

| 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 | 25,634.0 | 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 | 1,794.0 | 1,161.0 | 1,609.0 |
| assault | 1,496.0 | 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 | 262,500.0 | 45,780.0 | 66,100.0 | 46,100.0 | 67,100.0 | 48,700.0 | 87,600.0 |
| asteroids | 13,157.0 | 51,338.0 | 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 | 159,420.0 | 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 | 2,179.0 |
| 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 | 509,400.0 |
| beam rider | 5,775.0 | 9,108.0 | 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 | 2,096.0 | 280.0 | 1,318.0 | 644.0 | 862.0 | 1,208.0 | 1,454.0 | 966.0 | 1,640.0 |
| bowling | 154.8 | 69.0 | 30.6 | 49.2 | 47.6 | 45.8 | 44.2 | 49.0 | 51.6 | 48.0 |
| boxing | 4.3 | 100.0 | 99.4 | 79.0 | 75.4 | 79.4 | 99.2 | 100.0 | 78.6 | 80.2 |
| breakout | 31.8 | 384.0 | 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 | 143,275.4 | 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 | 33,220.0 |
| crazy climber | 35,411.0 | 36,160.0 | 16,780.0 | 44,340.0 | 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 | 430,010.0 | 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 | 23,619.0 | 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 | 20.0 | 3.2 | 19.6 | -4.0 | 16.0 |
| elevator action | n/a | 13,480.0 | 1,080.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1,300.0 |
| enduro | 309.6 | 500.0 | 2.6 | 229.2 | 169.4 | 359.4 | 145.8 | 381.0 | 137.4 | 330.8 |
| fishing derby | 5.5 | 30.0 | -83.8 | -39.0 | -68.0 | -16.2 | -77.0 | -50.2 | -61.8 | -53.0 |
| freeway | 29.6 | 31.0 | 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 | 6,398.0 | 1,494.0 | 5,970.0 |
| gopher | 2,321.0 | 18,256.0 | 1,036.0 | 18,472.0 | 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 | 5,540.0 |
| 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 | 29,708.0 |
| ice hockey | 0.9 | 55.0 | -13.6 | -7.0 | -6.0 | 6.6 | -12.4 | -2.6 | 5.2 | 18.2 |
| james bond | 406.7 | 23,070.0 | 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 | 255.6 |
| kangaroo | 3,035.0 | 8,760.0 | 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 | 6,030.0 | 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 | 63,780.0 | 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 | 4,367.0 | 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 | 23,033.0 | 13,746.8 | 21,833.0 |
| name this game | 4,076.0 | 9,354.0 | 7,070.0 | 13,478.0 | 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 | 7,636.0 | 6,790.0 | 7,460.0 | 5,386.0 | 7,570.0 |
| pitfall | n/a | n/a | -8.6 | -92.2 | -81.4 | -130.8 | -302.8 | -723.4 | -814.6 | -692.4 |
| pong | 9.3 | 21.0 | -20.8 | 0.8 | -7.4 | 17.6 | -4.2 | 15.2 | -1.4 | 18.2 |
| private eye | 69,571.0 | -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 | 40,350.0 |
| riveraid | 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 | 15,302.0 |
| road runner | 7,845.0 | 94,940.0 | 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 | 68.0 | 3.2 | 32.8 | 31.0 | 52.6 | 31.2 | 47.4 | 30.0 | 51.8 |
| sequest | 20,182.0 | 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 | -15,244.2 | -15,806.6 | -15,473.6 |
| solaris | n/a | n/a | 1,356.0 | 2,300.0 | 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 | 4,362.0 |
| 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 | 17,160.0 |
| tennis | -8.9 | 24.0 | -23.4 | -22.2 | -18.6 | -2.2 | -5.4 | 14.8 | 3.2 | -3.4 |
| time pilot | 5,925.0 | 35,000.0 | 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 | 191.6 | 147.4 | 191.2 |
| up n down | 9,082.0 | 110,036.0 | 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 | 1,200.0 | 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 | 441,094.2 | 203,765.4 | 382,294.8 | 216,468.6 | 378,815.4 | 188,604.4 | 375,073.0 |
| wizard of wor | 4,757.0 | 121,060.0 | 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 | 23,261.8 | 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 | 38,700.0 |
| # ≥ 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%) | 37 (75.5%) |
| # ≥ 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%) | 40 (81.6%) |
| # best in game | 5 (8.6%) | 24 (41.3%) | 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.

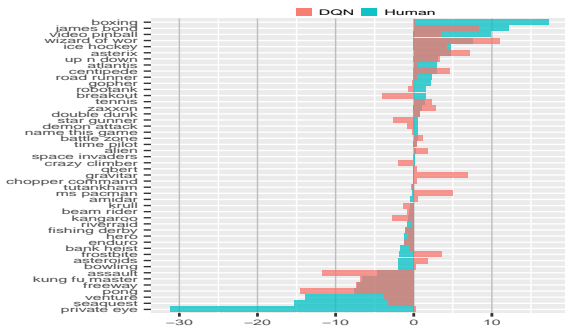


Figure 3: Comparison of RAS Rollout IW(1) with time budget of 0.5 seconds with the human player and DQN using relative scores over 48 games. Blue bars depict RAS Rollout IW(1) scores (r) vs. human scores (h), while red bars, RAS Rollout IW(1) scores vs. DQN scores (d). The bar has positive length $(r - h)/h$ 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 .

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