Post-Retrieval Semantic Re-Ranking via Zero-shot LLMs for Segmentation-Free Document Image Keyword Spotting

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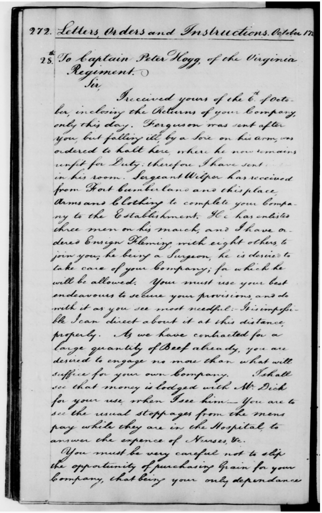
Keyword Spotting Overview

Document preservation

- digitization → collections of document images

Document image analysis

- search
- summarize
- automatic translation
- question answering
- named entity linking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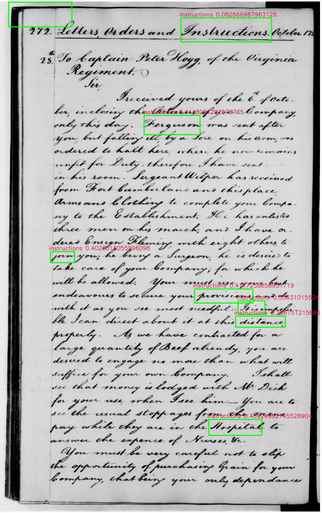
Problem

- efficient retrieval of keywords in digitized documents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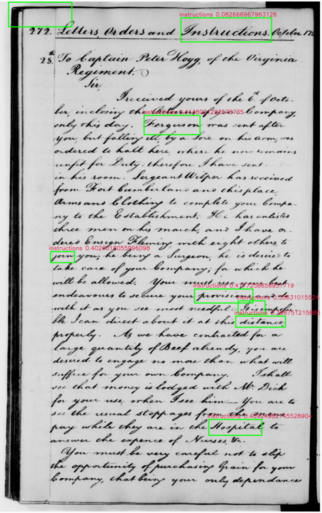
- efficient retrieval of keywords in digitized documents

Naive approach

- text transcription (e.g., OCR)
- retrieval on text



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Problem

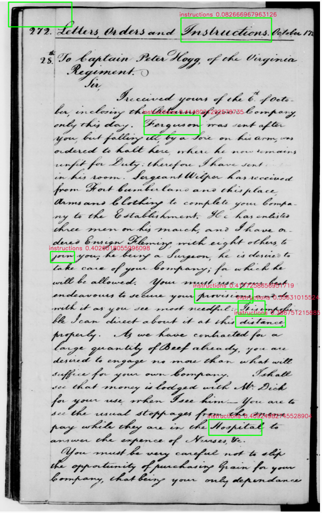
- efficient retrieval of keywords in digitized documents

Naive approach

- text transcription (e.g., OCR)
- retrieval on text
- recognition errors

Challenges

- intra/inter- writer variability
- physical deterioration: ink fading, staining, paper degradation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Keyword Spotting

KWS: *recognition-free* image retrieval

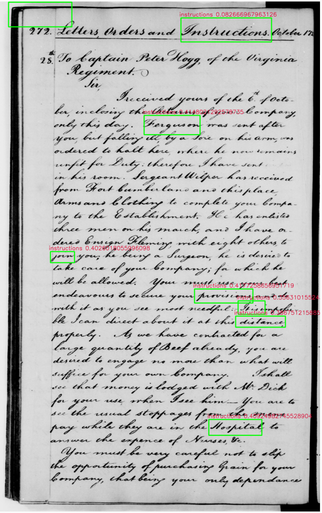
- given a keyword find all instances in document corpus
- returned them sorted by relevance

