Supplementary Material: A Vote-and-Verify Strategy for Fast Spatial Verification in Image Retrieval

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1 Distractor Sets

We introduce four new distractor sets consisting of geo-tagged images from the Yahoo 100M image dataset [3]. There are 724,445 images in total: The first dataset consists of images taken between 2km and 50km from the center of the University of Oxford, UK (140,848 images; DD coord.: 51.750318,-1.255942). The other three datasets were collected from 30 cities across the UK (170,980 images), 30 cities across continental Europe (179,287 images), and 30 cities across the continental United States (233,330 images). For the latter three distractor sets, cities were manually chosen to be spread across the respective area. The UK and Europe datasets consist of images taken within 1km of each city center, while the US dataset consists of images taken within 2km of each center. We downloaded images to a maximum resolution of 1024px in either dimension, with larger images being resized accordingly. A full listing of the 30 cities used for each distractor set is given in Table 1.

2 Query Dataset

Additionally, we introduce a new query image set, termed *World5k*, for the purpose of image retrieval, again consisting of images from [3]. This image set consists of 5,320 images collected from 61 sites around the world, plus an additional 163 query images. These image collections were obtained by combining geo-tag information with overlap information from Heinly *et al.* [1]. Unlike query sets such as the Oxford5k dataset [2], our query images are full-size (up to 1024px), rather than cropped regions of a larger image. We do not consider quality of view when computing retrieval results (*i.e.* "junk" versus "ok" versus "good" in Oxford5k). Also different from Oxford5k, our new query dataset only consists of landmark images – every image in the dataset has at least one associated query image, and there are no distractor images. As a result, the dataset has low inter-landmark confusion. A full list of the various landmarks and their number of images can be found in Table 2.

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3 Results on Different Vocabularies

In this section, we present additional image retrieval results for vocabulary sizes of 20k words and 1M words. As in the main paper, we compute mean average precision (mAP) and timings for the Oxford5k, Paris6k, and World5k query datasets using vocabularies learned from the Paris6k, Oxford5k, and Oxford5k datasets, respectively. Tables 3 to 8 show the results for the various methods and distractor sets tested in the original paper. The results for 20k words outperform the results for 1M words in terms of mAP, since we use a Hamming embedding to mitigate quantization artifacts.

4 Source Code and Datasets

The new query and distractor image datasets and the source code for our method are released to the public at https://github.com/vote-and-verify.

References

1. Heinly, J., Schönberger, J.L., Dunn, E., Frahm, J.M.: Reconstructing the world* in six days *(as captured by the yahoo 100 million image dataset). In: CVPR. (2015)
2. Philbin, J., Chum, O., Isard, M., Sivic, J., Zisserman, A.: Object retrieval with large vocabularies and fast spatial matching. In: CVPR. (2007)
3. Thomee, B., Shamma, D.A., Friedland, G., Elizalde, B., Ni, K., Poland, D., Borth, D., Li, L.J.: Yfcc100m: The new data in multimedia research. Comm. ACM (2016)

Table 1. City names and decimal degrees coordinates for the UK, Europe, and US distractor image sets.

30 Cities – UK		30 Cities – Europe		30 Cities – US	
Basingstoke	51.266872,-1.092034	Antwerp	51.219360,4.402323	Atlanta	33.749711,-84.387990
Bath	51.375835,-2.359896	Athens	37.984473,23.728726	Austin	30.266775,-97.741049
Bedford	52.136242,-0.467031	Belgrade	44.787389,20.449370	Boise	43.618683,-116.218450
Birmingham	52.487244,-1.891099	Bucharest	44.426931,26.102699	Boston	42.361317,-71.059218
Bristol	51.455206,-2.588308	Budapest	47.498295,19.038287	Chapel Hill	35.913266,-79.054799
Cambridge	52.206307,0.121360	Carcassone	43.212050,2.352857	Charleston	32.776583,-79.929281
Canterbury	51.280364,1.078872	Chisinau	47.010851,28.861608	Chicago	41.875586,-87.631911
Cardiff	51.482126,-3.179155	Clermont-Ferrand	45.776943,3.086891	Cleveland	41.498854,-81.696533
Chelmsford	51.736199,0.468642	Colmar	48.079357,7.358125	Dallas	32.777876,-96.795204
Cheltenham	51.899389,-2.078354	Haarlem	52.387375,4.645754	Denver	39.737859,-104.986954
Coventry	52.408016,-1.519383	Hamburg	53.550740,9.990988	Fresno	36.742774,-119.779282
Ely	52.399677,0.262364	Innsbruck	47.269218,11.403219	Kansas City	39.100894,-94.583279
Exeter	50.718880,-3.534147	Kosice	48.716305,21.260816	Los Angeles	34.050908,-118.245591
Gloucester	51.864423,-2.238221	Lisbon	38.722062,-9.139605	Louisville	38.254534,-85.760548
Grimsby	53.567564,-0.079957	Marseille	43.296863,5.367715	Minneapolis	44.977719,-93.262853
Harrogate	53.994819,-1.541618	Minsk	53.915535,27.546862	Nashville	36.168268,-86.773579
Hereford	52.056545,-2.715996	Mont Saint-Michel	48.636009,-1.511136	New Orleans	29.951103,-90.072337
Hull	53.745470,-0.336278	Odessa	46.482881,30.723797	Orlando	28.537869,-81.379738
Ipswich	52.056755,1.148030	Prague	50.075404,14.442463	Philadelphia	39.952115,-75.166100
Leicester	52.636890,-1.140028	Riga	56.948934,24.101005	Phoenix	33.450555,-112.075196
Lincoln	53.230418,-0.540391	Seville	37.389551,-5.984928	Pittsburg	40.440901,-79.994920
Northampton	52.240725,-0.902543	Siena	43.318798,11.330417	Portland	45.523175,-122.677426
Norwich	52.630866,1.297492	Sofia	42.697682,23.322572	Providence	41.823767,-71.414829
Peterborough	52.569473,-0.241060	St. Petersburg	59.935281,30.331548	Reno	39.529784,-119.815142
Salisbury	51.069136,-1.794783	Strasbourg	48.573181,7.750076	Salt Lake City	40.761246,-111.897484
Stoke-on-Trent	53.003535,-2.179314	Tirana	41.327883,19.818681	San Antonio	29.422762,-98.489006
Stratford-upon-Avon	52.191909,-1.708276	Vilnius	54.685341,25.282767	San Francisco	37.775179,-122.421581
Winchester	51.060470,-1.310492	Wroclaw	51.107661,17.038297	Santa Fe	35.686356,-105.939490
Wrexham	53.043190,-2.992631	Yverdon-les-Bains	46.780767,6.640544	Seattle	47.606031,-122.333847
York	53.959803,-1.087630	Zagreb	45.815294,15.981496	Washington, D.C.	38.903068,-77.036884

