

Should we use Neuron Coverage as a Test Adequacy Criterion? The Deep Reinforcement Learning Case

ABSTRACT

Recent increase in use of RL, and specifically DRL, in real-world scenarios is increasing the need for an approach to systematic software testing of DRL-based applications. Multiple approaches to testing DNN, an integral part of DRL, have been proposed, but their applicability to DRL has not been investigated. Specifically, neuron coverage in DNN is accepted to be a valid test adequacy metric, as in DNN more extensive coverage allows the network to train for edge cases. In this study, we investigate whether neuron coverage is a suitable metric for DRL testing approaches. As DRL relies on the environment reward to infer the desired behavior, we evaluate whether neuron coverage could be considered an adequate metric, if it is correlated with the rewards obtained by the DRL system. To that effect, we investigate the relationship between multiple aspects of neuron coverage and the rewards in 19 different DRL applications, selected to cover the range of DNN architectures and reward models. We found no evidence of correlation between neuron coverage and higher rewards in DRL, suggesting that in DRL neuron coverage alone cannot be considered a suitable metric for test adequacy.

THE MOUNTAIN CAR PROBLEM

branavg model

Input	Input Shape: (2,2)
Layer 1	Layer Shape: (20,2)
<i>Layer 2 Flatten</i>	Layer Shape: (40)
Layer 3	Layer Shape: (18)
Layer 4	Layer Shape: (10)
Layer 5	Layer Shape: (3)

Figure 1. Network architecture of branavg model

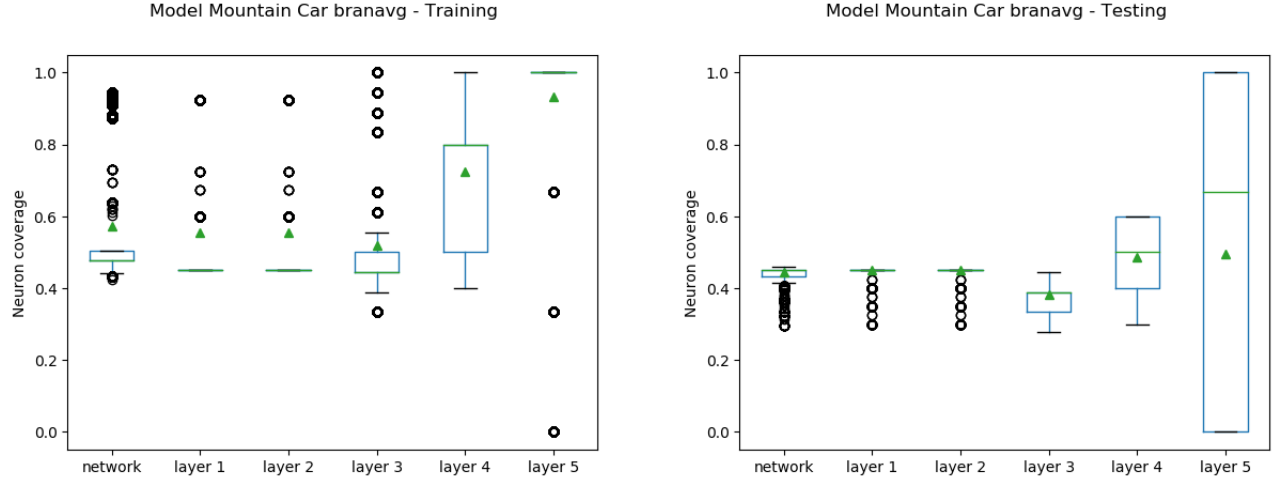


Figure 2. Distribution of cumulative coverage for branavg model during training and testing phase on MC