Enables

- efficient keyword-based search
- improved browsing experience

Avoids

- automatic transcription → no recognition errors
- manual annotation → cost effective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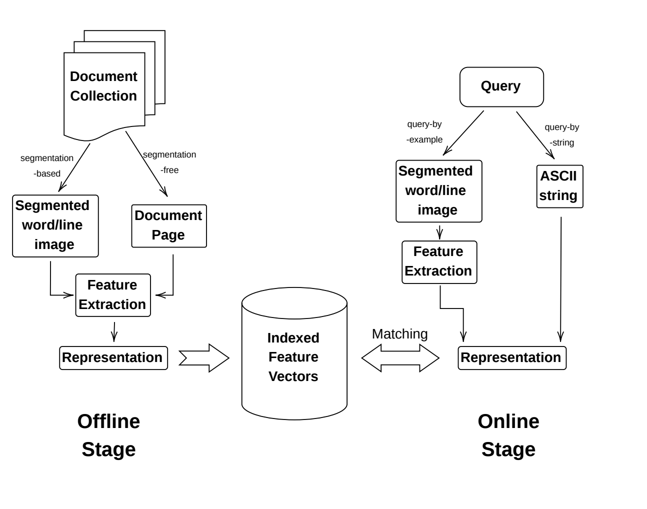
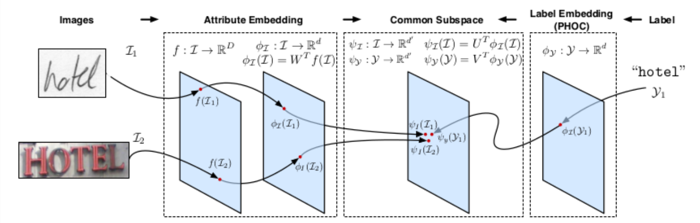
Keyword Spotting: General Architecture



Giotis et al. [1]

Keyword Spotting: General Architecture



Figures: Almazán et al. [2] and Wilkinson, Lindström, and Brun [3]

Keyword Spotting: Taxonomies

KWS approaches classified by assumptions

- Input Modularity
  - query-by-example: image example
  - query-by-string: alphanumeric string
- Segmentation
  - segmentation-based: word images or line images
  - segmentation-free: document images
- Machine Learning
  - learning-free: handcraft features, no manual annotations
  - learning-based: superior performance (CNN, HMM, SVM)
- Similarity
  - verbatim: visual resemblance
  - semantic: semantic resemblance
  - hybrid: verbatim & semantic

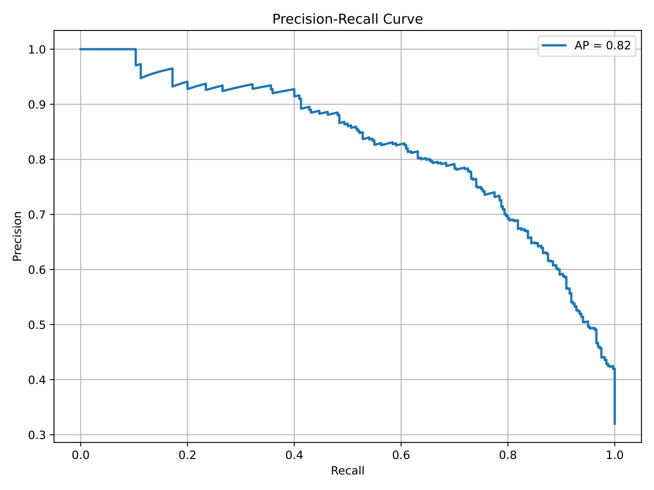
Keyword Spotting: Metrics

Information Retrieval Metrics

- Precision $= \frac{\text{number of } \textbf{relevant retrieved} \text{ instances}}{\text{number of } \textbf{retrieved} \text{ instances}} = \frac{TP}{TP+FP}$
- Recall $= \frac{\text{number of } \textbf{relevant retrieved} \text{ instances}}{\text{number of } \textbf{relevant} \text{ instances}} = \frac{TP}{TP+FN}$
- Average Precision $= \frac{1}{R}\sum_{k=1}^{n} \mathrm{P@}k \cdot rel(k)$
  - Precision at rank k: $\mathrm{P@}k =$ precision of top k retrievals
  - $rel(k) = \begin{cases} 1, & \text{if k-th instance relevant} \\ 0, & \text{otherwise} \end{cases}$
  - R total relevant items
- Mean Average Precision (mAP):
  mean of Average Precision computed over all queries

Keyword Spotting: Metrics

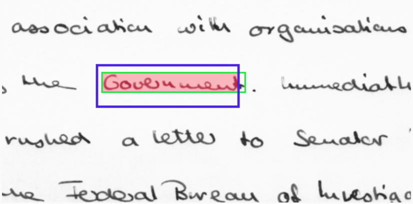
Average Precision estimates area under Precision-Recall curve.



Keyword Spotting: Metrics

When is an instance relevant?