Table 2. Name, number of database images, and number of query images for each of the 61 landmarks in our new query set.

Name	# Database	# Query	Name	# Database	# Query
Alhambra Palace	48	1	Notre Dame, Rosary Window	100	3
Arc de Triomphe	85	3	Palace of Versailles, Chapel	100	3
Basilica di Santa Croce	71	2	Palace of Westminster	100	3
Bellagio	78	3	Pantheon (exterior)	100	3
Blue Mosque (exterior)	30	1	Pantheon (interior)	100	3
Blue Mosque (interior)	100	3	Palais Garnier	100	3
Brandenburg Gate	100	3	Petra, Jordan	93	3
British Museum (exterior)	100	3	Piazza dei Miracoli	100	3
British Museum (interior)	83	3	Piazza della Signoria	94	3
Buckingham Palace	100	3	Piazza di Spagna	100	3
Colosseum (exterior)	100	3	Piazza San Marco	100	3
Colosseum (interior)	100	3	Pieta Michaelangelo	100	3
Eiffel Tower (night)	80	3	Prague Castle	32	1
Esplanade des Invalides	47	1	Reichstag	63	2
Florence Cathedral	84	3	Royal Palace, Amsterdam	39	1
Forbidden City (entrance)	81	3	Ruins of St. Paul's	100	3
Freiburger Munster	31	1	Sacre Coeur	100	3
Golden Gate Bridge	87	3	Senso-ji Temple	100	3
Grand Central Terminal, New York	100	3	St. Paul's Cathedral	100	3
Hagia Sophia (interior)	100	3	St. Peter's Basilica (interior)	100	3
Itsukushima Shrine	41	1	St. Peter's Square	100	3
Kinkaku-ji Temple	98	3	St. Vitus Cathedral	100	3
Kiyomizu-dera Temple	98	3	Sydney Harbour Bridge	74	2
London Bridge	100	3	Taj Mahal	100	3
London Eye	82	3	Taj Mahal, entrance	60	2
Louvre	100	3	Todai-ji Temple	100	3
Milan Cathedral	100	3	Trevi Fountain	100	3
Mount Rushmore	100	3	Victor Emmanuel II Monument	100	3
National Gallery, London	100	3	Western Wall, Jerusalem	92	3
Natural History Museum, London	49	1	Westminster Abbey	100	3
Notre Dame Cathedral	100	3			

Table 3. Verification accuracy and efficiency measured on the Oxford5k dataset using a vocabulary of 20k words. The best, second-best, and third-best results are highlighted for each column.

