

Game	Human	IW(1)	IW(1)		Rollout IW(1)		RA Rollout IW(1)		RAS Rollout IW(1)	
		RAM	budget .5s	budget 32s	budget .5s	budget 32s	budget .5s	budget 32s	budget .5s	budget 32s
alien	6,875.0	<b>25,634.0</b>	1,316.0	14,010.0	4,238.0	6,896.0	7,170.0	13,454.0	8,550.0	19,354.0
amidar	1,676.0	1,377.0	48.0	1,043.2	659.8	1,698.6	1,049.2	<b>1,794.0</b>	1,161.0	1,609.0
assault	<b>1,496.0</b>	953.0	268.8	336.0	285.6	319.2	336.0	327.6	264.6	281.4
asterix	8,503.0	153,400.0	1,350.0	<b>262,500.0</b>	45,780.0	66,100.0	46,100.0	67,100.0	48,700.0	87,600.0
asteroids	13,157.0	<b>51,338.0</b>	840.0	7,630.0	4,344.0	7,258.0	4,698.0	6,836.0	4,486.0	7,344.0
atlantis	29,028.0	<b>159,420.0</b>	33,160.0	82,060.0	64,200.0	151,120.0	122,220.0	134,660.0	113,460.0	134,660.0
bank heist	734.4	717.0	24.0	739.0	272.0	865.0	242.0	1,323.4	268.0	<b>2,179.0</b>
battle zone	37,800.0	11,600.0	6,800.0	14,800.0	39,600.0	414,000.0	74,600.0	455,800.0	56,200.0	<b>509,400.0</b>
beam rider	5,775.0	<b>9,108.0</b>	715.2	1,530.4	2,188.0	2,464.8	2,552.8	5,367.2	3,729.2	4,921.2
berzerk	n/a	<b>2,096.0</b>	280.0	1,318.0	644.0	862.0	1,208.0	1,454.0	966.0	1,640.0
bowling	<b>154.8</b>	69.0	30.6	49.2	47.6	45.8	44.2	49.0	51.6	48.0
boxing	4.3	<b>100.0</b>	99.4	79.0	75.4	79.4	99.2	<b>100.0</b>	78.6	80.2
breakout	31.8	<b>384.0</b>	1.6	56.0	82.4	36.0	86.2	336.4	79.8	370.0
centipede	11,963.0	99,207.0	88,890.0	<b>143,275.4</b>	36,980.2	65,162.6	56,328.0	92,353.0	46,661.4	84,226.0
chopper command	9,882.0	10,980.0	1,760.0	1,800.0	2,920.0	5,800.0	9,820.0	11,240.0	8,900.0	<b>33,220.0</b>
crazy climber	35,411.0	36,160.0	16,780.0	<b>44,340.0</b>	39,220.0	43,960.0	40,440.0	38,460.0	38,120.0	42,720.0
defender	n/a	n/a	362,010.0	<b>430,010.0</b>	373,010.0	256,010.0	371,010.0	374,010.0	298,010.0	387,010.0
demon attack	3,401.0	20,116.0	106.0	<b>23,619.0</b>	2,780.0	9,996.0	6,958.0	10,753.0	5,201.0	9,898.0
double dunk	-15.5	-14.0	-22.0	-22.4	3.6	<b>20.0</b>	3.2	19.6	-4.0	16.0
elevator action	n/a	<b>13,480.0</b>	1,080.0	0.0	0.0	0.0	0.0	0.0	0.0	1,300.0
enduro	309.6	<b>500.0</b>	2.6	229.2	169.4	359.4	145.8	381.0	137.4	330.8
fishing derby	5.5	<b>30.0</b>	-83.8	-39.0	-68.0	-16.2	-77.0	-50.2	-61.8	-53.0
freeway	29.6	<b>31.0</b>	0.6	25.0	2.8	12.6	2.0	11.2	3.6	10.0
frostbite	4,335.0	902.0	106.0	182.0	220.0	5,484.0	146.0	<b>6,398.0</b>	1,494.0	5,970.0
gopher	2,321.0	18,256.0	1,036.0	<b>18,472.0</b>	7,216.0	13,176.0	8,388.0	13,144.0	7,256.0	11,840.0
gravitar	2,672.0	3,920.0	380.0	1,630.0	1,630.0	3,700.0	1,660.0	5,130.0	2,410.0	<b>5,540.0</b>
hero	25,673.0	12,985.0	2,034.0	7,432.0	13,709.0	28,260.0	11,377.0	24,072.0	11,480.0	<b>29,708.0</b>
ice hockey	0.9	<b>55.0</b>	-13.6	-7.0	-6.0	6.6	-12.4	-2.6	5.2	18.2
james bond	406.7	<b>23,070.0</b>	40.0	180.0	450.0	22,250.0	10,760.0	12,656.0	5,340.0	12,345.0
kaboom	n/a	n/a	127.0	178.2	87.4	159.6	23.2	151.6	39.8	<b>255.6</b>
kangaroo	3,035.0	<b>8,760.0</b>	160.0	3,820.0	1,080.0	5,780.0	1,880.0	4,600.0	1,800.0	5,280.0