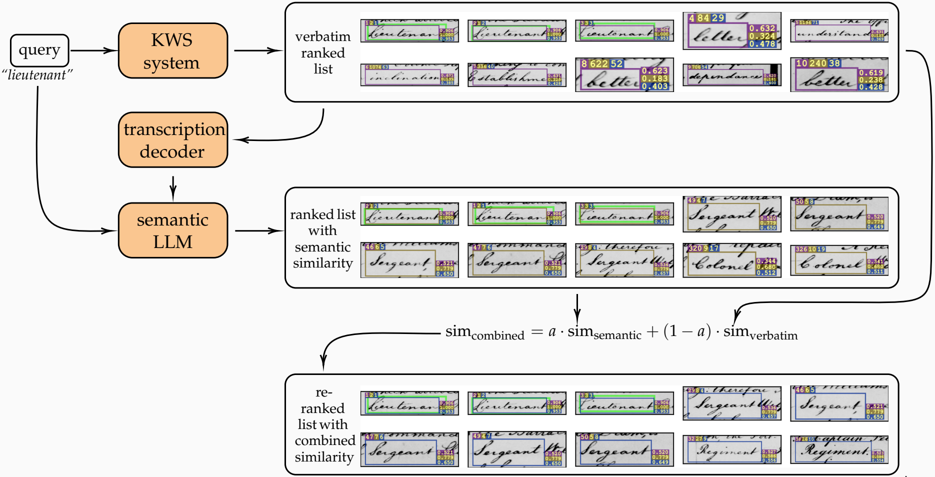
- Intersection over Union (IoU)



- $\text{IoU}(\text{prediction}, \text{ground-truth}) \geq \text{threshold}$
- typical thresholds: $\begin{cases} 0.25 & \rightarrow \quad \text{mAP@25} \\ 0.5 & \rightarrow \quad \text{mAP@50} \end{cases}$
- at most one instance considered relevant

Proposed System

Post-retrieval semantic re-ranking via zero-shot LLMs for segmentation-free KWS



Proposed System: Overview

Post-retrieval semantic re-ranking via zero-shot LLMs for segmentation-free KWS

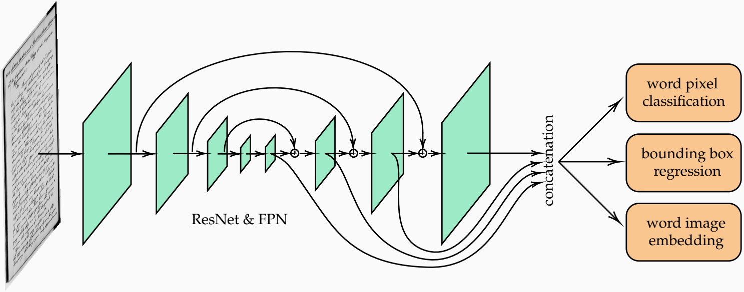
Objectives

1. improve exact retrieval (increase mAP)
2. enhance semantic quality of search

Pipeline variants

- **KWS Baselines**: WordRetrievalNet, KWS-Simplified
- **Decoders**: KWS-Simplified-based, TrOCR (visual-textual transformer)
- **Semantic LLM**: Roberta, MPNet, MiniLM

Baseline: WordRetrievalNet

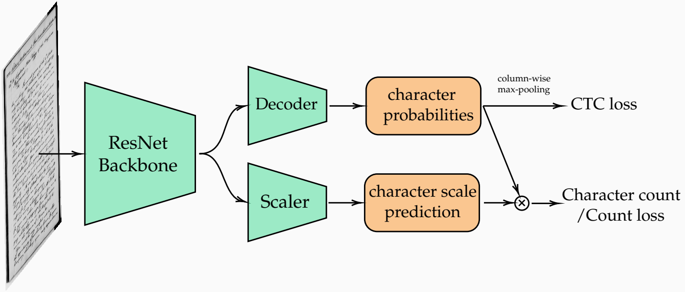


Loss

- dice coefficient loss: $1 - \frac{2|X \cap Y|}{|X| + |Y|}$
- distance-IoU loss: IoU loss penalizing center distances
- cosine loss

Zhao et al. [4]

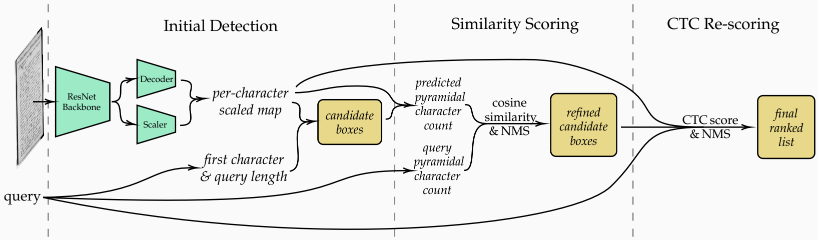
Baseline: Segmentation-free KWS Simplified