	–	F100k	Ox	UK	EU	US	Ox+UK	Ox+EU	Ox+US	UK+EU	UK+US	EU+US	Ox+UK+EU	Ox+UK+US	Ox+EU+US	UK+EU+US	Ox+UK+EU+US	All
mAP [%]																		
Pure Retrieval	72.5	62.7	61.0	55.1	54.3	55.9	53.0	52.6	53.6	50.9	51.0	50.9	49.7	49.8	49.7	48.7	47.8	47.4
FSM Aff	**82.0**	**78.1**	**75.8**	**71.6**	**72.5**	**75.0**	**70.0**	**70.8**	**72.5**	**69.0**	**70.0**	**70.6**	**67.7**	**68.7**	**68.9**	**67.8**	**66.1**	**65.5**
+ Eff. Inl. Eval	**81.4**	**77.8**	**75.5**	**71.3**	**71.9**	**74.6**	**69.7**	**70.4**	**72.1**	**68.7**	**69.7**	**70.2**	**67.5**	**68.4**	**68.6**	**67.5**	**65.9**	**65.5**
+ Eff. Inl. Post	79.5	75.7	73.5	69.3	70.1	72.3	67.8	68.7	70.3	66.8	67.7	68.4	65.8	66.6	66.9	65.7	64.2	63.7
FSM-R Aff	**81.8**	**77.9**	**75.5**	**71.3**	**72.0**	**74.6**	**69.6**	**70.4**	**72.1**	**68.6**	**69.7**	**70.1**	**67.3**	**68.3**	**68.4**	**67.4**	**65.7**	65.2
+ Eff. Inl. Eval	81.2	77.6	**75.1**	70.9	71.6	**74.2**	69.4	**70.2**	**71.7**	68.4	69.3	69.8	67.2	68.1	68.3	67.2	65.6	**65.8**
+ Eff. Inl. Post	79.2	75.5	73.1	68.9	69.6	71.9	67.4	68.4	69.8	66.5	67.4	68.0	65.5	66.3	66.5	65.4	63.9	63.5
FSM Sim	81.2	77.5	75.0	**71.0**	71.8	74.1	69.3	70.1	71.6	68.4	**69.4**	69.9	67.1	67.9	68.2	67.3	65.5	65.1
+ Eff. Inl. Eval	80.6	77.0	74.8	**71.0**	71.8	74.0	69.3	**70.2**	**71.7**	68.4	69.3	69.9	67.2	68.0	68.3	67.3	**65.7**	**65.5**
+ Eff. Inl. Post	78.2	74.8	72.6	68.6	69.3	71.7	67.2	67.9	69.7	66.2	67.0	67.6	65.1	65.9	66.3	65.2	63.6	63.3
FSM-R Sim	80.6	77.3	74.5	70.5	71.2	73.6	68.9	69.6	71.1	67.9	68.9	69.4	66.6	67.5	67.7	66.8	65.1	64.9
+ Eff. Inl. Eval	80.2	76.9	74.5	70.6	71.4	73.6	69.0	69.8	71.3	68.0	68.9	69.6	66.9	67.7	68.0	66.9	65.4	**65.4**
+ Eff. Inl. Post	77.5	74.6	71.7	67.7	68.4	70.8	66.3	67.0	68.8	65.3	66.2	66.8	64.3	65.1	65.5	64.4	62.9	63.1
HPM	70.3	64.3	62.8	58.7	58.0	60.4	57.6	57.0	58.8	56.0	56.8	56.5	55.2	55.9	55.6	54.9	54.1	53.7
ADV	73.5	66.6	64.7	59.7	59.5	63.1	58.6	58.4	61.0	57.1	58.4	58.2	56.4	57.5	57.3	56.5	55.7	55.5
PGM	72.1	60.7	58.8	51.8	51.8	52.0	49.5	49.9	50.0	47.6	47.2	47.9	46.6	46.4	46.7	45.8	44.7	44.3
Ours	80.6	76.1	73.1	69.2	69.9	71.7	67.4	68.0	69.3	66.6	67.4	67.9	65.2	65.9	66.2	65.3	63.8	63.5
+ Eff. Inl. Post	79.8	76.3	73.8	69.7	70.0	72.4	68.2	68.7	70.4	67.0	68.0	68.3	65.9	66.8	66.9	65.8	64.5	64.0
Runtime [s]																		
FSM Aff	94.2	118.8	126.2	157.9	162.4	144.2	182.7	180.8	168.5	192.1	182.6	185.0	191.6	182.1	180.6	190.9	191.9	189.9
+ Eff. Inl. Eval	1493.8	1751.3	1807.1	2149.0	2200.7	1930.2	2191.4	2163.7	2001.0	2280.4	2183.7	2212.9	2253.4	2164.3	2146.6	2249.9	2238.0	2218.4
+ Eff. Inl. Post	94.2	119.0	126.4	158.3	162.7	145.2	184.0	183.0	171.4	193.7	184.3	187.5	194.0	184.2	182.1	192.8	193.3	192.5
FSM-R Aff	53.1	71.1	75.6	99.8	101.7	84.5	104.9	103.2	91.8	111.1	105.0	107.7	110.9	103.5	102.0	109.5	109.6	108.9
+ Eff. Inl. Eval	1230.9	1430.5	1470.7	1740.0	1786.8	1573.7	1761.0	1739.8	1612.4	1825.4	1752.7	1783.9	1822.6	1734.7	1721.0	1795.9	1784.6	1765.6
+ Eff. Inl. Post	53.9	72.2	76.7	101.4	103.4	86.1	107.4	105.4	94.0	114.0	107.1	109.7	113.1	105.7	104.3	111.9	111.6	111.4
FSM Sim	96.0	119.9	127.2	158.3	163.8	148.0	188.8	187.9	176.1	198.6	188.0	193.4	196.5	187.3	184.8	195.5	195.3	192.9
+ Eff. Inl. Eval	1522.8	1777.6	1832.0	2180.5	2233.0	1955.3	2221.8	2196.2	2029.2	2313.4	2212.4	2245.8	2281.4	2192.7	2178.0	2279.2	2265.2	2244.9
+ Eff. Inl. Post	97.1	120.4	128.3	160.8	165.7	149.0	190.7	188.9	177.8	200.6	190.0	195.3	199.2	189.7	188.0	198.4	197.5	195.4
FSM-R Sim	51.8	68.3	72.6	95.7	98.1	81.3	101.0	99.6	88.5	107.4	100.8	103.8	106.2	99.4	97.8	105.4	105.3	104.5
+ Eff. Inl. Eval	1239.3	1431.7	1469.0	1734.5	1789.7	1573.7	1755.5	1739.3	1609.6	1823.4	1751.9	1786.4	1813.2	1728.0	1720.3	1795.4	1782.1	1762.2
+ Eff. Inl. Post	52.6	69.4	73.8	97.3	99.9	82.9	103.4	102.1	90.6	109.6	103.1	106.2	108.7	101.7	100.1	108.0	107.6	107.1
HPM	**7.7**	**9.5**	**9.5**	**11.9**	**11.5**	**10.2**	**14.6**	**14.3**	**12.7**	**15.2**	**14.6**	**14.3**	**15.0**	**14.2**	**14.6**	**14.7**	**14.8**	**14.8**
ADV	14.1	15.9	16.6	19.9	21.0	18.5	22.1	21.4	20.6	22.9	21.8	23.0	23.2	21.9	21.6	22.8	22.5	22.3
PGM	17.8	18.9	18.7	19.8	20.7	19.5	20.7	20.7	**20.4**	21.3	21.0	21.1	20.9	20.6	20.7	21.0	**21.2**	20.7
Ours	**7.9**	**9.6**	**9.9**	**12.2**	**12.0**	**10.5**	**13.6**	**13.4**	**12.7**	**14.3**	**13.9**	**13.5**	**15.2**	**14.4**	**14.2**	**15.1**	**14.8**	**14.6**
+ Eff. Inl. Post	**8.2**	**10.6**	**11.1**	**13.7**	**13.6**	**12.0**	**15.6**	**15.3**	**14.3**	**16.4**	**15.7**	**15.5**	**17.1**	**16.0**	**15.8**	**16.8**	**16.2**	**16.1**

