recent advancements in Multimodal Large Language Models (MLLMs) have demonstrated significant improvement in offline video understanding. However, extending these capabilities to streaming video inputs, remains challenging, as existing models struggle to simultaneously maintain stable understanding performance, real-time responses, and low GPU memory overhead. To address this challenge, we propose ***HERMES***, a novel training-free architecture for real-time and accurate understanding of video streams. Based on a mechanistic attention investigation, we conceptualize KV cache as a hierarchical memory framework that encapsulates video information across multiple granularities. During inference, ***HERMES*** reuses a compact KV cache, enabling efficient streaming understanding under resource constraints. Notably, ***HERMES*** requires no auxiliary computations upon the arrival of user queries, thereby guaranteeing real-time responses for continuous video stream interactions, which achieves 10× faster TTFT compared to prior SOTA. Even when reducing video tokens by up to 68% compared with uniform sampling, ***HERMES*** achieves superior or comparable accuracy across all benchmarks, with up to 11.4% gains on streaming datasets.

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Homepage: https://hermes-streaming.github.io/
Repository: https://github.com/haowei-freesky/HERMES

1 Introduction

Recent years have witnessed remarkable evolution in the capabilities of Multimodal Large Language Models (MLLMs) in video understanding tasks [4, 12, 23]. Despite the progress, the rapid emergence of real-time applications demands stable long video understanding, low-latency response, and memory-efficient deployment. However, existing MLLMs struggle to simultaneously satisfy these requirements on streaming videos. Notably, TimeChat-Online [50] observes that a large number of streaming video tokens are redundant, motivating compression methods to address these challenges. While numerous compression techniques have been proposed for offline videos [40, 44, 48], most are ill-suited for memory management in streaming scenarios, as streaming inputs are unpredictable in future frames and queries.

To adapt to streaming inputs, recent research introduces specialized memory management techniques, which

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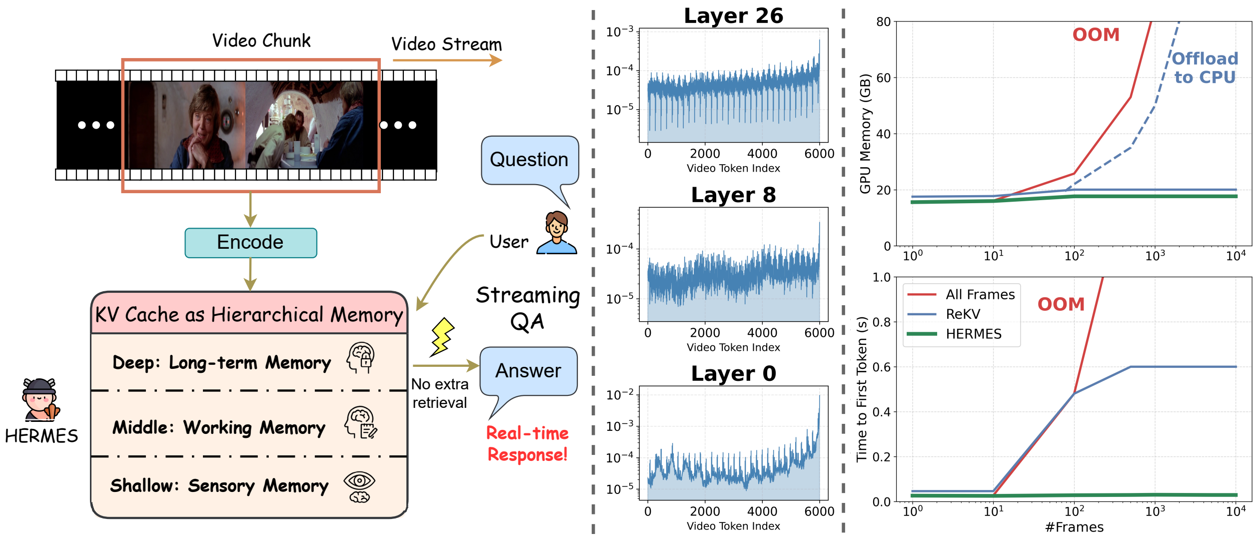
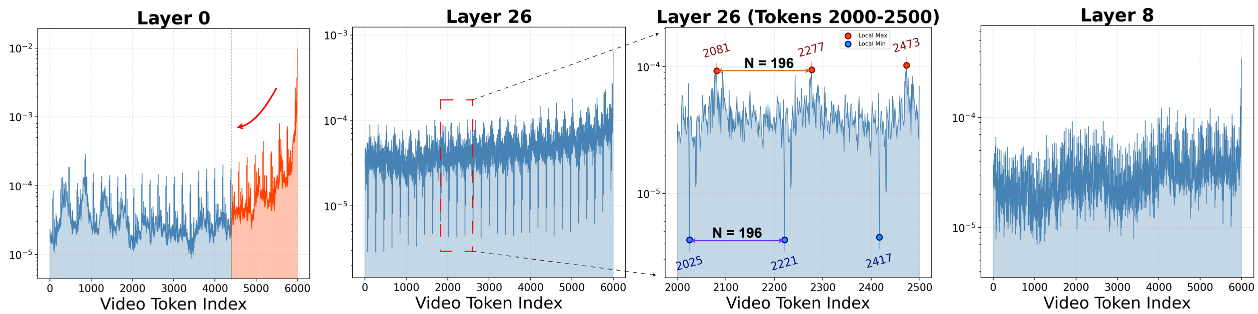


(a) ***HERMES*** **Framework** **(b)** Attention Analysis **(c)** Efficiency Test

Figure 1 **Left**: ***HERMES*** is a training-free approach for efficient streaming video understanding, enabling stable inference by reusing KV cache and performing hierarchical management of video tokens stored in KV cache. **Middle**: ***HERMES*** is based on a mechanistic investigation of the layer-wise attention preferences over hierarchical video information. **Right**: We evaluate LLaVA-OV-7B on a single A800 GPU (80 GB). As input frames increase, ***HERMES*** consistently maintains extremely low latency (TTFT < 30 ms) and stable GPU memory consumption, exhibiting no risk of OOM errors and requiring no auxiliary external computational resources.

generally fall into two paradigms: external memory and internal memory. External memory methods store video content as captions or raw vision patches in databases, and perform ad-hoc retrieval and multimodal prefilling at query time [45, 47], suffering from high latency and a lack of end-to-end cohesion. Additionally, many of these methods necessitate costly model-specific training [41, 46, 51]. In contrast, internalizing memory directly into the key-value cache (KV cache) remains underexplored, yet is crucial for low-latency responses and seamless end-to-end reasoning over stored video contexts. Moreover, KV cache naturally acts as a latent, model-intrinsic memory [19] that frequently interacts with the video stream, making it particularly suitable for training-free memory management. ReKV [13] and LiveVLM [31] are representative training-free, cache-based methods for streaming memory management. They store previous video segments in external CPU or disk and need to perform an additional retrieval when a user query arrives, which still rely on external computational resources and leads to significant latency. StreamMem [49] leverages chat template tokens to guide compression but lacks fine-grained KV management and mechanistic interpretability.

To overcome the aforementioned limitations of existing streaming video methods, we propose ***HERMES*** (KV Cache as **H**i**ER**archical **M**emory for **E**fficient **S**treaming Video Understanding), a training-free and plug-and-play approach that can be seamlessly integrated into existing MLLMs. Grounded in a mechanistic investigation of layer-wise attention shown in Fig. 1b, we conceptualize KV cache as a hierarchical memory framework that stores video information across multiple levels of granularity: shallow layers function as sensory memory, exhibiting a strong recency bias toward newly arriving frames; deep layers act as long-term memory, focusing on frame-level rhythmic anchor tokens; and middle layers serve as transitional working memory that balances recency information with frame-level semantic representations. Our method ***HERMES*** comprises three components: hierarchical KV cache management, cross-layer memory smoothing, and position re-indexing. During inference, ***HERMES*** reuses the compact KV cache and requires no auxiliary computations or external devices upon the arrival of user queries, thereby guaranteeing real-time responses. Experiments show that ***HERMES*** maintains stable and accurate performance with up to 68% fewer video tokens, while maintaining consistently low response latency and a constant GPU memory footprint.



(a) Shallow layer attention. **(b)** Deep layer attention. **(c)** Middle layer attention.

Figure 2 Visualization of the average attention weights (log scale) for user queries over video tokens in LLaVA-OV-7B with a FIFO KV cache budget of 6K video tokens per layer, averaged across 300 user video questions.

To summarize, our main contributions are as follows:

1. Grounded in a mechanistic analysis on attention visualization, we pioneer the conceptualization of KV cache as a hierarchical video memory framework across multiple granularities.
2. We propose ***HERMES***, a training-free method for streaming video understanding by reusing hierarchically managed KV cache. Despite reducing video tokens by up to 68%, ***HERMES*** achieves competitive accuracy, with gains of up to 11.4% on streaming benchmarks.
3. ***HERMES*** exhibits outstanding efficiency in streaming scenarios. Compared to the prior training-free SOTA method, it achieves up to a 10× speedup in latency. With a constant, compact GPU memory footprint and no auxiliary computation at query time, ***HERMES*** ensures consistently low-latency responses.

2 Layer-wise Preference for Hierarchical Streaming Video Information

Sliding Window is a standard paradigm for streaming video processing by incrementally encoding the continuous video stream chunk by chunk. When KV cache reaches the pre-defined memory budget, token eviction is triggered, and deciding which tokens to keep is crucial for stable understanding. Existing methods [13, 46, 49] rely on coarse-grained eviction strategies such as FIFO uniformly across all layers, overlooking layer-wise attention preferences.