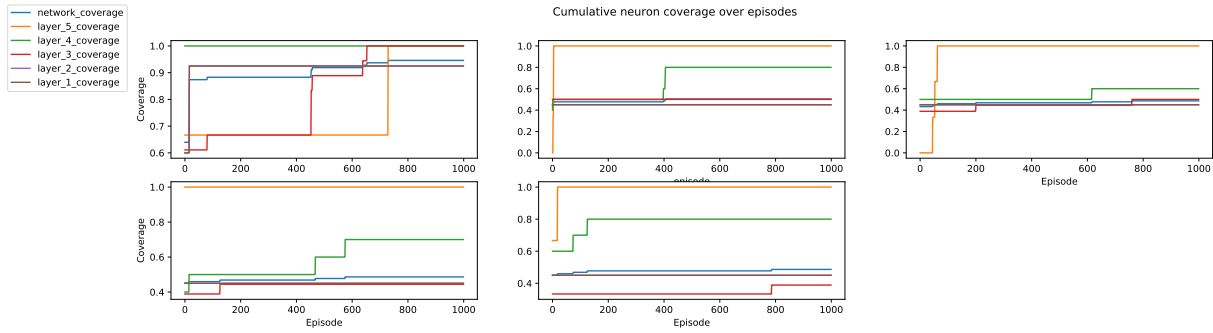


Figure 3. CNC and CNCL over episodes for branavg model during training phase on MC

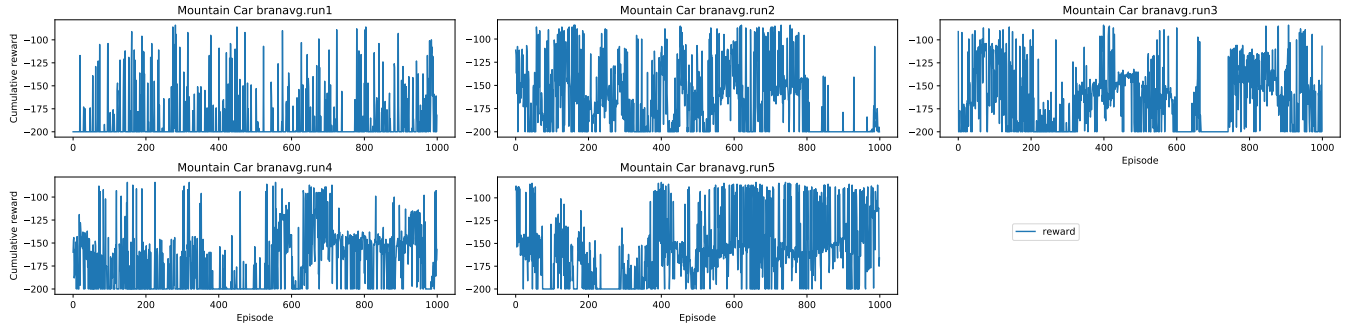


Figure 4. Cumulative reward over episodes for branavg model during training phase on MC

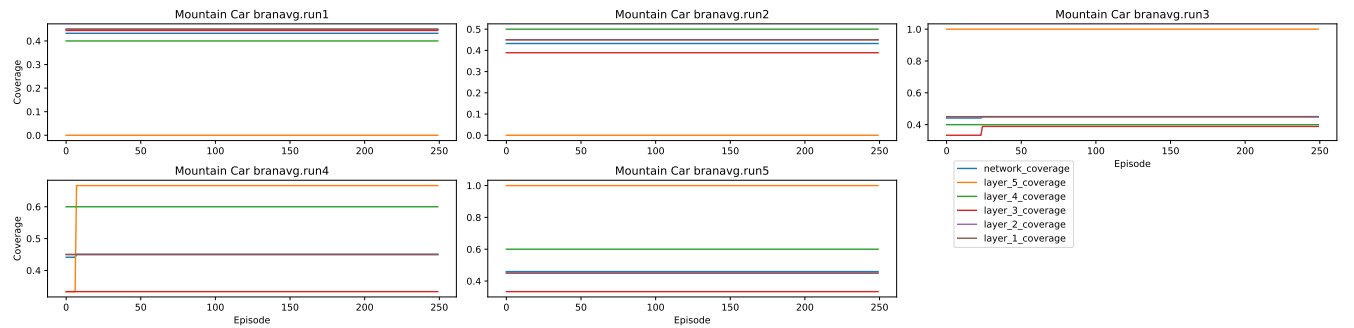


Figure 5. CNC and CNCL over episodes for branavg model during testing phase on MC

Harshitandro model

Input	Input Shape: (2)
Layer 1:	Layer Shape: 256
Layer 2:	Layer Shape: 256
Layer 3:	Layer Shape: 2