Table 4. Verification accuracy and efficiency measured on the Paris6k dataset using a vocabulary of 20k words.

	–	F100k	EU	US	EU+US	UK+EU+US	Ox+UK+EU+US	All
mAP [%]								
Pure Retrieval	68.5	56.9	52.1	51.5	47.6	45.8	45.2	44.2
FSM Aff	**74.2**	**65.6**	**60.6**	**61.7**	**58.1**	**56.6**	**55.9**	**54.9**
+ Eff. Inl. Eval	**74.4**	**65.6**	**60.6**	**61.7**	**58.0**	**56.5**	**55.9**	**54.8**
+ Eff. Inl. Post	73.2	64.4	59.3	60.4	56.8	55.3	54.7	53.7
FSM-R Aff	**74.1**	**65.4**	**60.5**	**61.6**	**58.0**	**56.5**	**55.9**	**54.7**
+ Eff. Inl. Eval	**74.1**	**65.2**	**60.3**	**61.3**	**57.7**	**56.2**	**55.5**	54.4
+ Eff. Inl. Post	73.0	64.0	59.0	60.1	56.5	55.0	54.4	53.4
FSM Sim	73.9	**65.2**	60.2	**61.3**	57.6	**56.2**	**55.6**	54.6
+ Eff. Inl. Eval	73.8	65.1	60.0	61.2	57.5	56.0	55.4	54.4
+ Eff. Inl. Post	72.6	63.8	58.7	59.8	56.3	55.0	54.3	53.2
FSM-R Sim	73.5	64.9	59.8	60.9	57.3	55.9	55.3	54.4
+ Eff. Inl. Eval	73.4	64.8	59.7	60.8	57.1	55.7	55.0	54.2
+ Eff. Inl. Post	72.2	63.4	58.3	59.5	56.0	54.6	54.0	52.8
HPM	68.7	58.4	52.9	53.8	50.1	48.7	48.1	47.2
ADV	67.2	56.3	53.9	55.3	51.7	50.2	49.3	48.3
PGM	67.1	55.4	50.5	48.9	45.5	43.8	43.2	42.3
Ours	73.0	63.7	58.6	59.6	56.0	54.7	54.0	53.0
+ Eff. Inl. Post	73.1	63.8	58.8	60.1	56.4	55.0	54.3	53.3
Runtime [s]								
FSM Aff	145.0	223.6	234.9	224.1	282.3	309.7	341.2	349.4
+ Eff. Inl. Eval	1815.1	2396.9	2530.6	2500.3	2747.4	2776.0	2875.6	3002.9
+ Eff. Inl. Post	145.6	223.7	235.3	224.8	285.5	310.8	344.2	352.6
FSM-R Aff	78.3	128.6	135.0	126.7	151.2	165.8	182.0	185.7
+ Eff. Inl. Eval	1367.1	1697.9	1834.5	1746.6	1896.4	1932.2	1981.0	2021.5
+ Eff. Inl. Post	79.2	129.9	136.6	128.2	153.7	168.3	185.0	188.4
FSM Sim	143.5	218.8	230.6	218.6	284.0	306.2	334.1	343.2
+ Eff. Inl. Eval	1827.4	2422.3	2539.5	2528.2	2792.4	2789.7	2888.0	3031.2
+ Eff. Inl. Post	144.1	220.2	231.2	220.2	285.4	308.6	339.8	347.1
FSM-R Sim	75.9	123.6	130.0	121.2	147.4	160.3	173.6	177.6
+ Eff. Inl. Eval	1366.3	1693.0	1829.3	1737.2	1892.9	1920.8	1966.0	2005.7
+ Eff. Inl. Post	76.9	125.0	131.8	123.0	150.3	162.7	176.4	180.3
HPM	**8.6**	**12.5**	**15.0**	**13.4**	**17.4**	**17.7**	**18.5**	**18.8**
ADV	16.3	21.1	22.8	21.6	25.4	26.6	27.6	28.0
PGM	22.4	24.2	24.8	25.0	26.1	26.6	27.1	27.8
Ours	**9.3**	**13.1**	**15.7**	**13.6**	**17.3**	**18.4**	**19.5**	**19.8**
+ Eff. Inl. Post	**9.8**	**14.4**	**17.4**	**15.1**	**19.3**	**20.6**	**21.8**	**22.2**