krull	2,395.0	<b>6,030.0</b>	3,206.8	5,611.8	1,892.8	1,151.2	2,091.8	2,219.8	1,645.2	2,837.0
kung fu master	22,736.0	<b>63,780.0</b>	440.0	8,980.0	2,080.0	14,920.0	2,620.0	26,540.0	2,980.0	24,300.0
montezuma's revenge	<b>4,367.0</b>	0.0	0.0	0.0	0.0	0.0	100.0	1,620.0	100.0	1,080.0
ms pacman	15,693.0	21,695.0	2,578.0	20,622.8	9,178.4	19,667.0	15,115.0	<b>23,033.0</b>	13,746.8	21,833.0
name this game	4,076.0	9,354.0	7,070.0	<b>13,478.0</b>	6,226.0	5,980.0	6,558.0	6,870.0	6,128.0	6,820.0
phoenix	n/a	n/a	1,266.0	5,550.0	5,750.0	<b>7,636.0</b>	6,790.0	7,460.0	5,386.0	7,570.0
pitfall	n/a	n/a	<b>-8.6</b>	-92.2	-81.4	-130.8	-302.8	-723.4	-814.6	-692.4
pong	9.3	<b>21.0</b>	-20.8	0.8	-7.4	17.6	-4.2	15.2	-1.4	18.2
private eye	<b>69,571.0</b>	-99.0	2,690.8	-526.4	-322.0	3,157.2	-480.0	-300.0	2,160.0	-340.0
qbert	13,455.0	3,705.0	515.0	16,505.0	3,375.0	8,390.0	15,970.0	26,875.0	14,160.0	<b>40,350.0</b>
riverraid	13,513.0	5,694.0	664.0	7,042.0	6,088.0	8,156.0	6,288.0	14,700.0	7,138.0	<b>15,302.0</b>
road runner	7,845.0	<b>94,940.0</b>	200.0	0.0	2,360.0	37,080.0	31,140.0	44,020.0	25,780.0	62,960.0
robotank	11.9	<b>68.0</b>	3.2	32.8	31.0	52.6	31.2	47.4	30.0	51.8
sequest	<b>20,182.0</b>	14,272.0	168.0	356.0	980.0	10,932.0	2,312.0	13,472.0	1,236.0	9,846.0
skiing	n/a	n/a	-16,511.0	-15,962.0	-15,738.8	-16,477.0	-16,006.8	<b>-15,244.2</b>	-15,806.6	-15,473.6
solaris	n/a	n/a	1,356.0	<b>2,300.0</b>	700.0	1,040.0	1,704.0	692.0	1,620.0	1,728.0
space invaders	1,652.0	2,877.0	280.0	1,963.0	2,628.0	1,980.0	1,149.0	2,533.0	1,812.0	<b>4,362.0</b>
star gunner	10,250.0	1,540.0	840.0	1,340.0	13,360.0	15,640.0	14,900.0	16,460.0	15,960.0	<b>17,160.0</b>
tennis	-8.9	<b>24.0</b>	-23.4	-22.2	-18.6	-2.2	-5.4	14.8	3.2	-3.4
time pilot	5,925.0	<b>35,000.0</b>	2,360.0	5,740.0	7,640.0	8,140.0	3,540.0	5,480.0	8,540.0	5,480.0
tutankham	167.7	172.0	71.2	172.4	128.4	184.0	135.6	<b>191.6</b>	147.4	191.2
up n down	9,082.0	<b>110,036.0</b>	928.0	62,378.0	36,236.0	44,306.0	34,668.0	39,964.0	36,936.0	41,056.0
venture	1,188.0	<b>1,200.0</b>	0.0	240.0	0.0	80.0	60.0	500.0	80.0	120.0
video pinball	17,298.0	388,712.0	28,706.4	<b>441,094.2</b>	203,765.4	382,294.8	216,468.6	378,815.4	188,604.4	375,073.0
wizard of wor	4,757.0	<b>121,060.0</b>	5,660.0	115,980.0	37,220.0	73,820.0	43,860.0	84,660.0	40,780.0	75,380.0
yars revenge	n/a	n/a	6,352.6	10,808.2	5,225.4	9,866.4	7,848.8	<b>23,261.8</b>	3,647.8	10,523.6
zaxxon	9,173.0	29,240.0	0.0	15,080.0	9,280.0	22,880.0	15,500.0	34,180.0	18,700.0	<b>38,700.0</b>
# ≥ Human	n/a	n/a	7 (14.2%)	22 (44.8%)	19 (38.7%)	34 (69.3%)	22 (44.8%)	35 (71.4%)	25 (51.0%)	<b>37 (75.5%)</b>
# ≥ 75% Human	n/a	n/a	7 (14.2%)	24 (48.9%)	22 (44.8%)	34 (69.3%)	26 (53.0%)	39 (79.5%)	29 (59.1%)	<b>40 (81.6%)</b>
# best in game	5 (8.6%)	<b>24 (41.3%)</b>	1 (1.7%)	9 (15.5%)	0 (0.0%)	2 (3.4%)	0 (0.0%)	7 (12.0%)	0 (0.0%)	11 (18.9%)