Figure 6. Network architecture of harshitandro model

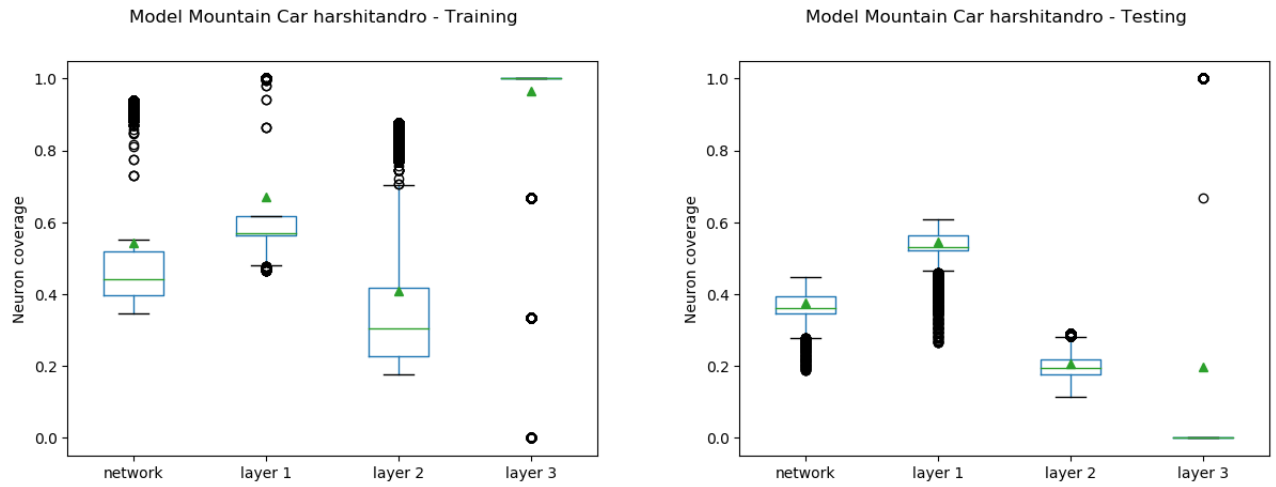


Figure 7. Distribution of cumulative coverage for harshitandro model during training and testing phase on MC

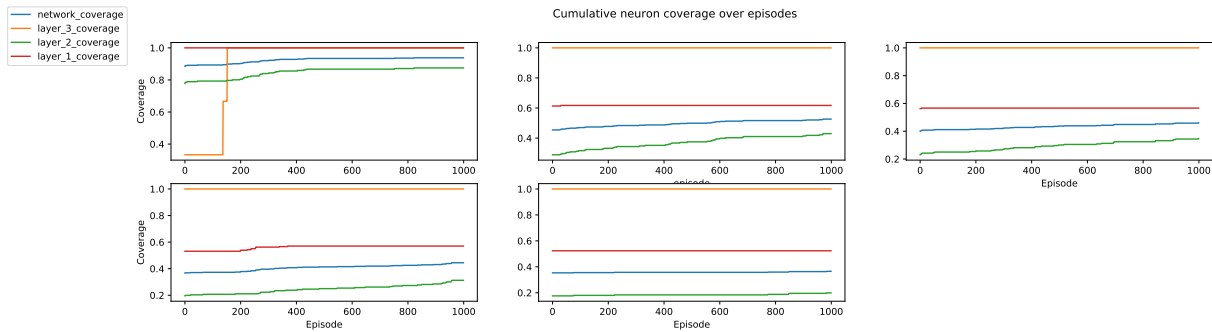


Figure 8. CNC and CNCL over episodes for harshitandro model during training phase on MC

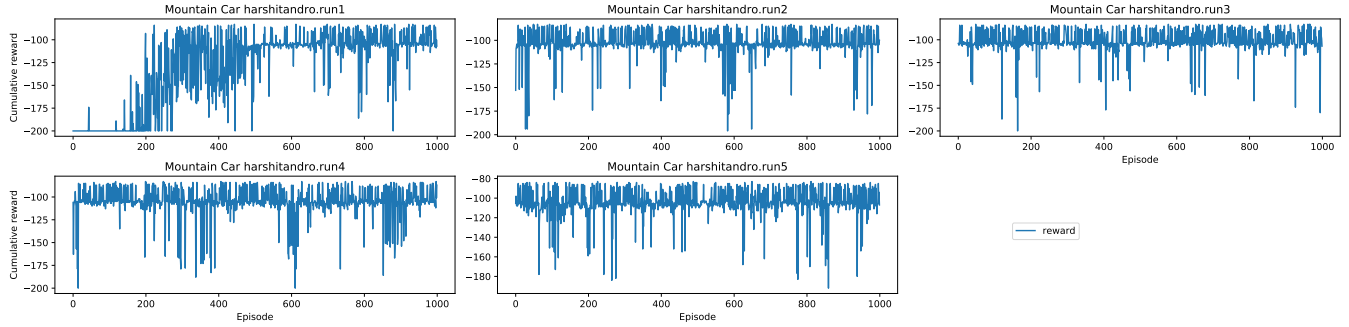


Figure 9. Cumulative reward over episodes for harshitandro model during training phase on MC