Table 5. Verification accuracy and efficiency measured on our new World5k dataset using a vocabulary of 20k words.

	–	EU	US	EU+US	UK+EU+US	Ox+UK+EU+US
mAP [%]						
Pure Retrieval	94.8	87.8	88.4	85.4	84.5	84.1
FSM Aff	**97.8**	**94.1**	**95.2**	**93.1**	**92.4**	**92.2**
+ Eff. Inl. Eval	**97.6**	**94.0**	**95.2**	**93.1**	**92.4**	**92.1**
+ Eff. Inl. Post	97.1	93.4	94.6	92.5	91.8	91.5
FSM-R Aff	**97.7**	**94.0**	**95.2**	**93.1**	**92.4**	**92.1**
+ Eff. Inl. Eval	97.4	93.8	94.9	92.8	**92.2**	91.9
+ Eff. Inl. Post	96.9	93.1	94.4	92.2	91.6	91.3
FSM Sim	**97.7**	**94.0**	**95.1**	**93.0**	**92.4**	**92.1**
+ Eff. Inl. Eval	**97.6**	**93.9**	**95.1**	**92.9**	**92.3**	**92.0**
+ Eff. Inl. Post	97.0	93.3	94.5	92.4	91.8	91.5
FSM-R Sim	97.5	93.8	**95.0**	92.8	**92.2**	91.9
+ Eff. Inl. Eval	97.3	93.6	94.8	92.7	92.0	91.8
+ Eff. Inl. Post	96.8	93.1	94.3	92.2	91.5	91.3
HPM	92.9	87.4	88.2	86.0	85.3	85.0
ADV	90.8	77.9	79.2	76.1	74.9	74.3
PGM	93.8	86.3	86.1	83.3	82.5	82.0
Ours	96.4	92.3	93.3	91.3	90.7	90.4
+ Eff. Inl. Post	96.3	92.3	93.4	91.3	90.7	90.5
Runtime [s]						
FSM Aff	1056.3	1939.3	1787.9	2320.6	2520.9	2708.6
+ Eff. Inl. Eval	17921.0	25481.0	24010.0	26954.8	27758.7	28482.6
+ Eff. Inl. Post	1059.4	1947.3	1794.0	2334.1	2542.2	2742.2
FSM-R Aff	570.0	1146.6	1051.3	1306.0	1421.4	1490.0
+ Eff. Inl. Eval	13560.9	18038.3	17125.0	18657.7	19023.4	19352.0
+ Eff. Inl. Post	576.1	1156.2	1060.3	1323.2	1436.2	1522.0
FSM Sim	1040.9	1918.5	1766.6	2364.3	2527.8	2694.6
+ Eff. Inl. Eval	18097.0	25675.6	24188.3	27230.4	28026.4	28741.6
+ Eff. Inl. Post	1046.1	1928.3	1775.6	2385.7	2546.2	2723.1
FSM-R Sim	547.2	1100.0	1006.0	1279.3	1373.2	1435.0
+ Eff. Inl. Eval	13576.6	17941.0	17041.0	18595.3	18944.4	19263.3
+ Eff. Inl. Post	554.2	1110.1	1015.6	1296.7	1389.9	1464.1
HPM	**50.0**	**88.4**	**83.2**	**126.8**	**130.9**	**136.9**
ADV	101.5	150.4	139.3	172.3	175.8	183.9
PGM	90.3	118.0	112.8	**131.6**	**135.8**	**140.6**
Ours	**51.8**	**94.2**	**93.8**	**121.3**	**149.4**	**126.0**
+ Eff. Inl. Post	**57.2**	**106.4**	**107.7**	143.4	172.7	147.4

Table 6. Verification accuracy and efficiency measured on the Oxford5k dataset using a vocabulary of 1M words. The best, second-best, and third-best results are highlighted for each column.