Offline stage

- character c, image coordinates (i,j), $F(i,j,c)$ probability, $S(i,j)$ scale
- $y_c = \sum_{i=s_1}^{e_1} \sum_{j=s_2}^{e_2} F(i,j,c) \cdot S(i,j)$ (regression)
- Connectionist Temporal Classification (CTC)
- training and pre-computing of F, S

Retsinas, Sfikas, and Nikou [5]



Online stage

- estimate first character location based on query first char
- estimate bounding box with query length
- pyramidal counting (like PHOC)
- CTC-based re-scoring

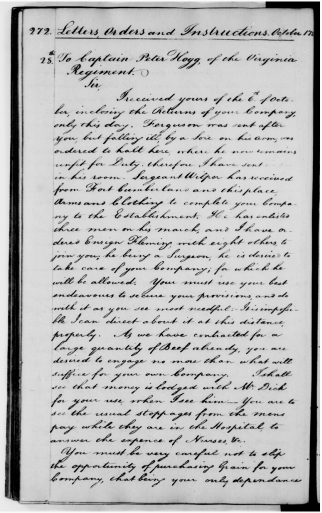
Retsinas, Sfikas, and Nikou [5]

Experimental Evaluation

George Washington Dataset (GW)

- 20 handwritten letters
- $4,860$ annotated words
- few writers (single-writer)
- 4-fold cross validation
- 14 train/1 validate/5 test
- test queries: all unique transcriptions test pages

Lavrenko, Rath, and Manmatha [6]



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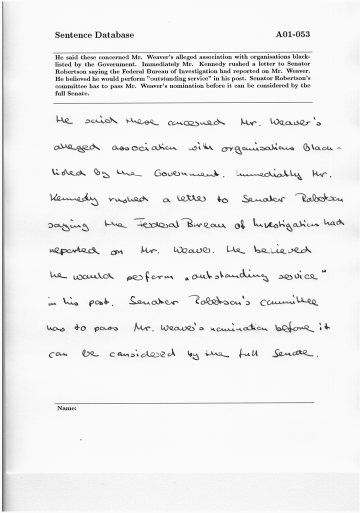
IAM Handwriting Database

- $1,539$ forms
- $115,320$ annotated words
- 657 writers
- official split (1,087/220/232)
- test queries: all unique transcriptions test pages, excluding stopwords, non alphanumeric

Marti and Bunke [7]



Sentence Database A01-053

He said these concerned Mr. Weaver's alleged association with organisations black-listed by the Government. Immediately Mr. Kennedy rushed a letter to Senator Robertson saying the Federal Bureau of Investigation had reported on Mr. Weaver. He believed he would perform "outstanding service" in his post. Senator Robertson's committee has to pass Mr. Weaver's nomination before it can be considered by the full Senate.

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in his post. Senator Robertson's committee
has to pass Mr. Weaver's nomination before it
can be considered by the full Senate.

Name:

Experimental Evaluation: Implementation

Training on GW ($\times 4$)

- WordRetrievalNet 120 epochs
- KWS-Simplified 200 epochs

Training on IAM

- WordRetrievalNet 80 epochs

Fine-tuned on GW ($\times 4$)