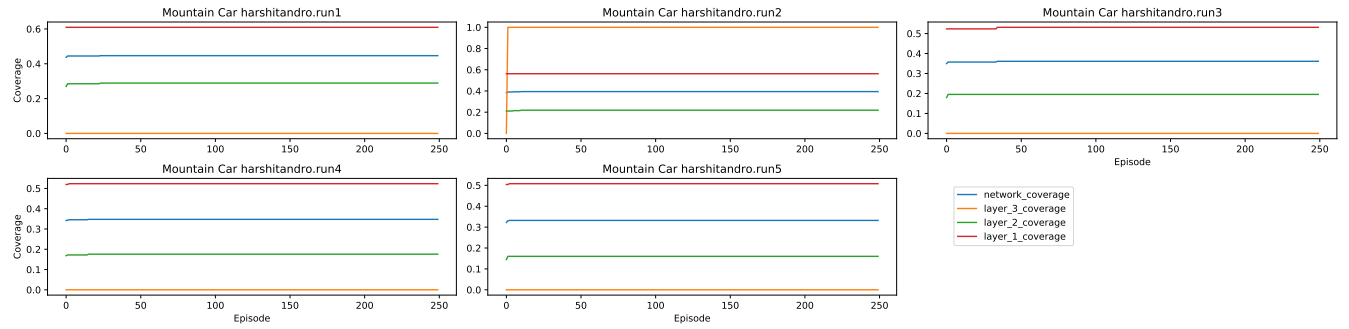


Figure 10. CNC and CNCL over episodes for harshitandro model during testing phase on MC

Kxl4126 model

Input	Input Shape: (2)
Layer 1:	Layer Shape: 64
Layer 2:	Layer Shape: 64
Layer 3:	Layer Shape: 32
Layer 4:	Layer Shape: 3

Figure 11. Network architecture of kxl4126 model

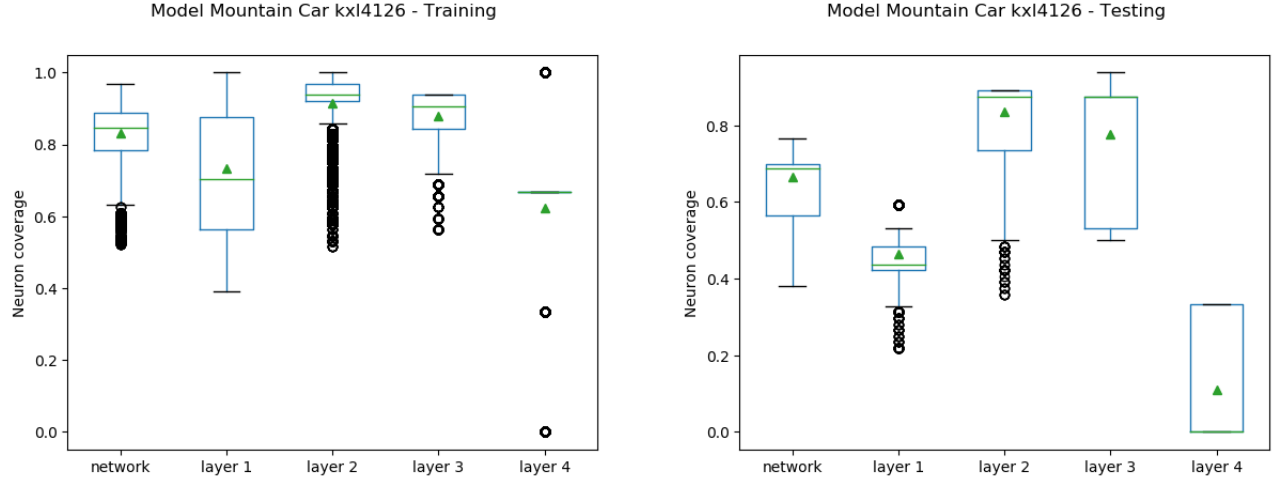


Figure 12. Distribution of cumulative coverage for kxl4126 model during training and testing phase on MC