	–	F100k	Ox	UK	EU	US	Ox+UK	Ox+EU	Ox+US	UK+EU	UK+US	EU+US	Ox+UK+EU	Ox+UK+US	Ox+EU+US	UK+EU+US	Ox+UK+EU+US	All
mAP [%]																		
Pure Retrieval	74.8	65.4	63.4	60.0	59.2	59.2	57.5	56.6	56.8	55.9	55.9	55.2	54.3	54.3	53.7	53.5	52.2	51.7
FSM Aff	**77.2**	71.1	68.8	66.4	67.0	67.6	64.8	65.3	65.7	64.5	64.7	65.3	63.3	63.4	64.0	63.7	62.6	62.2
+ Eff. Inl. Eval	**77.3**	**71.8**	**70.0**	**67.6**	**68.2**	**68.8**	**66.3**	**66.8**	**67.2**	**66.0**	**66.1**	**66.8**	**64.9**	**64.9**	**65.7**	**65.2**	**64.3**	**63.9**
+ Eff. Inl. Post	**77.2**	**71.5**	69.4	67.0	**67.6**	68.2	65.6	**66.1**	66.5	**65.3**	65.4	66.1	64.2	64.2	**65.0**	**64.5**	63.5	63.2
FSM-R Aff	**77.2**	71.1	68.8	66.4	67.0	67.6	64.8	65.3	65.7	64.5	64.7	65.3	63.3	63.4	64.0	63.7	62.6	62.2
+ Eff. Inl. Eval	**77.4**	**71.8**	**70.0**	**67.5**	**68.2**	**68.7**	**66.3**	**66.8**	**67.2**	**66.0**	**66.1**	**66.8**	**64.9**	**64.9**	**65.7**	**65.2**	**64.3**	**64.0**
+ Eff. Inl. Post	**77.2**	**71.6**	69.4	67.0	67.5	68.1	**65.7**	66.0	66.5	**65.3**	65.4	66.0	64.2	64.2	**65.0**	64.4	63.5	63.3
FSM Sim	76.6	70.6	68.3	65.9	66.5	66.9	64.2	64.6	65.1	64.0	64.2	64.8	62.7	62.8	63.4	63.2	62.1	61.8
+ Eff. Inl. Eval	76.9	71.2	**69.5**	66.9	**67.6**	68.2	65.6	**66.1**	**66.7**	**65.3**	**65.5**	**66.2**	**64.3**	**64.4**	**65.0**	**64.6**	**63.7**	**63.4**
+ Eff. Inl. Post	76.7	70.9	68.9	66.2	66.9	67.6	64.8	65.3	65.9	64.5	64.7	65.3	63.4	63.4	64.1	63.7	62.8	62.6
FSM-R Sim	76.6	70.5	68.2	65.8	66.4	66.9	64.1	64.6	65.1	63.9	64.1	64.7	62.7	62.8	63.4	63.2	62.1	61.8
+ Eff. Inl. Eval	76.9	71.2	**69.5**	66.9	67.5	68.2	65.6	**66.1**	66.6	**65.3**	**65.5**	66.1	64.2	**64.3**	**65.0**	**64.6**	**63.6**	63.3
+ Eff. Inl. Post	76.7	70.8	68.9	66.2	66.8	67.6	64.7	65.2	65.8	64.4	64.7	65.3	63.3	63.4	64.0	63.6	62.7	62.5
HPM	72.8	63.6	61.3	57.9	57.9	58.1	56.0	56.0	56.2	55.2	55.1	55.1	54.1	54.0	54.0	53.7	52.8	52.5
ADV	75.8	70.0	67.8	65.3	65.5	66.5	63.7	63.9	64.7	63.4	63.7	63.9	62.2	62.5	62.7	62.6	61.6	61.2
PGM	74.8	64.7	62.2	58.8	58.6	58.1	55.6	55.7	55.5	54.6	54.3	54.3	52.7	52.5	52.6	52.1	50.7	50.2
Ours	76.8	70.5	68.1	65.5	66.2	66.4	63.7	64.2	64.4	63.4	63.4	64.0	62.0	62.1	62.7	62.3	61.1	60.8
+ Eff. Inl. Post	**77.2**	**71.6**	**69.9**	**67.2**	**68.0**	**68.4**	**66.0**	**66.5**	**66.8**	**65.6**	**65.6**	**66.3**	**64.4**	**64.4**	**65.2**	**64.6**	**63.7**	63.3
Runtime [s]																		
FSM Aff	25.9	27.9	40.8	44.5	44.5	43.5	52.1	52.9	52.1	53.6	54.8	52.0	53.6	53.8	56.2	55.5	54.1	54.8
+ Eff. Inl. Eval	173.4	184.3	199.3	232.9	228.1	213.6	238.2	236.7	222.5	249.5	241.0	238.2	252.6	245.1	245.4	252.6	257.8	258.1
+ Eff. Inl. Post	23.3	27.5	41.2	45.4	45.2	43.3	52.0	52.9	52.3	54.6	53.5	53.8	54.6	54.8	56.5	54.5	55.3	56.0
FSM-R Aff	2.5	2.9	3.7	4.3	4.2	4.1	5.1	5.1	5.2	5.3	5.4	5.4	5.6	5.5	5.6	5.7	5.9	6.1
+ Eff. Inl. Eval	87.2	100.3	112.6	142.9	138.8	123.6	148.2	145.6	131.8	157.4	150.2	147.7	161.0	154.1	152.7	161.8	165.4	165.6
+ Eff. Inl. Post	2.6	3.0	3.9	4.6	4.4	4.3	5.5	5.6	5.4	5.7	5.6	5.6	6.0	6.0	6.0	6.1	6.3	6.6
FSM Sim	25.2	30.1	44.3	48.4	48.4	47.8	56.8	57.0	57.3	58.5	57.7	57.8	58.9	59.4	61.2	58.9	59.5	60.1
+ Eff. Inl. Eval	180.6	192.2	208.6	241.3	235.9	221.2	247.9	244.9	231.8	258.5	249.9	245.9	262.0	255.3	253.9	260.8	266.3	265.5
+ Eff. Inl. Post	25.3	30.2	44.6	48.8	48.5	48.2	57.3	58.0	57.8	59.6	58.8	58.8	59.6	60.9	61.3	61.1	60.7	61.6
FSM-R Sim	2.4	2.7	3.5	4.1	4.0	3.9	4.8	4.9	4.9	5.2	5.0	5.1	5.4	5.3	5.4	5.5	5.6	5.8
+ Eff. Inl. Eval	86.4	99.6	111.8	141.9	137.5	122.2	146.6	144.3	130.6	156.2	148.7	145.6	159.9	153.0	151.5	160.1	164.0	164.1
+ Eff. Inl. Post	2.5	2.8	3.7	4.4	4.2	4.1	5.2	5.2	5.3	5.5	5.3	5.5	5.8	5.7	5.8	5.9	6.3	6.3
HPM	**0.6**	**0.5**	**0.7**	**1.0**	**0.9**	**0.8**	**1.0**	**1.0**	**0.8**	**1.1**	**1.0**	**0.9**	**1.0**	**0.9**	**1.0**	**1.0**	**1.0**	**1.3**
ADV	**0.9**	1.1	**1.3**	**1.8**	**1.7**	**1.6**	2.0	2.0	1.8	2.3	2.0	2.1	2.4	2.3	2.3	2.4	2.5	2.5
PGM	14.8	11.4	11.6	12.4	12.3	12.5	12.1	12.1	11.9	11.8	12.0	11.8	12.0	12.1	12.3	12.0	11.8	11.8
Ours	**0.8**	**0.6**	**0.7**	**1.0**	**0.9**	**0.8**	**1.1**	**1.1**	**1.0**	**1.2**	**1.2**	**1.1**	**1.3**	**1.2**	**1.2**	**1.4**	**1.4**	**1.4**
+ Eff. Inl. Post	**0.8**	**0.7**	**0.8**	**1.1**	**1.0**	**0.9**	**1.2**	**1.2**	**1.1**	**1.4**	**1.3**	**1.2**	**1.4**	**1.3**	**1.4**	**1.5**	**1.5**	**1.6**