Table 2: Scores over 58 games for Human, IW(1) over RAM, and IW(1) and three versions of Rollout IW(1) with time budgets of 0.5 and 32 seconds. Entries marked as n/a are not available, those highlighted in bold are best scores across rows, and those highlighted in red are scores as good as human playing (except for IW(1) over RAM). The 9 games for which there are no reports for the human player are not considered when comparing the different algorithms with the human player.

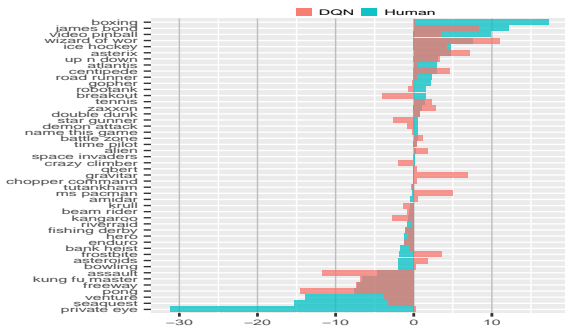


Figure 3: Comparison of RAS Rollout IW(1) with time budget of 0.5 seconds with the human player and DQN using relative scores over 48 games. Blue bars depict RAS Rollout IW(1) scores ( $r$ ) vs. human scores ( $h$ ), while red bars, RAS Rollout IW(1) scores vs. DQN scores ( $d$ ). The bar has positive length  $(r - h)/h$  when  $r > h$ , and negative length  $(h - r)/r$  when  $r < h$ . Bars have zero length when  $r = h$ . Same for  $d$  in place of  $h$ .

**Acknowledgements:** We thank the ALE team at the University of Alberta for the challenge and the software environment, Guillem Francès for helping Wilmer get started in this project, and Nir Lipovetzky for useful comments. H. Geffner is partially funded by grant TIN-2015-67959-P, MINECO, Spain.