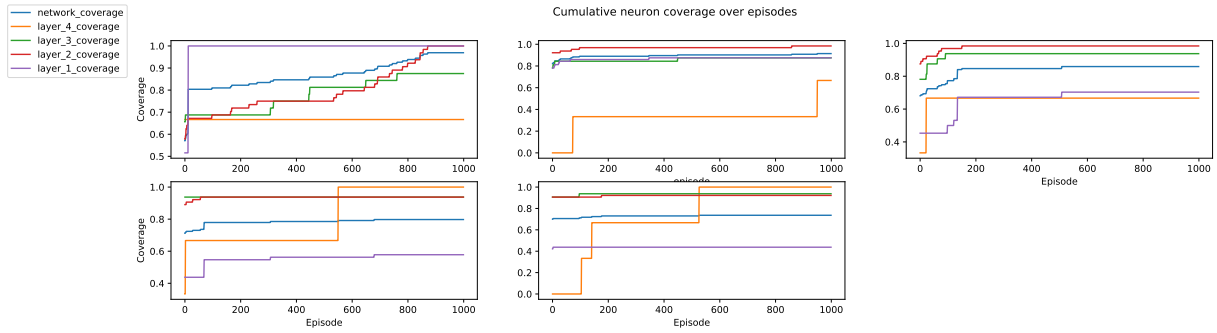


Figure 13. CNC and CNCL over episodes for kxl4126 model during training phase on MC

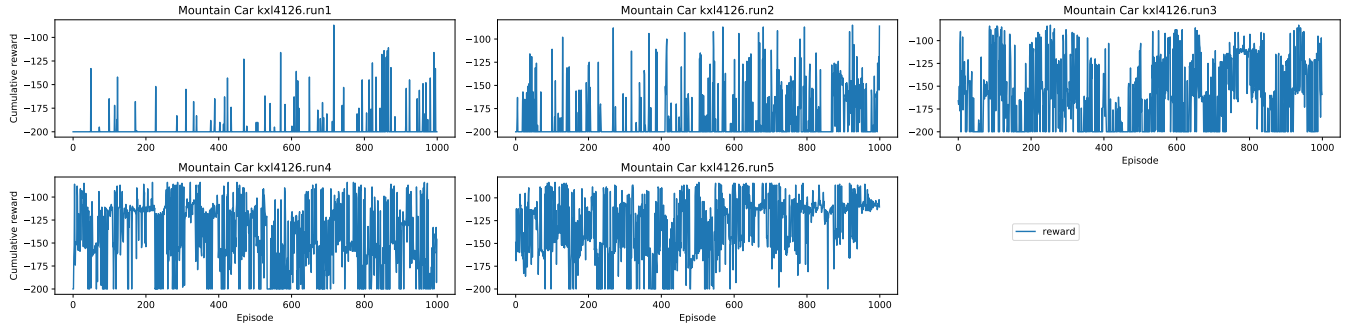


Figure 14. Cumulative reward over episodes for kxl4126 model during training phase on MC

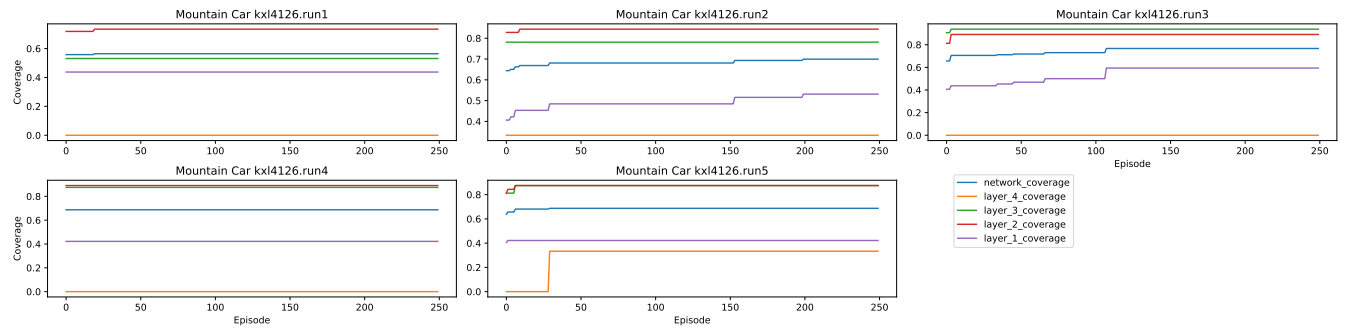


Figure 15. CNC and CNCL over episodes for kxl4126 model during testing phase on MC