Table 7. Verification accuracy and efficiency measured on the Paris6k dataset using a vocabulary of 1M words.

	–	F100k	EU	US	EU+US	UK+EU+US	Ox+UK+EU+US	All
mAP [%]								
Pure Retrieval	70.2	60.1	55.5	54.0	50.7	49.0	48.1	47.8
FSM Aff	**72.2**	64.5	**60.1**	59.6	56.9	55.7	55.2	**54.9**
+ Eff. Inl. Eval	**72.4**	**64.9**	**60.6**	**60.1**	**57.5**	**56.3**	**55.7**	**55.4**
+ Eff. Inl. Post	72.1	**64.6**	60.0	59.6	56.9	55.6	55.0	**54.9**
FSM-R Aff	**72.2**	64.5	**60.1**	59.6	56.9	55.7	55.2	54.9
+ Eff. Inl. Eval	**72.3**	**64.7**	**60.4**	**59.9**	**57.3**	**56.1**	**55.5**	**55.2**
+ Eff. Inl. Post	72.0	64.5	59.8	59.4	56.7	55.4	54.9	54.7
FSM Sim	72.0	64.0	59.7	59.3	56.6	55.4	54.9	54.5
+ Eff. Inl. Eval	72.1	64.4	**60.1**	**59.8**	**57.0**	**55.8**	**55.3**	54.8
+ Eff. Inl. Post	71.9	64.0	59.5	59.2	56.5	55.2	54.7	54.3
FSM-R Sim	71.9	63.9	59.6	59.2	56.5	55.2	54.7	54.3
+ Eff. Inl. Eval	72.0	64.2	59.9	59.6	56.9	55.7	55.1	54.6
+ Eff. Inl. Post	71.8	63.8	59.3	59.0	56.2	55.0	54.5	54.0
HPM	70.0	60.5	54.8	54.4	50.9	49.5	48.8	48.5
ADV	69.4	61.9	58.5	58.3	55.7	54.3	53.8	53.4
PGM	69.9	59.7	54.7	53.1	49.8	48.0	47.3	46.9
Ours	71.5	63.4	58.6	58.2	55.5	54.4	53.8	53.6
+ Eff. Inl. Post	72.0	64.3	59.7	59.3	56.7	55.5	54.9	54.6
Runtime [s]								
FSM Aff	35.9	46.9	59.6	57.9	80.4	84.5	86.2	88.7
+ Eff. Inl. Eval	324.6	415.1	432.6	434.0	492.5	529.0	540.1	581.0
+ Eff. Inl. Post	35.9	47.2	60.2	58.8	81.7	84.2	88.1	89.9
FSM-R Aff	6.4	8.6	10.0	10.2	13.6	15.6	15.4	16.7
+ Eff. Inl. Eval	181.1	243.2	285.0	286.9	335.2	366.4	375.6	386.6
+ Eff. Inl. Post	6.6	8.9	10.4	10.6	14.2	16.1	16.4	17.6
FSM Sim	38.8	46.8	64.3	62.2	86.6	87.1	92.1	87.6
+ Eff. Inl. Eval	361.2	440.7	468.4	471.2	530.3	561.9	575.1	603.0
+ Eff. Inl. Post	39.2	48.4	64.6	63.1	88.3	88.9	91.0	88.5
FSM-R Sim	6.3	8.3	9.6	9.8	13.2	14.8	14.9	16.1
+ Eff. Inl. Eval	178.3	241.2	280.2	283.8	331.0	361.9	370.7	381.3
+ Eff. Inl. Post	6.5	8.6	10.1	10.3	13.9	15.6	15.7	17.0
HPM	**1.1**	**1.3**	**1.4**	**1.5**	**2.0**	**2.4**	**2.4**	**2.7**
ADV	2.0	2.7	3.2	3.1	4.3	4.9	5.2	5.3
PGM	15.5	15.1	15.1	14.9	15.0	15.7	15.5	15.3
Ours	**1.0**	**1.4**	**1.7**	**1.7**	**2.4**	**2.8**	**2.9**	**3.1**
+ Eff. Inl. Post	**1.2**	**1.7**	**2.1**	**2.1**	**2.7**	**3.2**	**3.1**	**3.5**