- TrOCR 20 epochs

RoBERTa, MPNet, MiniLM: pre-trained

Experimental Evaluation: WordRetrievalNet

Semantic weight	Semantic LLM	George Washington Dataset				IAM Handwriting Database			
		KWS-Simplified decoder		TrOCR decoder		KWS-Simplified decoder		TrOCR decoder	
		mAP@25	mAP@50	mAP@25	mAP@50	mAP@25	mAP@50	mAP@25	mAP@50
0.0*	all -MiniLM -L12 -v2	94.31 ± 1.8	88.29 ± 4.0	94.31 ± 1.8	88.29 ± 4.0	79.15	72.85	79.15	72.85
0.1		95.80 ± 1.5	89.51 ± 3.8	**94.51 ± 1.8**	**88.43 ± 4.0**	**80.60**	**73.98**	**82.04**	**75.40**
0.2		96.10 ± 1.5	89.75 ± 3.8	93.96 ± 2.0	87.84 ± 4.0	79.29	72.62	80.59	73.77
0.3		**96.30 ± 1.3**	**89.79 ± 3.7**	93.20 ± 2.1	87.07 ± 3.8	75.87	69.30	77.68	71.05
0.4		96.04 ± 1.5	89.64 ± 3.6	91.71 ± 2.5	85.73 ± 3.9	71.36	65.13	74.04	67.66
0.5		95.34 ± 1.4	89.01 ± 3.5	89.05 ± 2.9	83.19 ± 3.8	65.95	60.19	70.68	64.57
0.6		94.39 ± 1.5	88.20 ± 3.5	84.82 ± 4.2	79.41 ± 4.2	60.26	54.99	67.17	61.33
0.7		93.25 ± 1.6	87.37 ± 3.5	79.04 ± 4.8	74.03 ± 3.7	55.95	50.99	64.47	58.88
0.8		91.92 ± 1.9	86.26 ± 3.5	73.12 ± 6.1	68.42 ± 4.5	53.12	48.38	62.88	57.42
0.9		90.93 ± 2.0	85.42 ± 3.6	69.68 ± 6.6	65.20 ± 4.8	51.46	46.88	62.22	56.83
1.0		89.83 ± 2.2	84.28 ± 3.7	64.58 ± 7.5	60.07 ± 6.0	47.96	43.71	54.34	49.48
0.0*	all -mpnet -base -v2	94.31 ± 1.8	88.29 ± 4.0	94.31 ± 1.8	88.29 ± 4.0	79.15	72.85	79.15	72.85
0.1		95.90 ± 1.4	89.67 ± 3.8	**94.68 ± 1.6**	**88.62 ± 3.9**	**80.84**	**74.18**	**82.12**	**75.43**
0.2		96.27 ± 1.3	89.86 ± 3.8	94.09 ± 1.7	87.98 ± 3.8	80.01	73.21	80.77	74.02
0.3		96.50 ± 1.4	89.97 ± 4.0	93.07 ± 2.1	87.02 ± 3.7	77.55	70.82	77.87	71.29
0.4		**96.56 ± 1.5**	**90.08 ± 3.9**	91.78 ± 2.4	85.85 ± 3.7	73.86	67.22	74.73	68.33
0.5		96.00 ± 1.3	89.62 ± 3.6	89.42 ± 2.9	83.85 ± 3.8	69.24	62.95	71.23	65.12
0.6		95.04 ± 1.2	88.82 ± 3.5	85.13 ± 3.6	79.84 ± 3.8	63.70	57.97	67.84	61.99
0.7		93.83 ± 1.6	87.86 ± 3.4	79.10 ± 5.3	74.10 ± 4.1	58.18	52.97	65.43	59.78
0.8		92.57 ± 1.7	86.71 ± 3.4	74.06 ± 6.2	69.30 ± 4.6	53.92	49.10	63.80	58.25
0.9		91.53 ± 1.8	85.84 ± 3.6	70.50 ± 6.4	65.90 ± 4.6	51.43	46.89	62.78	57.36
1.0		90.21 ± 2.1	84.45 ± 3.7	64.91 ± 7.5	60.31 ± 6.0	49.26	44.84	54.99	50.11
0.0*	stsb -roberta -base	94.31 ± 1.8	88.29 ± 4.0	94.31 ± 1.8	88.29 ± 4.0	79.15	72.85	79.15	72.85
0.1		95.83 ± 1.6	89.60 ± 3.9	**94.58 ± 2.0**	**88.55 ± 4.2**	**81.16**	**74.49**	**81.88**	**75.18**
0.2		96.19 ± 1.3	89.82 ± 3.7	94.01 ± 2.1	87.91 ± 4.2	80.39	73.55	80.97	74.22
0.3		**96.59 ± 1.3**	**90.17 ± 3.7**	92.87 ± 2.9	86.92 ± 4.5	77.40	70.68	77.51	70.90
0.4		96.44 ± 1.6	89.99 ± 3.7	90.75 ± 3.2	84.96 ± 4.4	73.54	66.94	74.29	67.87
0.5		96.32 ± 1.6	89.90 ± 3.7	87.91 ± 3.5	82.32 ± 4.3	69.45	63.25	71.28	65.11
0.6		96.04 ± 1.7	89.57 ± 3.8	84.15 ± 4.3	78.83 ± 4.9	64.83	59.05	68.70	62.85
0.7		95.27 ± 1.7	88.91 ± 4.0	80.37 ± 4.4	75.25 ± 4.7	61.28	55.73	66.71	61.03
0.8		94.37 ± 1.8	88.08 ± 3.9	77.09 ± 4.4	72.16 ± 4.3	58.23	53.05	65.16	59.66
0.9		93.54 ± 2.0	87.46 ± 4.0	74.05 ± 4.8	69.22 ± 4.1	56.22	51.22	64.13	58.74
1.0		92.32 ± 2.2	86.19 ± 3.9	67.98 ± 5.4	63.34 ± 4.3	53.99	49.11	56.03	51.24