MLnewlifer model

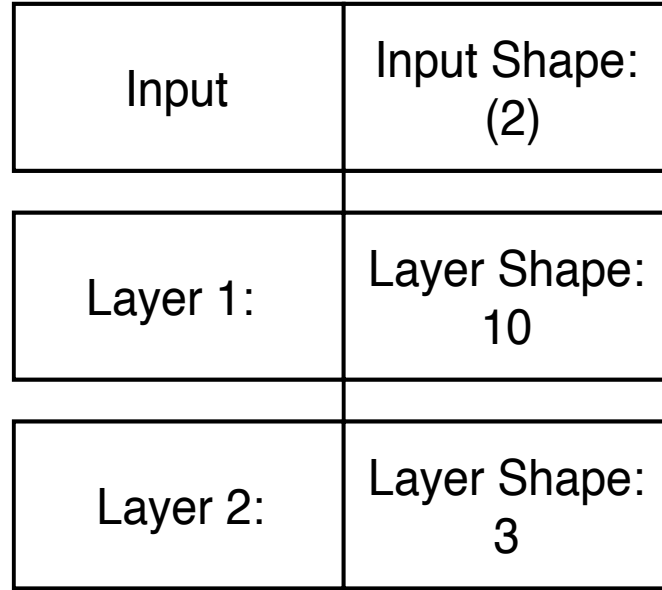


Figure 16. Network architecture of MLnewlifer model

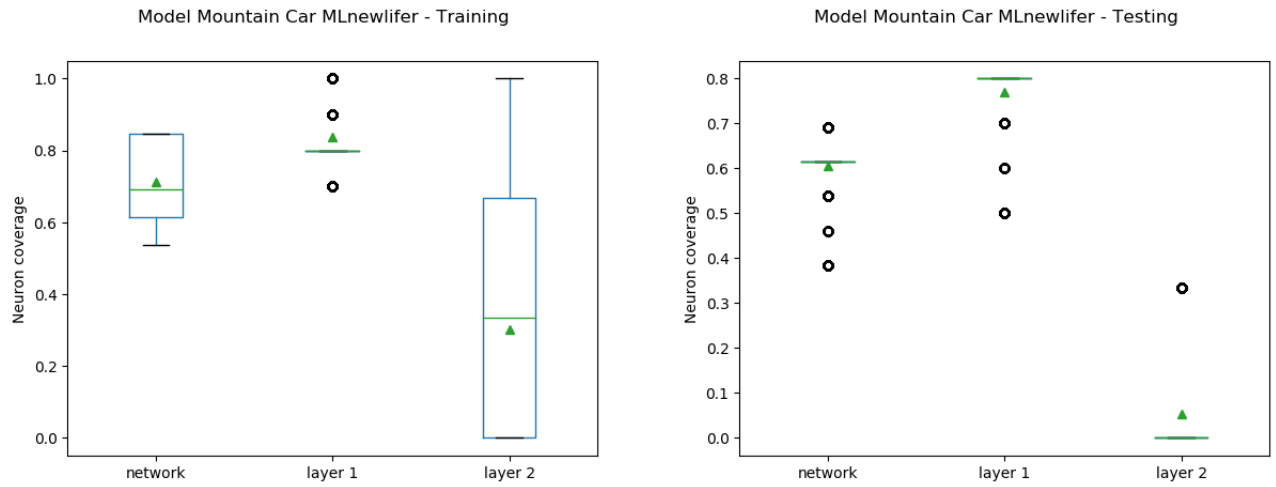


Figure 17. Distribution of cumulative coverage for MLnewlifer model during training and testing phase on MC