Table 8. Verification accuracy and efficiency measured on our new World5k dataset using a vocabulary of 1M words.

	–	EU	US	EU+US	UK+EU+US	Ox+UK+EU+US
mAP [%]						
Pure Retrieval	97.4	93.0	93.3	91.0	90.3	89.9
FSM Aff	**98.1**	**95.8**	**96.5**	**95.2**	**94.9**	**94.8**
+ Eff. Inl. Eval	**98.1**	**95.9**	**96.7**	**95.4**	**95.1**	**95.0**
+ Eff. Inl. Post	**98.0**	95.6	96.4	95.0	94.7	94.5
FSM-R Aff	**98.1**	**95.8**	**96.5**	**95.2**	**94.9**	**94.8**
+ Eff. Inl. Eval	**98.1**	**95.8**	**96.6**	**95.3**	**95.0**	**94.9**
+ Eff. Inl. Post	**97.9**	95.5	96.3	94.9	94.6	94.4
FSM Sim	**98.1**	**95.7**	**96.5**	95.1	94.8	94.6
+ Eff. Inl. Eval	**98.1**	**95.9**	**96.7**	**95.3**	**95.1**	**94.9**
+ Eff. Inl. Post	**97.9**	95.4	96.3	94.8	94.5	94.4
FSM-R Sim	**98.0**	95.6	96.4	95.0	94.7	94.6
+ Eff. Inl. Eval	**98.0**	**95.8**	**96.6**	**95.2**	**94.9**	**94.8**
+ Eff. Inl. Post	**97.9**	95.3	96.2	94.7	94.4	94.2
HPM	96.6	92.1	92.4	90.7	90.2	89.9
ADV	**97.9**	95.1	95.7	94.2	93.9	93.8
PGM	97.0	91.8	91.7	89.4	88.7	88.1
Ours	97.8	95.1	95.6	94.3	94.0	93.9
+ Eff. Inl. Post	97.8	95.3	96.0	94.8	94.5	94.3
Runtime [s]						
FSM Aff	197.3	292.2	282.7	374.3	382.1	383.1
+ Eff. Inl. Eval	2709.5	3543.6	3465.8	3879.3	4067.2	4185.8
+ Eff. Inl. Post	197.9	300.4	289.0	385.3	392.3	396.1
FSM-R Aff	38.3	61.4	61.3	85.6	91.5	93.6
+ Eff. Inl. Eval	1312.7	2079.1	2007.9	2356.2	2508.8	2599.1
+ Eff. Inl. Post	39.7	64.6	64.2	89.9	96.2	98.6
FSM Sim	216.9	322.8	309.9	418.8	423.0	420.4
+ Eff. Inl. Eval	2874.7	3702.7	3618.0	4032.9	4221.9	4332.6
+ Eff. Inl. Post	218.6	331.8	318.2	432.1	436.3	440.4
FSM-R Sim	37.9	59.4	59.3	82.8	88.3	90.7
+ Eff. Inl. Eval	1303.7	2055.8	1986.7	2325.2	2475.3	2563.4
+ Eff. Inl. Post	39.4	62.7	62.4	87.4	93.8	95.8
HPM	**6.4**	**9.7**	**9.8**	**12.0**	**12.7**	**13.5**
ADV	14.8	22.2	21.6	27.4	29.1	33.1
PGM	44.8	45.5	45.4	46.9	48.3	48.9
Ours	**6.3**	**11.0**	**10.6**	**13.2**	**13.9**	**15.0**
+ Eff. Inl. Post	**7.6**	**13.4**	**13.1**	**15.6**	**16.3**	**17.3**