To fill this gap, we conduct a mechanistic investigation of attention preferences in MLLM decoder layers, revealing how layers specialize in storing multiple-granularity video memory. To derive generalized insights, we randomly sample 100 video-question pairs from each of the short (62s[3] - 141s), medium (251s - 1,092s) and long (1,795s - 3,579s) duration subsets of the VideoMME benchmark [16] to cover diverse video durations and user queries. The video samples are uniformly sampled at 0.5 fps and subsequently fed into LLaVA-OV-7B in a streaming chunk-wise manner, with each chunk containing 8 frames. LLaVA-OV-7B consists of 28 decoder layers, and each video frame is uniformly encoded into 196 visual tokens. During the prefilling stage for video tokens, we maintain a constant budget $|M|$ of 6K video tokens per KV cache layer. After each eviction step, the positional indices of tokens per KV cache layer are re-indexing to contiguous $[0, |M|)$.

Layer-wise attention visualizations over video tokens maintained in a FIFO KV cache in Fig. 2 reveal three general stages of attention preference, along with more visualization results presented in App. A:

- **Shallow Layers as Sensory Memory**: As shown in Fig. 2a, the shallow layers (e.g., layer 0) exhibit an intense recency bias, with attention sharply concentrated on the most recent visual tokens and rapidly decaying over earlier ones. This behavior aligns with the concept of Sensory Memory [2, 37]: shallow

[3]To ensure the sliding window contains 6,000 tokens, a video at 0.5 fps for LLaVA-OV must have a duration of at least $6,000/196/0.5 \approx 62s$.

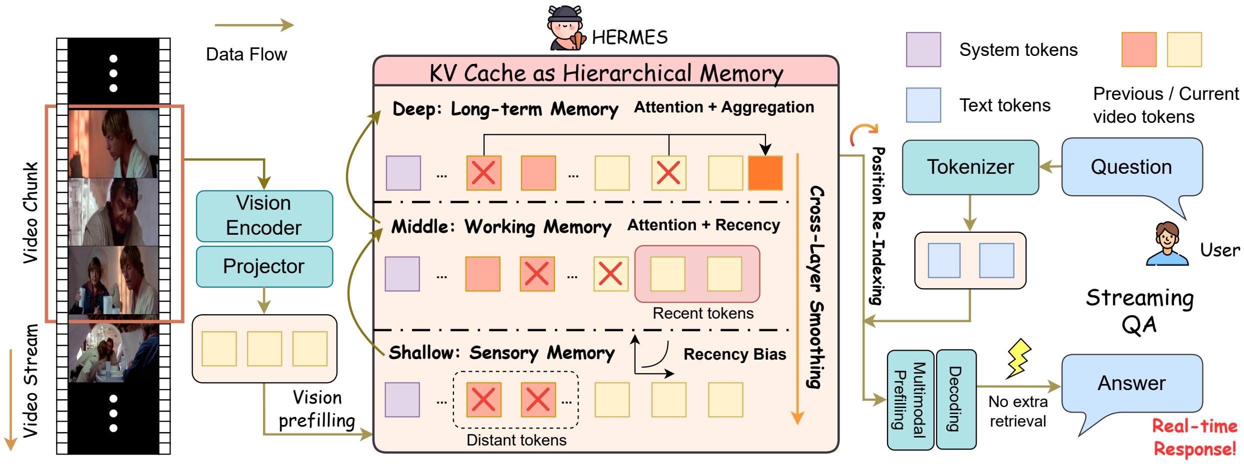


Figure 3 Overview of the ***HERMES*** architecture for streaming video QA. By implementing a hierarchical KV cache and specialized management strategies, ***HERMES*** enables real-time and accurate responses through direct cache reuse, eliminating the need for additional retrieval operations or external memory whenever users pose questions.

layers function as a short-lived buffer for the most recent visual inputs, enabling the model to quickly perceive incoming frames.

- **Deep Layers as Long-term Memory**: In deep layers (e.g., layer 26 in Fig. 2b), recency bias largely disappears. Instead, the attention pattern becomes highly sparse and rhythmic, with local extrema appearing at regular intervals. These extrema are exactly N = 196 tokens apart, matching to the number of tokens encoding a single frame in LLaVA-OV-7B. These local maxima can be regarded as frame-level "anchor tokens", summarizing the visual information of each frame. This pattern reflects Long-term Memory [2, 37]: deep layers store critical frame-level semantic representations for long-horizon understanding.
- **Middle Layers as Working Memory**: Middle layers (e.g., layer 8 in Fig. 2c) exhibit a gradual reduction in recency bias, with attention more evenly distributed across recent and earlier tokens. Simultaneously, the attention begins to transition toward the rhythmic patterns in the deep layers. This behavior corresponds to Working Memory [3, 19]: middle layers integrate recent and earlier visual information, bridging short-term sensory traces with frame-level semantic summaries.

3 HERMES

We propose ***HERMES***, a training-free framework that can be seamlessly integrated with MLLMs. As shown in Fig. 3, ***HERMES*** has three components: hierarchical KV cache management, cross-layer memory smoothing, and position re-indexing.

3.1 Hierarchical KV Cache Management

Motivated by the layer-wise attention patterns identified in Sec. 2, we design a hierarchical KV cache strategy. For each video token with KV cache index i at layer l, where i denotes its physical position in KV cache, we compute an importance score S_i^l to decide its retention:

- **Shallow Layers**: They act as sensory memory with strong recency bias. Inspired by Ebbinghaus' memory decay theory [14], we model token importance using an exponential forgetting curve based on temporal distance:

$$S_i^l = \alpha_i^l \cdot e^{-k\Delta t_i}, \Delta t_i = T - 1 - i, \tag{1}$$

where T is the total number of video tokens in the cache, $k > 0$ is the forgetting rate, α_i^l denotes the normalization factor.

- **Deep Layers**: Deep layers function as frame-level long-term memory with stable anchor tokens. Their attention distributions are sparse, and these anchor tokens consistently receive high attention across frames, making attention magnitude a reliable indicator of long-term importance. We therefore compute token importance directly from attention weights with respect to the user query. To handle unpredictable queries in streaming scenarios, we use a generic guidance prompt (see App. B) as a pseudo query. Token importance is computed as:
$$S_i^l = \alpha_i^l \cdot W_i^l, \tag{2}$$
where W_i^l denotes the attention weight of the i-th token at the layer l.

- **Middle Layers**: Middle layers serve as working memory, transitioning from recency-dominated shallow layers to attention-driven deep layers. We compute importance by interpolating recency and attention with a layer-dependent weight:
$$\omega^l = \omega_0 - \gamma \cdot \frac{l - l_{\text{short}}}{l_{\text{long}} - l_{\text{short}}}, \tag{3}$$
where l_{short} and l_{long} denote the layer indices, with $\omega_0 = 0.75$ and $\gamma = 0.6$. The importance score of token i at layer l is then computed as
$$S_i^l = (1 - \omega^l)\, A_i^l + \omega^l\, R_i^l, \tag{4}$$
where A_i^l and R_i^l denote the normalized attention weight and recency score, respectively, computed as in Eqs. (1) and (2).

3.2 Cross-Layer Memory Smoothing

Hierarchical KV cache management may introduce cross-layer inconsistency, as tokens at the same cache index can be evicted independently across layers, leading to misaligned visual memory. Since effective LLM memory relies on cross-layer interaction [6, 19, 33, 39], we address this issue with Cross-Layer Memory Smoothing.

Instead of treating video tokens at the same KV cache index as independent across layers, we propagate and smooth importance signals from deeper to shallower layers. Given raw importance scores S_i^l, the smoothed score is computed as:
$$\tilde{S}_i^l = (1 - \lambda_l) \cdot S_i^l + \lambda_l \cdot S_i^{l+1}, \tag{5}$$
$\lambda \in [0, 1]$ is the smoothing hyperparameter that controls the strength of cross-layer smoothing.

We then apply Top-K selection based on $\tilde{S}_i^l$ to maintain a fixed memory budget $|M|$ per layer:
$$\begin{aligned} \mathcal{I}_l &= \text{TopK}(\tilde{S}_l, |M|), \\ K_l &= K_l[\mathcal{I}_l], \quad V_l = V_l[\mathcal{I}_l]. \end{aligned} \tag{6}$$

To preserve long-term information, evicted tokens are aggregated into a **summary token** per layer, which compactly encodes long-term memory and is retained in the KV cache (see App. F).

3.3 Position Re-Indexing

Continuous accumulation of streaming inputs causes positional indices to exceed the model's maximum supported range, severely degrading text generation quality. To stabilize inference, we apply position re-indexing, which remaps positional indices to a contiguous range $[0, |M|)$ within the memory budget $|M|$. We design two strategies:

Lazy Re-Indexing Re-indexing is triggered only when positional indices approach the model limit, resulting in lower computational overhead. By preserving the original positional indices of recent tokens, it prevents positional drift compared to eager re-indexing, making it well suited for streaming video understanding.

Eager Re-Indexing Re-indexing is performed at each compression step, maintaining strictly contiguous RoPE indices in KV cache. While this strategy stabilizes long-range visual semantics [21, 22, 46], it leads to higher computational cost due to frequent re-indexing, making it more suitable for offline videos.

The details of re-indexing implementation for 1D RoPE (LLaVA-OV) and 3D M-RoPE (Qwen2.5-VL) are illustrated in App. E.1 and App. E.2, respectively.