*This is essentially the baseline model. It does not use a decoder.

Experimental Evaluation: KWS-Simplified

Semantic weight	Semantic LLM	George Washington Dataset				IAM Handwriting Database			
		KWS-Simplified decoder		TrOCR decoder		KWS-Simplified decoder		TrOCR decoder	
		mAP@25	mAP@50	mAP@25	mAP@50	mAP@25	mAP@50	mAP@25	mAP@50
0.0*	all-MiniLM-L12-v2	89.74 ± 0.7	72.29 ± 3.0	89.74 ± 0.7	72.29 ± 3.0	86.40	63.73	86.40	63.73
0.1		90.62 ± 0.5	72.77 ± 3.0	90.27 ± 0.8	72.53 ± 3.1	86.71	63.86	87.49	64.22
0.2		90.68 ± 0.4	72.82 ± 3.0	**90.38 ± 0.7**	**72.57 ± 3.1**	**86.79**	**63.94**	87.84	64.47
0.3		90.70 ± 0.5	72.84 ± 3.0	90.35 ± 0.7	72.55 ± 3.2	86.57	63.72	88.01	64.58
0.4		90.72 ± 0.5	72.84 ± 3.0	90.30 ± 0.7	72.51 ± 3.2	86.11	63.36	**88.06**	**64.60**
0.5		90.79 ± 0.4	72.90 ± 3.0	90.32 ± 0.6	72.55 ± 3.2	85.65	63.01	87.74	64.43
0.6		90.85 ± 0.5	72.93 ± 3.0	90.32 ± 0.6	72.54 ± 3.2	84.66	62.38	87.28	64.17
0.7		**90.91 ± 0.5**	**72.97 ± 3.0**	90.26 ± 0.7	72.51 ± 3.2	83.32	61.47	86.30	63.56
0.8		90.83 ± 0.4	72.90 ± 2.9	90.12 ± 0.6	72.42 ± 3.1	81.31	60.20	84.66	62.49
0.9		90.82 ± 0.4	72.89 ± 2.9	89.93 ± 0.6	72.29 ± 3.0	77.61	57.85	81.51	60.47
1.0		90.43 ± 0.7	72.73 ± 2.7	87.16 ± 0.6	70.39 ± 2.1	71.97	54.39	76.74	57.24
0.0*	all-mpnet-base-v2	89.74 ± 0.7	72.29 ± 3.0	89.74 ± 0.7	72.29 ± 3.0	86.40	63.73	86.40	63.73
0.1		90.63 ± 0.5	72.78 ± 3.0	90.22 ± 0.7	72.49 ± 3.1	86.69	**63.88**	87.53	64.25
0.2		90.69 ± 0.5	72.83 ± 3.0	90.31 ± 0.7	72.51 ± 3.1	**86.70**	63.87	87.89	64.51
0.3		90.72 ± 0.5	72.84 ± 3.0	90.29 ± 0.6	72.49 ± 3.1	86.56	63.75	88.16	64.80
0.4		90.81 ± 0.5	72.91 ± 3.1	**90.32 ± 0.7**	**72.54 ± 3.1**	86.32	63.59	**88.25**	**64.88**
0.5		90.86 ± 0.5	72.96 ± 3.1	90.29 ± 0.7	72.53 ± 3.2	85.91	63.33	87.97	64.69
0.6		90.87 ± 0.4	72.94 ± 3.0	90.26 ± 0.6	72.49 ± 3.1	85.03	62.71	87.52	64.37
0.7		**90.94 ± 0.5**	**72.97 ± 3.1**	90.10 ± 0.7	72.39 ± 3.1	84.15	62.10	86.60	63.77
0.8		90.91 ± 0.5	72.96 ± 3.0	90.06 ± 0.6	72.35 ± 3.0	82.56	61.09	85.07	62.78
0.9		90.85 ± 0.4	72.92 ± 3.0	89.74 ± 0.4	72.09 ± 2.9	79.47	59.19	81.97	60.86
1.0		90.47 ± 0.5	72.78 ± 2.8	87.06 ± 0.7	70.23 ± 2.1	74.04	55.89	77.30	57.78
0.0*	stsb-roberta-base	89.74 ± 0.7	72.29 ± 3.0	89.74 ± 0.7	72.29 ± 3.0	86.40	63.73	86.40	63.73
0.1		90.62 ± 0.5	72.78 ± 3.0	90.21 ± 0.6	72.46 ± 3.0	86.58	63.82	87.35	64.13
0.2		90.63 ± 0.5	72.79 ± 3.0	90.27 ± 0.6	72.47 ± 3.0	**86.78**	**63.85**	87.78	64.52
0.3		90.66 ± 0.5	72.80 ± 3.0	90.27 ± 0.6	72.47 ± 3.1	86.72	63.74	88.04	64.72
0.4		90.76 ± 0.5	72.88 ± 3.0	90.32 ± 0.6	72.52 ± 3.1	86.45	63.59	**88.12**	**64.84**
0.5		90.89 ± 0.5	**72.97 ± 3.1**	**90.33 ± 0.5**	**72.54 ± 3.1**	85.87	63.29	87.62	64.60
0.6		90.90 ± 0.4	**72.97 ± 3.1**	90.30 ± 0.4	72.50 ± 3.0	85.09	62.79	86.78	64.16
0.7		**90.92 ± 0.4**	**72.97 ± 3.1**	90.13 ± 0.4	72.41 ± 2.9	83.82	61.99	85.44	63.32
0.8		90.86 ± 0.4	72.92 ± 3.0	89.96 ± 0.5	72.28 ± 2.9	81.96	60.79	83.06	61.79
0.9		90.74 ± 0.4	72.86 ± 3.0	89.75 ± 0.5	72.12 ± 2.8	79.45	59.12	80.17	59.88
1.0		90.33 ± 0.5	72.71 ± 2.8	87.08 ± 0.9	70.24 ± 2.0	76.10	57.18	76.49	57.40