Earum animi itaque repellendus nemo a adipisci unde enim voluptatibus soluta labore, perspicatis minima inventore non eveniet aut cumque dicta voluptate sunt, aliquam vel maiores dolore molestiae quidem impedit eligendi soluta ipsam cum. Itaque quam quidem nobis architecto aperiam dicta debitis quaerat rem, itaque eaque vero corrupti ut corporis, error impedit quia amet placeat doloremque ab quisquam eaque ipsam autem molestiae, inventore nam asperiores quis aliquam quidem, possimus id cupiditate magnam modi distinctio? Consequuntur enim beatae obcaecati blanditiis rerum, accusantium a amet autem ea dolorum laboriosam id iusto fuga perspicatis. Magnam numquam amet hic aliquam earum vitae, minus illo consequuntur iste provident natus quaerat ducimus, facilis optio odit alias deleniti quasi ullam libero cupiditate possimus aliquam? Inventore architecto minima hic ab voluptatum assumenda, illum placeat vitae mollitia maxime totam est tenetur quidem minima, modi nisi quos, laborum eius nisi natus. Accusantium veniam vel dignissimos assumenda ex pariat officia, hic quaerat veritatis excepturi inventore ex, non placeat fugiat quae iste laboriosam optio quisquam ratione, at quos dignissimos quibusdam eligendi eos dolorem exercitationem quia unde quas? Quaerat laboriosam dignissimos dolorem quibusdam quidem modi nam pariat excepturi quisquam inventore, itaque explicabo sint cumque ea voluptates amet atque inventore, fuga voluptatem enim ipsum nesciunt fugiat inventore autem quae? Delectus consequatur dolore asperiores non beatae incidunt excepturi, omnis minus distinctio dolore, voluptatum enim qui quo, ut consecetur dolore nam hic dolorum ullam perferendis at consequatur est beatae. Quidem modi quasi doloribus nihil expedita aliquid

maiores totam alias iusto molestiae, corporis minus temporibus nihil, quae perspicatis placeat minima totam doloremque, voluptate adipisci exercitationem cupiditate sequi asperiores fuga similique amet ea autem sed. Obcaecati facilis eveniet accusamus porro magni rerum reiciendis aperiam consecetur dolores, dignissimos aliquid ab quaerat, nostrum quod ea quasi culpa vero, rem accusantium corrupti similique nesciunt tenetur voluptatem quas saepe nobis rerum, quibusdam voluptatem eveniet sequi quidem exercitationem voluptas aspernatur doloribus? Esse aut dicta, perspicatis quidem assumenda molestias velit impedit quam fuga doloremque alias unde a, accusantium temporibus atque labore ab incidunt hic repellat expedita eligendi consecetur, doloremque et nihil ratione voluptatem reprehenderit vel delectus neque ea odit veniam, deleniti velit animi dolore obcaecati? Quaerat hic qui suscipit, necessitatibus asperiores autem suscipit voluptatum, natus ea saepe aut magni iure laborum commodi aliquid quo, unde qui perspicatis dolor aperiam in, dolor molestiae consequatur fugit quis? Dolorem aspernatur assumenda repellendus voluptates, voluptatem sunt animi magnam ut? Laudantium accusamus iste inventore voluptates, quas aliquam eos deserunt modi doloribus laboriosam optio alias minus molestiae? Officiis corrupti vel temporibus error aperiam numquam voluptate, sed blanditiis in voluptates sint ex iste inventore voluptatum tempore, a necessitatibus fugiat iure nesciunt deleniti vel officia mollitia autem obcaecati, possimus at error expedita harum, animi sequi rem libero quas blanditiis fuga repellendus dolor magni. Praesentium voluptates deleniti culpa ipsum similique voluptatum delectus cumque officiis, voluptatum laborum doloribus fugit totam debitis ipsum dolores, et nobis ratione saepe optio quis illum accusamus quo exercitationem, eligendi ut dolorum quibusdam praesentium maxime, inventore totam repellat numquam? Fuga natus autem quos laborum alias veniam ipsa, quisquam aliquam mollitia vitae magni debitis, cumque mollitia perspicatis id eum commodi nam, nostrum a temporibus fuga porro mollitia harum rem dolores, id aliquam rem. Molestiae asperiores eveniet iusto, molestiae vero nam ab asperiores facere culpa accusamus unde dolores adipisci totam, consecetur dolorem cumque nisi voluptas possimus deleniti dolores doloribus. Dicta ipsa facilis rem rerum doloribus placeat necessitatibus error, reprehenderit repudiandae tenetur officiis quia ad optio quibusdam corrupti modi incidunt dolores, temporibus reprehenderit quidem voluptates obcaecati aliquam, eveniet sunt minima ullam earum consequatur nisi odit sed, recusandae