4 Experiments

4.1 Experimental Setup

Benchmarks. We evaluate ***HERMES*** on diverse streaming and offline benchmarks. For streaming understanding, we use StreamingBench [27], OVO-Bench [25] and RVS (including RVS-Ego and EVS-Movie) [53]. For offline video evaluation, we adopt one short video dataset MVBench [24], along with two long video datasets, VideoMME [16] and Egoschema [30]. We conduct evaluation on the official dev split of Egoschema and report VideoMME results without subtitles. Our benchmark selection covers both multiple-choice and open-ended questions as QA form. The details of utilized benchmarks are demonstrated in App. D.

Models. To further verify the broad applicability of our method, we select two popular open-source MLLM series, LLaVA-OneVision (LLaVA-OV) [23] and Qwen2.5-VL [5]. Each is tested across two different parameter scales, covering a large range from 0.5B to 32B. For Qwen2.5-VL, we maintain its native dynamic resolution on video input, ensuring a fair comparison with the base model.

Implementation Details. For evaluating ***HERMES*** across all benchmarks, each video is encoded and processed chunk by chunk, with 16 frames per chunk, and sequentially prefilling the backbone LLM. Then, token compression is triggered once the predefined memory budget is exceeded.

For the layer partition, we follow the mechanistic investigations presented in Sec. 2: 10% shallow, 60% middle and 30% deep layers. A more comprehensive analysis of attention behaviors as supportive evidence can be found in Fig. 6. The cross-layer memory smoothing hyperparameter λ proposed in Sec. 3.2 is layer-dependent, with detailed configurations reported in App. C.

All evaluations are conducted using FP16 mixed precision and efficiency tests are conducted on a single A800 GPU, consistent with prior works [8, 13]. Greedy decoding is used to generate deterministic outputs. Accuracy evaluations can be completed on one H200 GPU.

4.2 Main Results

Streaming Video Understanding Extensive experiments on streaming benchmarks reveal the key findings:

(1) ***HERMES*** *outperforms on multiple-choice streaming datasets, showing exceptional real-time understanding and backward tracing capabilities*. As shown in Tab. 1, it achieves state-of-the-art performance on StreamingBench and OVO-Bench, significantly surpassing base models and training-free baselines. Built on Qwen2.5-VL-7B, ***HERMES*** reaches 79.44% and 59.21% accuracy using only 4K video tokens, improving over Qwen2.5-VL-7B by 6.13% and 6.93%, while outperforming all 7B-scale open-source online and offline models. Full results on StreamingBench and OVO-Bench are shown in Tab. 11 and Tab. 12 respectively.

(2) ***HERMES*** *excels on open-ended streaming tasks, showing fine-grained temporal and spatial comprehension*. On RVS-Ego and RVS-Movie (Tab. 2), we evaluate the model answer by GPT-3.5-turbo-0125 on accuracy and score (1–5 scale), consistent with compared baselines. ***HERMES*** consistently surpasses all prior training-free methods and improves accuracy by up to 11.4% over the base model with uniformly sampled 64 frames. These extensive experiments demonstrate ***HERMES***'s strong abilities in various streaming tasks, as well as its general applicability across foundation models. Moreover, we provide case studies from RVS benchmark,

Model	#Frames	StreamingBench Real-Time	OVO-Bench Real-Time	OVO-Bench Backward	Avg.
Human	-	91.46	93.20	92.33	92.83
Proprietary MLLMs					
Gemini 1.5 pro [12]	1 fps	75.69	69.32	62.54	66.41
GPT-4o [32]	64	73.28	64.46	60.75	62.87
Claude 3.5 Sonnet [1]	20	72.44	-	-	-
Open-source Offline MLLMs					
Video-LLaMA2-7B [11]	32	49.52	-	-	-
VILA-1.5-8B [26]	14	52.32	-	-	-
Video-CCAM-14B [15]	96	53.96	-	-	-
LongVA-7B [54]	128	59.96	-	-	-
Qwen2-VL-7B [43]	64	69.04	60.65	48.58	54.62
InternVL-V2-8B [10]	16	63.72	60.73	44.00	52.37
LLaVA-NeXT-Video-32B [28]	64	66.96	-	-	-
MiniCPM-V-2.6-8B [18]	32	67.44	-	-	-
Open-source Online MLLMs					
Flash-VStream-7B [52]	-	23.23	29.86	25.35	27.61
VideoLLM-online-8B [7]	2 fps	35.99	20.79	17.73	19.26
Dispider-7B [35]	1 fps	67.63	54.55	36.06	45.31
TimeChat-Online-7B [50]	1 fps	75.36	61.90	41.70	51.80
StreamForest-7B [51]	1 fps	77.26	61.20	52.02	56.61
Training-free Offline-to-Online Methods					
LLaVA-OV-7B [23]	64	71.34	63.06	43.64	53.35
+ ReKV [13]	0.5 fps	69.22	57.33	44.16	50.75
+ LiveVLM [31]	0.5 fps	72.92	-	-	-
+ StreamKV [9]	0.5 fps	68.80	-	-	-
+ HERMES (6K tokens)	0.5 fps	72.63	65.07	48.80	56.94
+ HERMES (4K tokens)	0.5 fps	**73.23**	**66.34**	**50.20**	**58.27**
LLaVA-OV-0.5B [23]	64	59.64	49.70	34.59	42.15
+ ReKV [13]	0.5 fps	57.39	43.77	33.06	38.42
+ HERMES (6K tokens)	0.5 fps	61.04	50.34	34.75	42.55
+ HERMES (4K tokens)	0.5 fps	**62.04**	**50.72**	**34.80**	**42.76**
Qwen2.5-VL-7B [5]	1 fps	73.31	59.90	44.65	52.28
+ HERMES (6K tokens)	1 fps	78.72	68.42	48.10	58.26
+ HERMES (4K tokens)	1 fps	**79.44**	**68.98**	**49.43**	**59.21**
Qwen2.5-VL-32B [5]	1 fps	74.27	64.40	50.33	57.37
+ HERMES (6K tokens)	1 fps	**80.20**	71.93	**57.71**	**64.82**
+ HERMES (4K tokens)	1 fps	80.08	**72.37**	55.42	63.90

Table 1 Performance comparison (%) on StreamingBench and OVO-Bench. The "Avg." column reports the results of the average accuracy of real-time visual perception and backward tracing tasks.

showing finer-grained temporal (shown in Fig. 11) and spatial understanding (shown in Fig. 12) abilities of ***HERMES*** than its base model.

Offline Video Understanding The results presented in Tab. 4 demonstrate the *competitive performance of **HERMES** across multiple temporal scales on offline benchmarks*, compared to the base model and other training-free methods. Under a limited budget of video tokens, ***HERMES*** achieves performance that is better than or comparable to the corresponding base models. ***HERMES*** based on LLaVA-OV-7B surpasses the base model on long video datasets Egoschema and VideoMME, achieving 60.29% and 58.85%, respectively, and attains 56.92% accuracy on the short video dataset MVBench, which is comparable to the base model's 57.02%.

4.3 Efficiency Analysis

To evaluate the efficiency of ***HERMES***, we utilize three metrics: peak GPU memory usage, Time to First Token (TTFT), defined as the latency measured from the moment a user inputs a query to the decoding of the first output token, and Time Per Output Token (TPOT) across varying numbers of input frames. All

Model	RVS-Ego		RVS-Movie	
	Acc	Score	Acc	Score
LLaVA-OV-7B [23]	56.2	3.7	43.0	3.3
+ ReKV† [13]	63.7	4.0	54.4	3.6
+ ReKV w/o off. [13]	55.8	3.3	50.8	3.4
+ Flash-VStream [52]	57.0	4.0	53.1	3.3
+ InfiniPot-V [22]	57.9	3.5	51.4	3.5
+ StreamMem [49]	57.6	3.8	52.7	3.4
+ StreamingTOM [8]	58.3	3.9	53.2	3.5
+ HERMES (6K tokens)	**60.3**	**4.0**	**54.4**	**3.6**
+ HERMES (4K tokens)	58.3	3.9	**54.4**	**3.6**
LLaVA-OV-0.5B [23]	51.8	3.7	37.2	3.2
+ ReKV† [13]	54.7	3.9	44.6	3.4
+ HERMES (6K tokens)	**53.0**	**3.8**	**42.5**	**3.4**
+ HERMES (4K tokens)	52.7	3.8	41.7	**3.4**

Table 2 Performance on RVS-Ego and RVS-Movie. †: ReKV caches the KV states of all previously seen frames and is therefore treated as an upper bound.

Metric	Frames			
	16	64	256	512
Chunk Size: 8				
GPU Mem. / GB ↓	16.54	16.66	16.66	16.66
TTFT / ms ↓	27.01	28.41	28.44	28.41
TPOT / ms ↓	24.43	23.89	24.02	23.98
Chunk Size: 16				
GPU Mem. / GB ↓	17.46	17.66	17.66	17.66
TTFT / ms ↓	27.02	28.97	28.50	28.38
TPOT / ms ↓	24.50	23.59	23.56	53.63

Table 3 Efficiency across input frame numbers under two chunk sizes. "TTFT" denotes *Time to First Token* and "TPOT" denotes *Time Per Output Token*.