*This is essentially the baseline model. It does not use a decoder.

Baseline: WordRetrievalNet > KWS-Simplified

	GW (mAP@25/50)	IAM (mAP@25/50)
WordRetrievalNet	+2.3/+0.9	+3.0/+2.6
KWS-Simplified	+1.2/+0.7	+1.9/1.2

- WordRetrievalNet: query-independent pre-compute word locations
- WordRetrievalNet more candidates → more efficient re-ranking
- KWS-Simplified fewer candidates to pick from (no query expansion)
- small gains mAP@50 on GW

Experimental Evaluation: Results Overview

Decoder

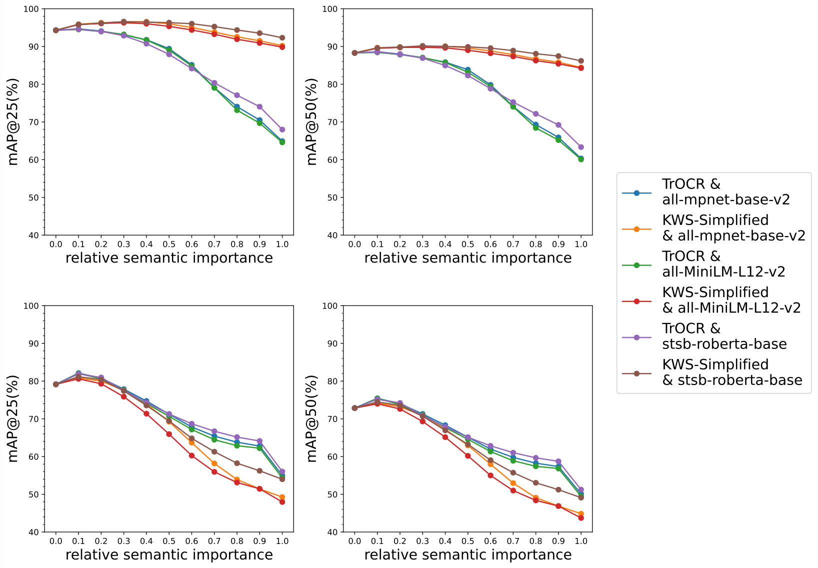
- on GW: KWS-Simplified $>$ TrOCR
  - mAP@25%: $+2.3\% > +0.6\%$
  - mAP@50%: $+0.9\% > +0.3\%$
- on IAM: KWS-Simplified $<$ TrOCR
  - mAP@25%: $+2.0\% < +3.0\%$
  - mAP@50%: $+1.6\% < +2.6\%$
- final performance shaped by accuracy of initial bounding boxes, not only decoder
- importance of holistic design (end-to-end)