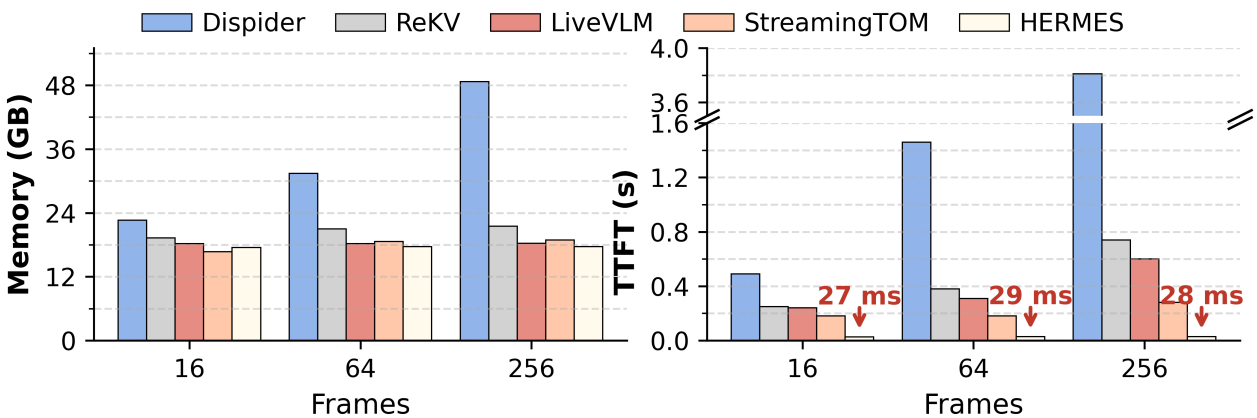


Figure 4 GPU memory and TTFT latency comparison across input frame numbers. ***HERMES*** achieves 10 × faster in TTFT compared to prior SOTA.

experiments are conducted using LLaVA-OV-7B as the base model with a 4K-token memory budget. Fig. 4 shows the comparison of memory usage and TTFT among ***HERMES*** and representative streaming methods. Unlike Dispider and LiveVLM, ***HERMES*** consistently maintains stable memory usage and TTFT as frames increase. Notably, under the 256-frame setting, ***HERMES*** achieves 1.04× reduction in peak memory compared to the prior SOTA LiveVLM, while achieving an impressive 10× speedup in TTFT over the prior SOTA StreamingTOM.

We further examine the efficiency of ***HERMES*** under varying encoded video chunk sizes, with the results shown in Tab. 3. GPU memory usage does not increase with longer video lengths due to the fixed memory budget. TTFT and TPOT remain consistently low across varying video lengths and encoding chunk sizes, confirming real-time responsiveness in practical streaming scenarios.

4.4 Ablation Study

We conduct ablation studies to evaluate the contributions of ***HERMES***'s components and hyperparameter choices, covering: (1) KV cache memory budget, (2) cross-layer memory smoothing and its hyperparameters, (3) position re-indexing strategies for streaming and offline datasets, and (4) summary tokens for long-term

Model	#Frames	MVBench	Egoschema	VideoMME Long	VideoMME Avg.
Proprietary MLLMs					
Gemini 1.5 pro [12]	1 fps	75.69	69.32	62.54	66.41
GPT-4o [32]	64	73.28	64.46	60.75	62.87
Claude 3.5 Sonnet [1]	20	72.44	-	-	-
Open-source Offline MLLMs					
Video-LLaMA2-7B [11]	32	49.52	-	-	-
VILA-1.5-8B [26]	14	52.32	-	-	-
Video-CCAM-14B [15]	96	53.96	-	-	-
LongVA-7B [54]	128	59.96	-	-	-
LLaVA-Video-7B [55]	32	58.60	57.3	-	63.30
Qwen2-VL-7B [43]	64	67.00	66.70	-	63.30
InternVL-V2-8B [10]	16	65.80	-	-	56.30
Kangaroo-7B [29]	64	64.60	-	-	-
LLaVA-NeXT-Video-32B [28]	64	66.96	-	-	-
MiniCPM-V-2.6-8B [18]	32	67.44	-	-	-
Open-source Online MLLMs					
Dispider-7B [35]	1 fps	-	55.60	-	57.20
TimeChat-Online-7B [50]	1 fps	75.36	61.90	41.70	53.22
StreamForest-7B [51]	1 fps	70.20	-	-	61.40
Training-free Offline-to-Online Methods					
LLaVA-OV-7B [23]	64	**57.02**	59.93	48.00	57.67
+ ReKV [13]	0.5 fps	56.83	**60.70**	46.89	57.74
+ HERMES (6K tokens)	0.5 fps	56.95	60.23	49.11	58.44
+ HERMES (4K tokens)	0.5 fps	56.92	60.29	**49.22**	**58.85**
Qwen2.5-VL-7B [5]	1 fps	65.00	58.47	53.89	**64.52**
+ HERMES (6K tokens)	1 fps	65.40	59.47	**54.44**	62.00
+ HERMES (4K tokens)	1 fps	**65.53**	**59.97**	53.44	60.63

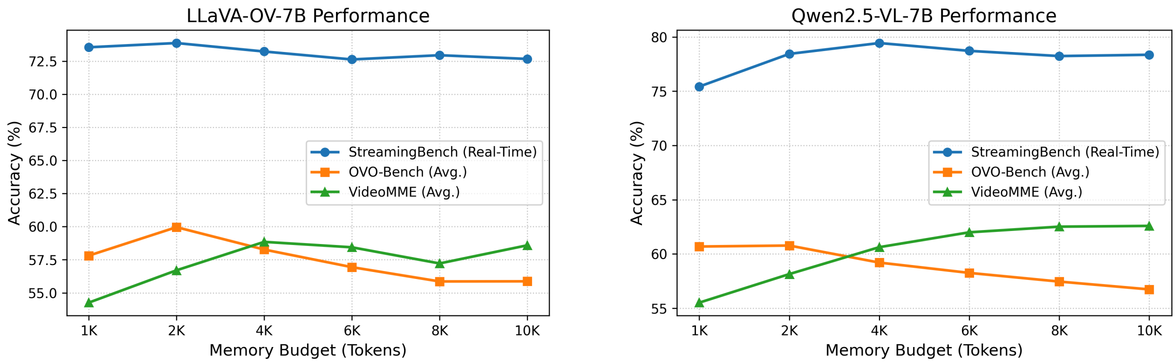
Table 4 Performance comparison (%) on offline benchmarks.

memory retention.

Memory Budget To investigate the impact of memory budget on understanding performance, we conduct ablations by varying the memory budget $|M|$ from 1K to 10K. As shown in Fig. 5a, for ***HERMES*** built upon LLaVA-OV-7B, the performance on both streaming and offline datasets stabilizes once memory budget reaches 4K. Notably, streaming datasets can tolerate a smaller memory budget. In contrast, the performance on long offline datasets degrades significantly when the memory budget is below 4K. The ablation on Qwen2.5-VL-7B is provided in Fig. 5b, yielding conclusions consistent with those on LLaVA-OV-7B.

Cross-Layer Memory Smoothing In Tab. 5, we evaluate variants without the proposed cross-layer memory smoothing mechanism, as well as alternative hyperparameter configurations. All these variants exhibit degraded performance on the VideoMME benchmark, demonstrating both the critical role of memory smoothing and the effectiveness of our chosen hyperparameter settings.

Position Re-Indexing Strategies For all streaming evaluations, we adopt the lazy position re-indexing strategy, while we use the eager re-indexing strategy for offline evaluations. Ablation studies in Tab. 7 and Tab. 8 show



(a) Performance comparison of LLaVA-OV-7B across different memory budgets.

(b) Performance Comparison of Qwen2.5-VL-7B across Different Memory Budgets.

Hyperparameter			VideoMME			
λ_{deep}	λ_{mid}	$\lambda_{shallow}$	Short	Medium	Long	**Avg.**
0	0	0	69.67	51.11	43.44	54.74
0.5	0	0	69.67	51.44	43.56	54.89
0	0.5	0	70.89	54.78	46.44	57.37
0	0	0.5	70.89	54.44	47.00	57.44
0.5	0.5	0.5	**71.78**	54.78	47.33	57.96
0.4	0.3	0.1	71.33	**54.89**	**49.11**	**58.44**

Table 5 Ablation on different cross-layer memory smoothing hyperparameter λ.

Model	**Aggregation**	VideoMME			
		Short	Medium	Long	**Avg.**
LLaVA-OV-7B	-	69.89	55.11	48.00	57.67
+ HERMES	w/o	71.33	54.78	47.78	57.96
+ HERMES	w/	**71.33**	54.89	**49.11**	**58.44**

Table 6 Ablation on summary tokens in deep layers. The gray row is our default setting in all experiments.

the effectiveness of these strategies in their respective scenarios.

Summary Tokens in Deep Layers In Sec. 3.2, we aggregate the evicted tokens in each deep layer into one summary token at each compression step. The results in Tab. 6 indicate that these summary tokens effectively preserve long-term memory, leading to improved performance on VideoMME.

5 Related Work

Streaming Video Understanding Existing MLLMs [4, 5, 12, 23] are primarily designed for pre-defined offline videos and struggle with continuous streaming videos. While some prior works have adapted existing offline MLLMs to online settings [46, 50, 51], they rely on costly model-specific training. Training-free streaming methods, such as ReKV [13] and LiveVLM [31], prefill offload KV cache to external devices. At user query time, they retrieve the full KV cache and reconstruct it on the GPU, incurring high latency and overall memory usage. In contrast, StreamMem [49] heuristically reuses KV cache, but lacks fine-grained KV cache management and interpretability. Unlike prior training-free methods, ***HERMES*** is grounded in a systematic attention analysis with improved interpretability and reliability.

KV Cache Compression for Video Input Numerous KV cache compression techniques have been proposed for offline video understanding [40, 42, 44, 48], but most of these methods are poorly suited for streaming scenarios due to the unpredictable future frames and user queries [8]. Existing online KV cache compression paradigms [8, 13, 31, 49] largely overlook the inherently hierarchical storage structure of the KV cache. ***HERMES*** addresses this gap by introducing a hierarchical KV cache management strategy, which enables fine-grained memory utilization and low-latency responses.

Model	Re-Indexing	StrBench	OVO-Bench		
		Real-Time	Real-Time	Backward	Avg.
LLaVA-OV-7B	-	71.34	63.06	43.64	53.35
+ HERMES	lazy	**72.63**	**65.07**	**48.80**	**56.94**
+ HERMES	eager	72.30	64.91	47.21	56.06

Table 7 Ablation on different re-indexing strategies on streaming benchmarks. The gray row represents our default setting in all evaluations for streaming benchmarks. "StrBench" represents *StreamingBench*.

Model	Re-Indexing	VideoMME			
		Short	Medium	Long	Avg.
LLaVA-OV-7B	-	69.89	55.11	48.00	57.67
+ HERMES	lazy	69.67	51.67	43.44	54.93
+ HERMES	eager	**71.33**	54.89	**49.11**	**58.44**

Table 8 Ablation on different re-indexing strategies on offline benchmark VideoMME. The gray row represents our default setting in all evaluations for offline benchmarks.

6 Conclusion

This paper proposes ***HERMES***, a training-free framework for efficient streaming video understanding. Guided by mechanistic attention analysis, we conceptualizes KV cache as a hierarchical video memory system across multiple granularities. By introducing a cross-layer memory smoothing and position re-indexing, ***HERMES*** further enhances the understanding performance for long streaming input. Extensive experiments demonstrate that ***HERMES*** delivers accurate performance under continuously growing video streams, while consistently maintaining extremely low response latency and compact GPU memory usage, making it well suited for real-world streaming deployment.

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Appendix

Appendix Contents

A More Attention Visualization

We provide more detailed attention visualization in Fig. 6 under different sliding window sizes, showing that the observed attention patterns consistently hold across varying window lengths, thus confirming the generality of the findings in Sec. 2.

B Guidance Prompt

The following two figures show the local and global guidance prompt with and without conversation history to guide the token compression, respectively. For the deep layers, since they primarily focus on frame-level global semantic information, we employ a global guidance prompt as a pseudo-query to extract attention weights of video tokens. In contrast, the middle layers lie in a transition between recency-biased attention and global semantic focus. Therefore, we adopt a hybrid guidance strategy, in which the local guidance prompt and the global guidance prompt are concatenated into a single prompt string to jointly guide the token compression.

C Configuration of Cross-Layer Memory Smoothing

Given that long-term memory tends to remain relatively stable, while short-term memory focuses on diverse perception, we set different λ for different layer stages:

$$\lambda_l = \begin{cases} 0.1, & \text{if } l \in \mathcal{L}_{shallow} \\ 0.3, & \text{if } l \in \mathcal{L}_{middle} \\ 0.4, & \text{if } l \in \mathcal{L}_{deep} \end{cases} \tag{7}$$

The ablation study Tab. 5 shows the effectiveness of this hyperparameter choice.

D Details of evaluated benchmarks

Table 9 Key statistics of the streaming benchmarks. In the "Type" column, "MC" denotes multiple-choice questions, while "OE" denotes open-ended questions. In the "Benchmark" column, "rt" denotes real-time understanding subset, while "bw" denotes backward tracing subset.

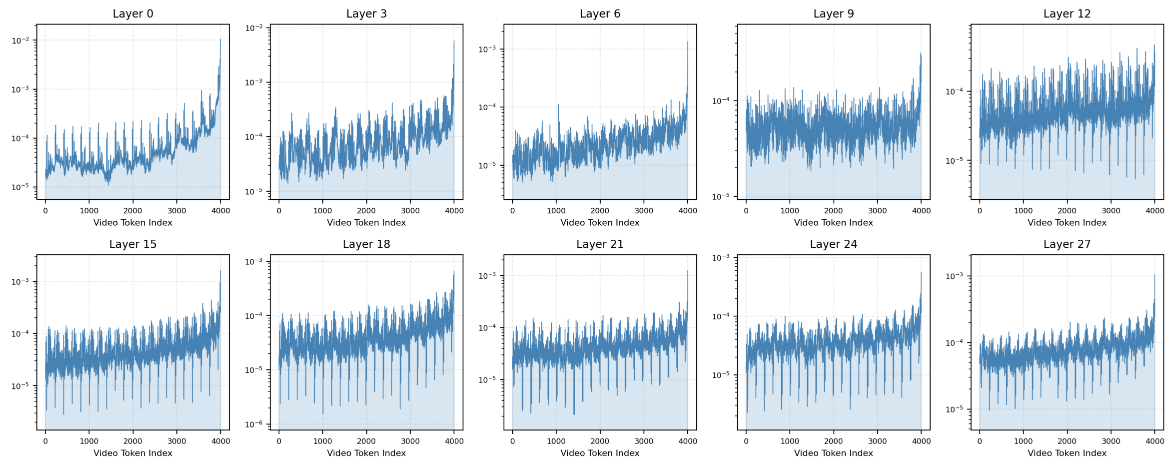
Benchmark	Duration	#Videos	#QA	Type
StreamingBench$_{rt}$	10.1min	500	2,500	MC
OVO-Bench$_{bw}$	5.9 min	275	631	MC
OVO-Bench$_{rt}$	8.8 min	237	837	MC
RVS-Ego	60 min	10	1,465	OE
RVS-Movie	30 min	22	1,905	OE

Table 10 Key statistics of the offline benchmarks. In the "Type" column, "MC" denotes multiple-choice questions.

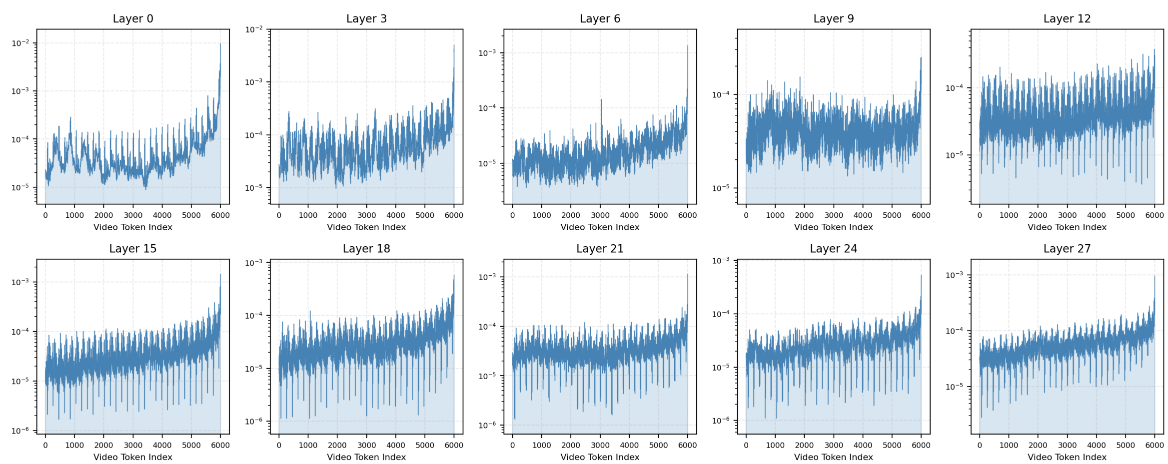
Benchmark	Duration	#Videos	#QA	Type
MVBench	16 s	3,641	4,000	MC
Egoschema	3 min	5,063	5,063	MC
VideoMME	17 min	900	2,700	MC

D.1 Streaming Benchmarks

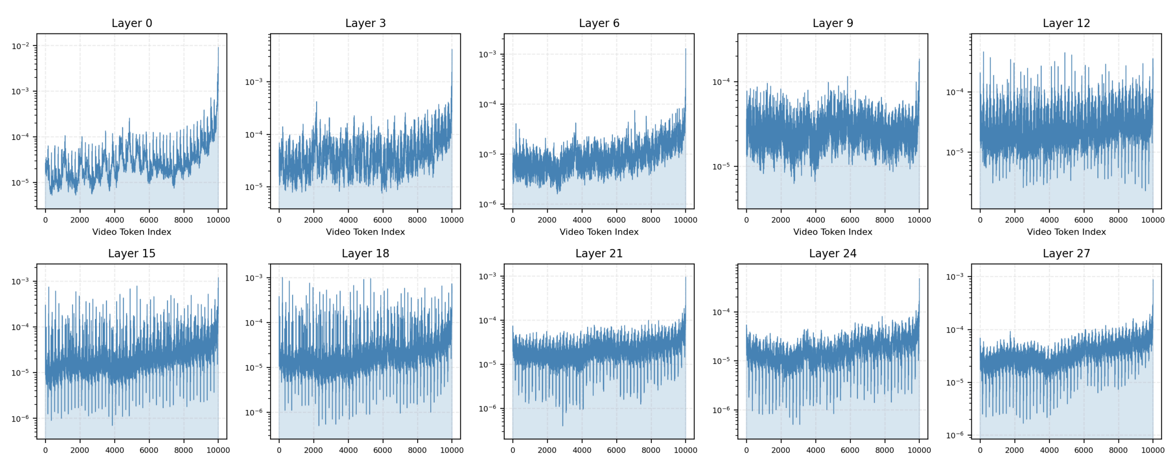
- **StreamingBench** [27] assesses the streaming video understanding capabilities of MLLMs. It evaluates three core aspects: real-time visual understanding, omni-source understanding, and contextual understanding. The Real-Time Visual Understanding subset is the most extensive component, featuring 2,500 questions across 500 videos. It covers 10 tasks, such as object perception and causal reasoning. In this paper, we focus on the Real-Time Visual Understanding subset for evaluation.
- **OVO-Bench** [25] evaluates the online reasoning and temporal awareness of MLLMs, featuring 644 videos with approximately 2,800 fine-grained multiple-choice QA pairs. It organizes 12 tasks into three distinct categories, which are real-time visual perception, backward tracing, and forward active responding. Given



(a) Sliding window of 4,000 video tokens



(b) Sliding window of 6,000 video tokens



(c) Sliding window of 10,000 video tokens

Figure 6 Visualization of the average attention weights of video tokens in LLaVA-OV-7B under different sliding window sizes.