Experimental Evaluation: Results Overview

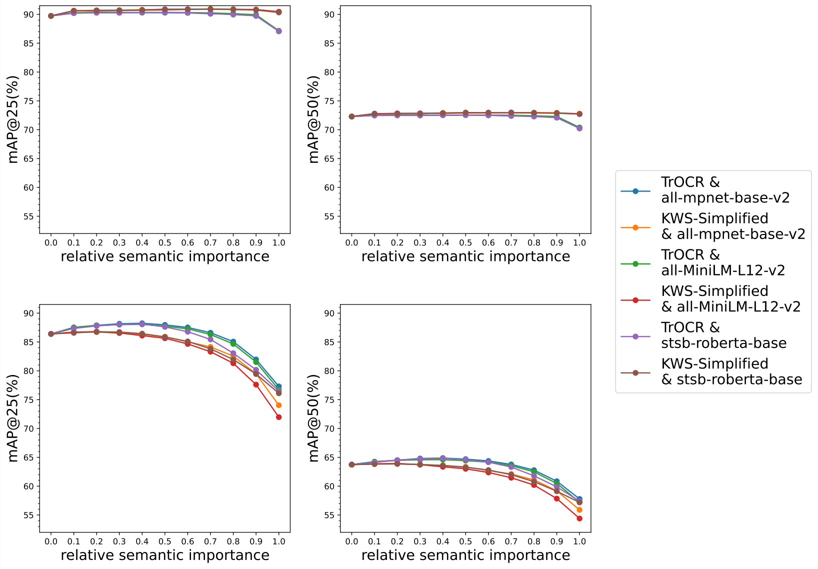
Semantic LLMs

- indistinguishable (usually less 0.3%, at most 0.5%)
- robustness and adaptability

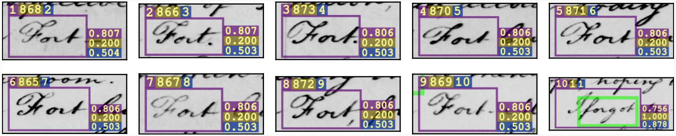
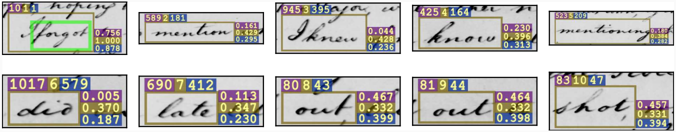
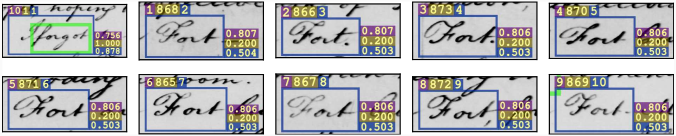
WordRetrievalNet Results



KWS-Simplified Results



Visual Examples

Similarity	Top-10 Ranked Lists
Verbatim	
Semantic	
Combined	

Visual Examples

Similarity	Top-21 Ranked Lists
Verbatim	
Semantic	
Combined	

Conclusion

Conclusions

- promising semantic re-ranking: modular, extension KWS system
- effective generalization across datasets
- consistent gains, adaptable to different LLMs
- low variability
- WordRetrievalNet on IAM
  - $+3.0\%$ (mAP@25: from 79.15% to 82.12%)
  - $+2.6\%$ (mAP@50: from 72.85% to 75.43%)
- KWS-Simplified on IAM
  - $+1.85\%$ (mAP@25: from 86.40% to 88.25%)
  - $+1.15\%$ (mAP@50: from 63.73% to 64.88%)
- WordRetrievalNet on GW: $+2.3\%$ (mAP@25: from 94.31% to 96.59%)
- KWS-Simplified on GW: $+1.2\%$ (mAP@25: from 89.74% to 90.94%)
- qualitive improvements

Future Directions

End-to-end semantic representations for segm-free KWS, too

- search
- summarize
- automatic translation
- question answering
- named entity linking

Thanks for your attention!

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