Find recent details related to: {last_conv}. Describe the current scene in detail, focusing on specific objects, fine-grained actions, and spatial relationships.

Figure 7 Local guidance prompt to guide the token compression if conversation history exists. ”last_conv” refers to the last user query and the corresponding model answer from the conversation history.

Describe the current scene in detail, focusing on specific objects, fine-grained actions, and spatial relationships.

Figure 8 Local guidance prompt to guide the token compression if there is no conversation history.

Context summary: {last_conv}. Summarize the video narrative, identifying main characters, key events, timeline changes, and the overall theme.

Figure 9 Global guidance prompt to guide the token compression if conversation history exists. ”last_conv” refers to the last user query and the corresponding model answer from the conversation history.

Summarize the video narrative, identifying main characters, key events, timeline changes, and the overall theme.

Figure 10 Global guidance prompt to guide the token compression if there is no conversation history.

that we do not focus on the proactive responding ability of MLLMs in this paper, we exclusively utilize the real-time perception and the backward tracing subsets.

- **RVS-Ego** and **RVS-Movie** [53] are designed to evaluate the real-time understanding capabilities of models in online streaming scenarios. The datasets consist of 10 long ego-centric videos from the Ego4D dataset [17] and 22 long movie clips from the MovieNet dataset [20] dataset, totaling over 21 hours of video content.

D.2 Offline Benchmarks

- **MVBench** [24] systematically evaluates the temporal understanding capabilities of MLLMs. It utilizes a novel static-to-dynamic method to define 20 distinct temporal tasks, such as action sequence and moving direction, which cannot be effectively solved with a single frame. The videos are collected from a wide range of datasets, including NTU RGB+D [36], Perception [34], etc.
- **Egoschema** [30] is a diagnostic benchmark designed to assess long-form video understanding abilities. Derived from Ego4D [17], it consists of over 5,000 human-curated multiple-choice QA pairs associated with egocentric video clips.
- **VideoMME** [16] is a full-spectrum, multimodal benchmark designed for the comprehensive evaluation of MLLMs in video analysis. It comprises 900 manually curated videos spanning six primary domains and diverse durations to assess temporal adaptability. The dataset features 2,700 high-quality QA pairs that necessitate processing multimodal inputs, including video frames, subtitles, and audio.

E Details of Position Re-Indexing

Inspired by StreamingVLM’s strategy of managing positional stability in streaming scenarios [46], we adopt a unified left-compaction re-indexing scheme to eliminate positional gaps introduced by KV-cache pruning while preserving the semantic anchoring of the system prompt. Concretely, system text tokens are kept fixed to provide a stable textual anchor, whereas retained video tokens are re-indexed in a left-compact manner and placed contiguously after the static prefix. To reuse cached key states without re-computation, we further apply a delta-based rotary correction that compensates for the positional displacement.

E.1 Re-indexing for LLaVA-OV (1D RoPE)

LLaVA-OV employs standard 1D RoPE, where each token is associated with a scalar positional index p. Therefore, we perform left-compaction of the 1D indices: the system prefix positions remain unchanged, while the retained positions of video tokens are reassigned to form a dense contiguous segment immediately following the fixed prefix.

Let offset denote the length of the system prompt prefix tokens, and let

$$\mathcal{P} = \{p_0 < p_1 < \cdots < p_{N-1}\}$$

be the sorted set of retained video token positions (excluding the fixed prefix). For a retained video token originally at position $p_{\mathrm{old}} \in \mathcal{P}$, its compacted 1D position is defined as

$$p_{\mathrm{new}} = \mathrm{offset} + \mathrm{rank}_{\mathcal{P}}(p_{\mathrm{old}}) . \tag{8}$$

This mapping removes gaps while preserving the original temporal ordering along the stream, and ensures that the video region occupies a dense range directly after the static text region.

To align cached key states with the updated positions, we avoid re-generating keys and instead apply a rotary delta correction induced by the positional shift. For a cached key vector $\mathbf{k}_{\mathrm{old}}$ associated with position p_{old} and remapped to p_{new}, we compute

$$\mathbf{k}_{\mathrm{new}} = \mathbf{k}_{\mathrm{old}} \odot \mathrm{RotaryDelta}(p_{\mathrm{old}}, p_{\mathrm{new}}) , \tag{9}$$

where the relative phase shift is

$$\mathrm{RotaryDelta}(p_{\mathrm{old}}, p_{\mathrm{new}}) = e^{i(p_{\mathrm{new}} - p_{\mathrm{old}})\boldsymbol{\theta}}, \tag{10}$$

and $\boldsymbol{\theta}$ denotes the RoPE frequency vector. This update preserves the correctness of attention under the new indexing while enabling direct reuse of the cached KV states.

E.2 Re-indexing for Qwen2.5-VL (3D M-RoPE)

For Qwen2.5-VL, video tokens are indexed by a 3D M-RoPE coordinate $\mathbf{p} = (p^{(t)}, p^{(h)}, p^{(w)})$, covering temporal and spatial dimensions. After pruning, the retained video tokens typically occupy sparse coordinates along each dimension $d \in \{t, h, w\}$. To eliminate the gaps without disturbing the monotonic ordering, we apply dimension-wise left-compaction independently along each axis, while keeping the system token prefix fixed.

Let

$$\mathcal{P}^{(d)} = \{p_0^{(d)} < p_1^{(d)} < \cdots < p_{N_d-1}^{(d)}\}$$

denote the sorted set of retained coordinates along dimension d. For a token originally located at $p_{\mathrm{old}}^{(d)} \in \mathcal{P}^{(d)}$, its compacted coordinate is defined by its rank within $\mathcal{P}^{(d)}$, shifted by the fixed prefix offset:

$$p_{\mathrm{new}}^{(d)} = \mathrm{offset} + \mathrm{rank}_{\mathcal{P}^{(d)}}\left(p_{\mathrm{old}}^{(d)}\right), \qquad d \in \{t, h, w\}. \tag{11}$$

This procedure yields a dense and contiguous (t, h, w) grid for the video tokens placed immediately after the static text region, thereby ensuring positional continuity while preserving the distinct semantic roles of temporal and spatial indices.

As in the 1D case, we reuse cached keys by applying a M-RoPE correction. Given a key $\mathbf{k}_{\mathrm{old}}$ associated with

$$\mathbf{p}_{\mathrm{old}} = (p_{\mathrm{old}}^{(t)}, p_{\mathrm{old}}^{(h)}, p_{\mathrm{old}}^{(w)})$$

and remapped to

$$\mathbf{p}_{\text{new}} = (p_{\text{new}}^{(t)}, p_{\text{new}}^{(h)}, p_{\text{new}}^{(w)}),$$

the corrected key is obtained as

$$\mathbf{k}_{\text{new}} = \mathbf{k}_{\text{old}} \odot \mathrm{RotaryDelta}(\mathbf{p}_{\text{old}}, \mathbf{p}_{\text{new}})\,, \tag{12}$$

with the relative phase shift:

$$\mathrm{RotaryDelta}(\mathbf{p}_{\text{old}}, \mathbf{p}_{\text{new}}) = \underset{d\in\{t,h,w\}}{\mathrm{Concat}} \left(e^{i(p_{\text{new}}^{(d)} - p_{\text{old}}^{(d)})\boldsymbol{\theta}^{(d)}} \right), \tag{13}$$

where Concat denotes the concatenation operation along the channel dimension, and $\boldsymbol{\theta}^{(d)}$ represents the rotary frequency vector corresponding to the channel section allocated for dimension d.

F Algorithm of Summary Tokens

Algorithm 1 Summary Token Aggregation

Require: K_p, V_p: Pruned KV tensors from visual tokens; P_p: Original position indices of pruned tokens; t: Target position index for the summary token.
Ensure: k_{sum}, v_{sum}: Single aggregated summary token cache.

Step 1: Aggregate Value
\# Simple spatial mean
$v_{sum} \leftarrow \text{Mean}(V_p)$

Step 2: Aggregate Key
\# Phase alignment before pooling
$\Delta\theta \leftarrow \text{RotaryDelta}(P_p \rightarrow t)$
\# Calculate rotation shift from P_p to t
$K_{aligned} \leftarrow \text{ApplyDelta}(K_p, \Delta\theta)$
\# Align all keys to the same phase
$k_{sum} \leftarrow \text{Mean}(K_{aligned})$

Step 3: Update KV Cache
$K_{new} \leftarrow \text{Concat}([K_{kept}, k_{sum}])$
$V_{new} \leftarrow \text{Concat}([V_{kept}, v_{sum}])$

return K_{new}, V_{new}

G Full Performances

G.1 StreamingBench

G.2 OVO-Bench

H Case Study

We provide six representative case study examples from RVS-Ego and RVS-Movie to demonstrate the advantages of ***HERMES*** compared to the foundation model LLaVA-OV-7B. During the understanding of streaming long videos, ***HERMES*** exhibits significantly finer-grained temporal (shown in Fig. 11) and spatial understanding Fig. 12 capabilities than its corresponding foundation model.

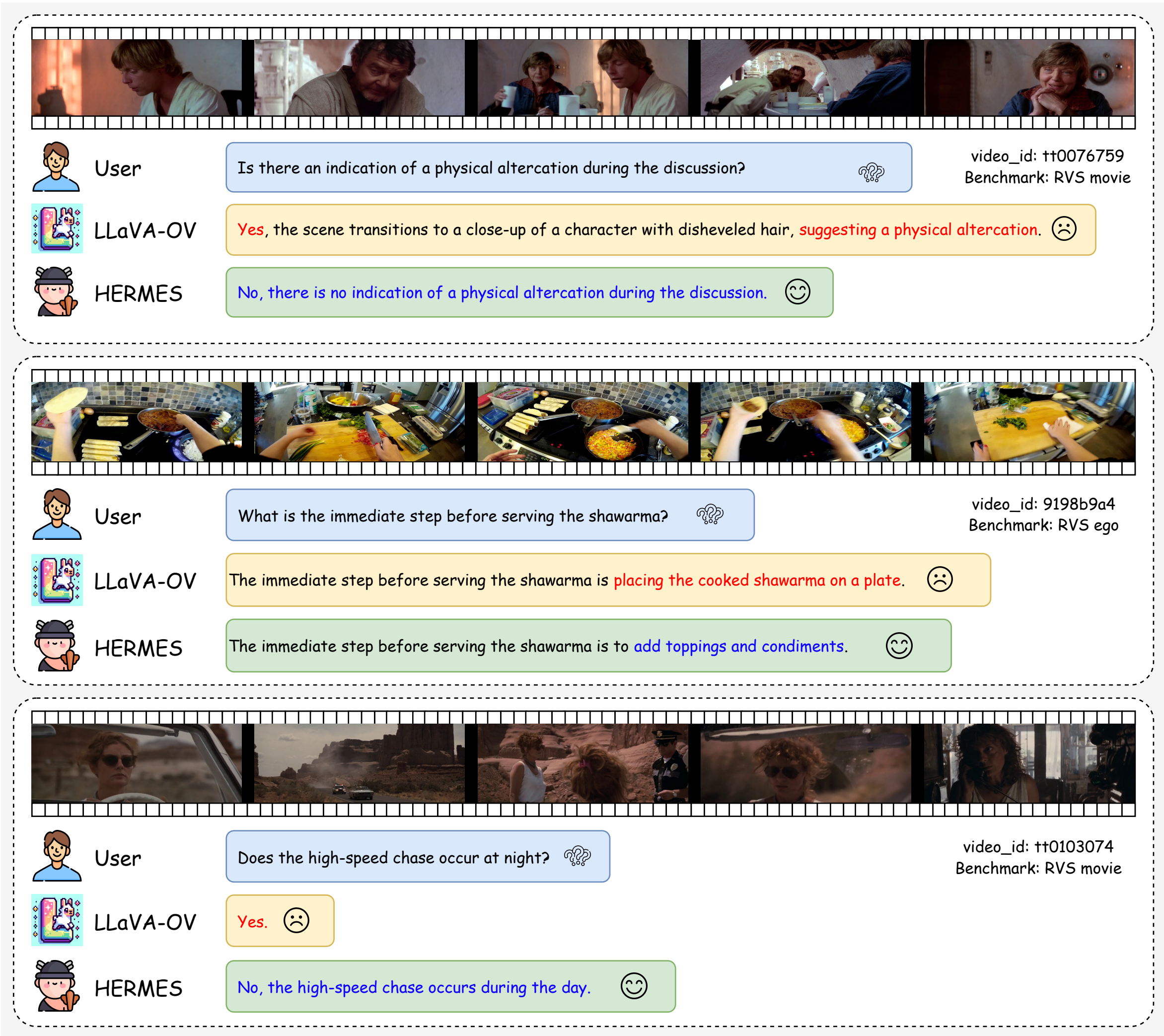


Figure 11 Cases demonstrating the superior fine-grained temporal understanding capability of ***HERMES*** relative to the LLaVA-OV-7B base model.

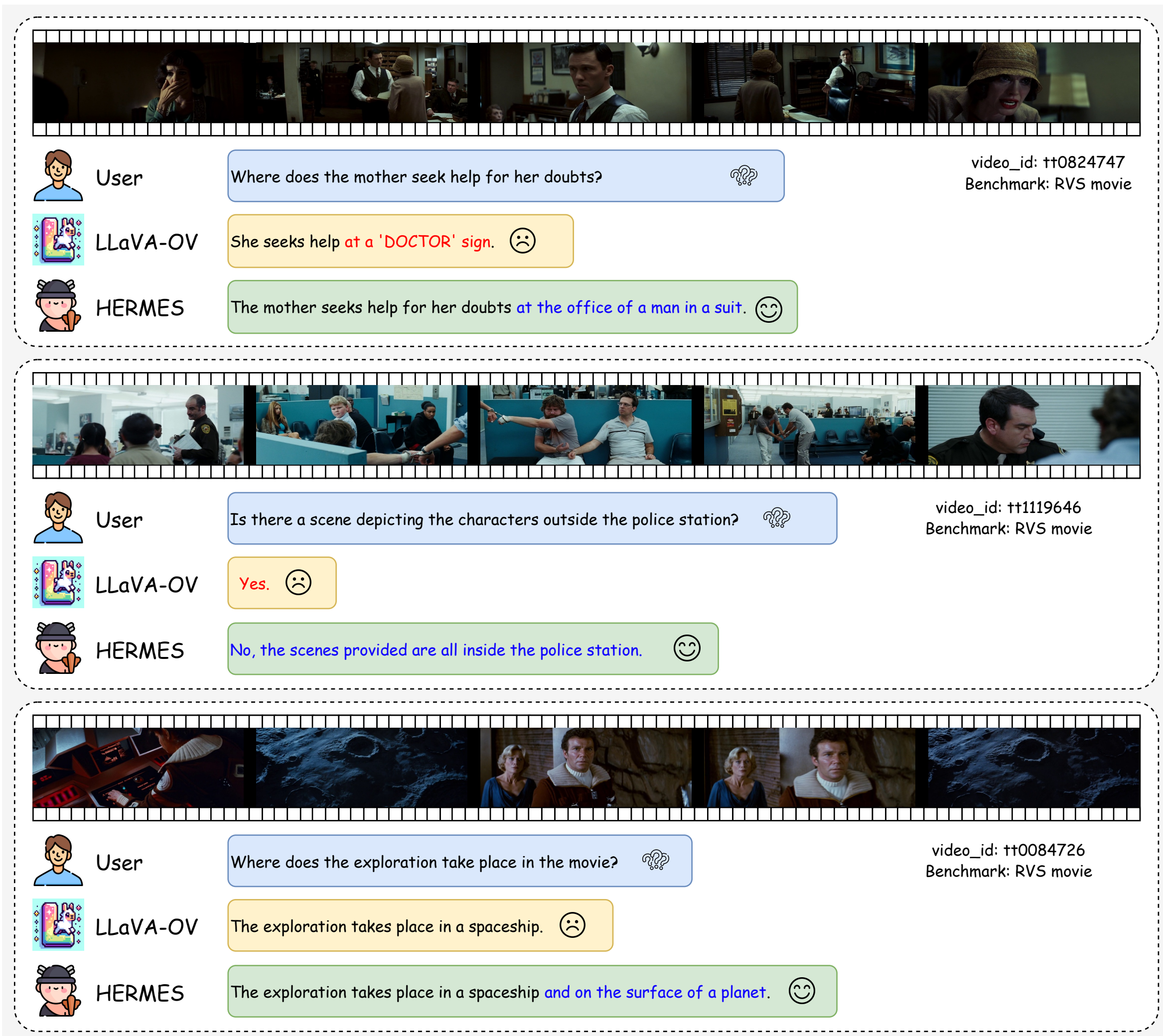


Figure 12 Cases demonstrating the superior fine-grained spatial understanding capability of ***HERMES*** relative to the LLaVA-OV-7B base model.

Table 11 Accuracy comparison (%) on StreamingBench focusing on *Real-Time Visual Understanding* tasks. Real-Time Visual Understanding tasks consists of Object Perception (OP), Causal Reasoning (CR), Clips Summarization (CS), Attribute Perception (ATP), Event Understanding (EU), Text-Rich Understanding (TR), Prospective Reasoning (PR), Spatial Understanding (SU), Action Perception (ACP), and Counting (CT).

Model	#Frames	OP	CR	CS	ATP	EU	TR	PR	SU	ACP	CT	Avg.
Human	-	89.47	92.00	93.60	91.47	95.65	92.52	88.00	88.75	89.74	91.30	91.46
Proprietary MLLMs												
Gemini 1.5 pro [12]	1 fps	79.02	80.47	83.54	79.67	80.00	84.74	77.78	64.23	71.95	48.70	75.69
GPT-4o [32]	64	77.11	80.47	83.91	76.47	70.19	83.80	66.67	62.19	69.12	49.22	73.28
Claude 3.5 Sonnet [1]	20	73.33	80.47	84.09	82.02	75.39	79.53	61.11	61.79	69.32	43.09	72.44
Open-source Offline MLLMs												
Video-LLaMA2-7B [11]	32	55.86	55.47	57.41	58.17	52.80	43.61	39.81	42.68	45.61	35.23	49.52
VILA-1.5-8B [26]	14	53.68	49.22	70.98	56.86	53.42	53.89	54.63	48.78	50.14	17.62	52.32
Video-CCAM-14B [15]	96	56.40	57.81	65.30	62.75	64.60	51.40	42.59	47.97	49.58	31.61	53.96
LongVA-7B [54]	128	70.03	63.28	61.20	70.92	62.73	59.50	61.11	53.66	54.67	34.72	59.96
InternVL-V2-8B [10]	16	68.12	60.94	69.40	77.12	67.70	62.93	59.26	53.25	54.96	56.48	63.72
Kangaroo-7B [29]	64	71.12	84.38	70.66	73.20	67.08	61.68	56.48	55.69	62.04	38.86	64.60
LLaVA-NeXT-Video-32B [28]	64	78.20	70.31	73.82	76.80	63.35	69.78	57.41	56.10	64.31	38.86	66.96
MiniCPM-V-2.6-8B [18]	32	71.93	71.09	77.92	75.82	64.60	65.73	70.37	56.10	62.32	53.37	67.44
Open-source Online MLLMs												
Flash-VStream-7B [52]	-	25.89	43.57	24.91	23.87	27.33	13.08	18.52	25.20	23.87	48.70	23.23
VideoLLM-online-8B [7]	2 fps	39.07	40.06	34.49	31.05	45.96	32.40	31.48	34.16	42.49	27.89	35.99
Dispider-7B [35]	1 fps	74.92	75.53	74.10	73.08	74.44	59.92	76.14	62.91	62.16	45.80	67.63
TimeChat-Online-7B [50]	1 fps	80.22	82.03	79.50	83.33	76.10	78.50	78.70	64.63	69.60	57.98	75.36
StreamForest-7B [51]	1 fps	83.11	82.81	82.65	84.26	77.50	78.19	76.85	69.11	75.64	54.40	77.26
Training-free Offline-to-Online Methods												
LLaVA-OV-7B [23]	32	78.75	78.12	80.76	**81.19**	71.70	72.59	72.22	63.82	66.01	38.34	71.34
+ ReKV [13]	0.5 fps	76.02	81.25	77.92	76.90	66.04	66.04	69.44	60.98	64.31	49.22	69.22
+ LiveVLM [31]	0.5 fps	**81.47**	78.13	83.28	79.08	69.57	**74.14**	**75.00**	**69.11**	67.71	40.41	72.92
+ StreamKV [9]	0.5 fps	73.80	77.30	85.90	77.50	**73.30**	63.90	69.40	61.40	63.20	35.80	68.80
+ HERMES (6K tokens)	0.5 fps	77.93	**82.03**	86.12	**81.19**	66.04	73.52	74.07	63.01	67.71	**45.08**	72.63
+ HERMES (4K tokens)	0.5 fps	79.02	81.25	**87.70**	80.20	69.18	71.96	73.15	66.26	**69.41**	43.52	**73.23**
LLaVA-OV-0.5B [23]	32	71.39	57.81	65.93	69.64	69.18	55.76	57.41	**52.85**	62.04	16.58	59.64
+ ReKV [13]	0.5 fps	65.12	60.16	66.56	66.01	66.67	52.96	57.41	48.37	60.34	18.13	57.39
+ HERMES (6K tokens)	0.5 fps	71.93	60.16	69.09	71.29	68.55	57.32	**60.19**	51.22	**63.74**	**19,69**	61.04
+ HERMES (4K tokens)	0.5 fps	**72.21**	**61.72**	**70.98**	**72.94**	**72.33**	**57.94**	**60.19**	**52.85**	**63.74**	19.17	**62.04**
Qwen2.5-VL-7B [5]	1 fps	77.93	76.56	78.55	80.86	76.73	76.95	80.56	65.45	65.72	**52.85**	73.31
+ HERMES (6K tokens)	0.5 fps	83.38	78.91	86.12	87.13	**78.62**	**86.60**	**84.26**	74.80	71.39	46.63	78.72
+ HERMES (4K tokens)	0.5 fps	**83.65**	**81.25**	**88.01**	**87.46**	76.73	**86.60**	82.41	**76.02**	**73.94**	46.63	**79.44**
Qwen2.5-VL-32B [5]	1 fps	76.29	79.69	78.55	**83.50**	76.10	79.44	80.56	61.38	68.27	**59.07**	74.27
+ HERMES (6K tokens)	0.5 fps	**84.47**	79.69	**87.70**	83.17	**81.76**	**88.16**	86.11	74.80	**77.62**	49.22	**80.20**
+ HERMES (4K tokens)	0.5 fps	83.92	**80.47**	**87.70**	**83.50**	80.50	**88.16**	**87.04**	**75.20**	77.34	48.19	80.08

Table 12 Accuracy comparison (%) on OVO-Bench focusing on *Real-Time Visual Perception* and *Backward Tracing* tasks. Real-Time Visual Perception tasks consist of Optical Character Recognition (OCR), Action Recognition (ACR), Attribute Recognition (ATR), Spatial Understanding (STU), Future Prediction (FPD), Object Recognition (OJR). Backward Tracing tasks consists of Episodic Memory (EPM), Action Sequence Identification (ASI), Hallucination Detection (HLD).

Model	**#Frames**	**Real-Time Visual Perception**							**Backward Tracing**				**Overall**
		OCR	ACR	ATR	STU	FPD	OJR	Avg.	EPM	ASI	HLD	Avg.	Avg.
Human	-	93.96	92.57	94.83	92.70	91.09	94.02	93.20	92.59	93.02	91.37	92.33	92.77
Proprietary MLLMs													
Gemini 1.5 Pro [12]	1fps	85.91	66.97	79.31	58.43	63.37	61.96	69.32	58.59	76.35	52.64	62.54	65.93
GPT-4o [32]	64	69.80	64.22	71.55	51.12	70.30	59.78	64.46	57.91	75.68	48.66	60.75	62.61
Open-source Offline MLLMs													
LLaVA-Video-7B [55]	64	69.80	59.63	66.38	50.56	72.28	61.41	63.34	51.18	64.19	9.68	41.68	52.51
Qwen2-VL-7B [43]	64	69.13	53.21	63.79	50.56	66.34	60.87	60.65	44.44	66.89	34.41	48.58	54.62
InternVL2-8B [10]	64	68.46	58.72	68.97	44.94	67.33	55.98	60.73	43.10	61.49	27.41	44.00	52.37
LongVU-7B [38]	1fps	55.70	49.54	59.48	48.31	68.32	63.04	57.40	43.10	66.22	9.14	39.49	48.45
Open-source Online MLLMs													
VideoLLM-online-8B [7]	2fps	8.05	23.85	12.07	14.04	45.54	21.20	20.79	22.22	18.80	12.18	17.73	19.26
Flash-VStream-7B [52]	1fps	25.50	32.11	29.31	33.71	29.70	28.80	29.86	36.36	33.78	5.91	25.35	27.61
Dispider-7B [35]	1fps	57.72	49.54	62.07	44.94	61.39	51.63	54.55	48.48	55.41	4.30	36.06	45.31
TimeChat-Online-7B [50]	1fps	75.20	46.80	70.70	47.80	69.30	61.40	61.90	55.90	59.50	9.70	41.70	51.80
StreamForest-7B [51]	1fps	68.46	53.21	71.55	47.75	65.35	60.87	61.20	58.92	64.86	32.26	52.02	56.61
Training-free Offline-to-Online Methods													
LLaVA-OV-7B [23]	32	67.79	55.05	72.41	48.31	72.28	62.50	63.06	57.24	55.41	18.28	43.64	53.35
+ ReKV [13]	0.5 fps	52.35	54.13	69.83	43.26	67.33	57.07	57.33	57.58	56.08	18.82	44.16	50.75
+ HERMES (6K tokens	0.5 fps	**72.48**	**62.39**	69.83	47.75	**73.27**	64.67	65.07	**61.28**	58.78	26.34	48.80	56.94
+ HERMES (4K tokens	0.5 fps	**72.48**	**62.39**	**74.14**	**50.56**	**73.27**	**65.22**	**66.34**	60.61	**61.49**	**28.49**	**50.20**	**58.27**
LLaVA-OV-0.5B [23]	32	53.69	53.21	48.28	**33.71**	**60.40**	**48.91**	49.70	46.13	45.27	**12.37**	34.59	42.15
+ ReKV [13]	0.5 fps	41.61	44.95	50.00	29.78	**60.40**	35.87	43.77	46.13	43.92	9.14	33.06	38.42
+ HERMES (6K tokens	0.5 fps	**57.05**	**49.54**	55.17	32.58	**60.40**	47.28	50.34	**47.81**	47.30	9.14	34.75	42.55
+ HERMES (4K tokens	0.5 fps	56.38	47.71	**56.90**	32.02	62.38	**48.91**	**50.72**	**47.81**	**47.97**	8.60	**34.80**	**42.76**
Qwen2.5-VL-7B [5]	1fps	67.79	55.05	67.24	42.13	66.34	60.87	59.90	**51.52**	58.78	23.66	44.65	52.28
+ HERMES (6K tokens	0.5 fps	**85.91**	60.55	**74.14**	52.81	70.30	**66.85**	68.42	49.49	61.49	33.33	48.10	58.26
+ HERMES (4K tokens	0.5 fps	85.23	**64.22**	71.55	**53.37**	**74.26**	65.22	**68.98**	48.48	**62.16**	**37.63**	**49.43**	**59.21**
Qwen2.5-VL-32B [5]	1fps	77.18	58.72	68.10	50.56	**74.26**	57.61	64.40	**58.59**	62.84	29.57	50.33	57.37
+ HERMES (6K tokens	0.5 fps	87.25	**66.06**	**74.14**	57.30	71.29	75.54	71.93	55.56	**70.27**	47.31	**57.71**	**64.82**
+ HERMES (4K tokens	0.5 fps	**88.59**	65.14	**74.14**	**58.99**	71.29	**76.09**	**72.37**	52.19	66.22	**47.85**	55.42	63.90