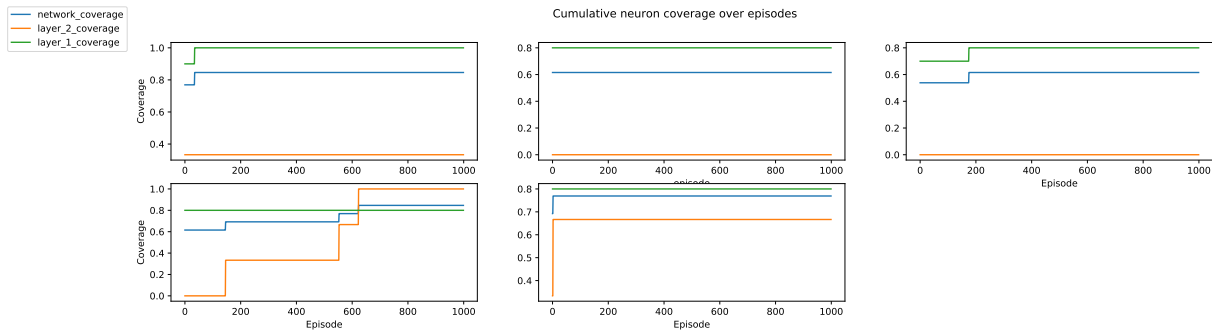


Figure 18. CNC and CNCL over episodes for MLnewlifer model during training phase on MC

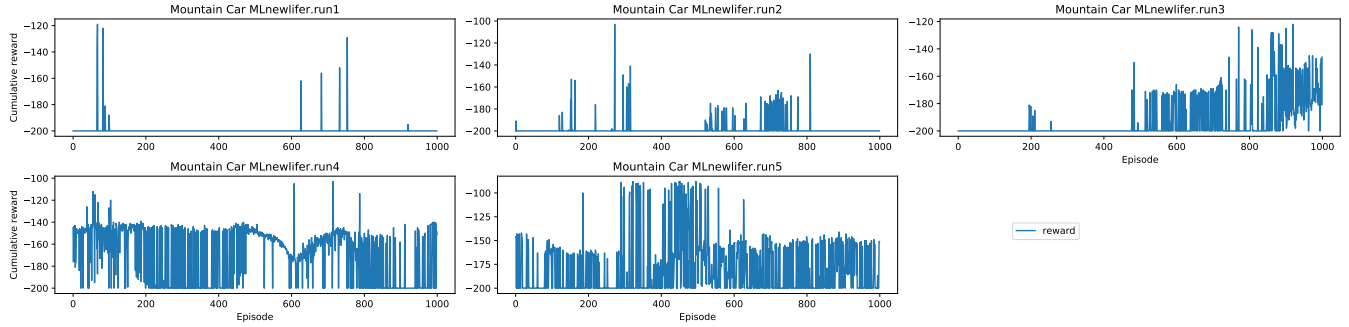


Figure 19. Cumulative reward over episodes for MLnewlifer model during training phase on MC

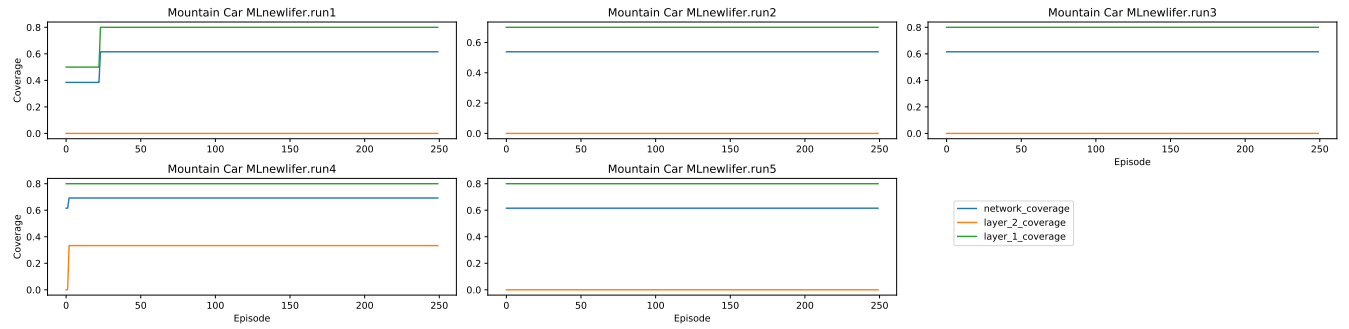


Figure 20. CNC and CNCL over episodes for MLnewlifer model during testing phase on MC

PylSER model

Input	Input Shape: (2)
Layer 1:	Layer Shape: 24
Layer 2:	Layer Shape: 48
Layer 3:	Layer Shape: 3

Figure 21. Network architecture of pylSER model

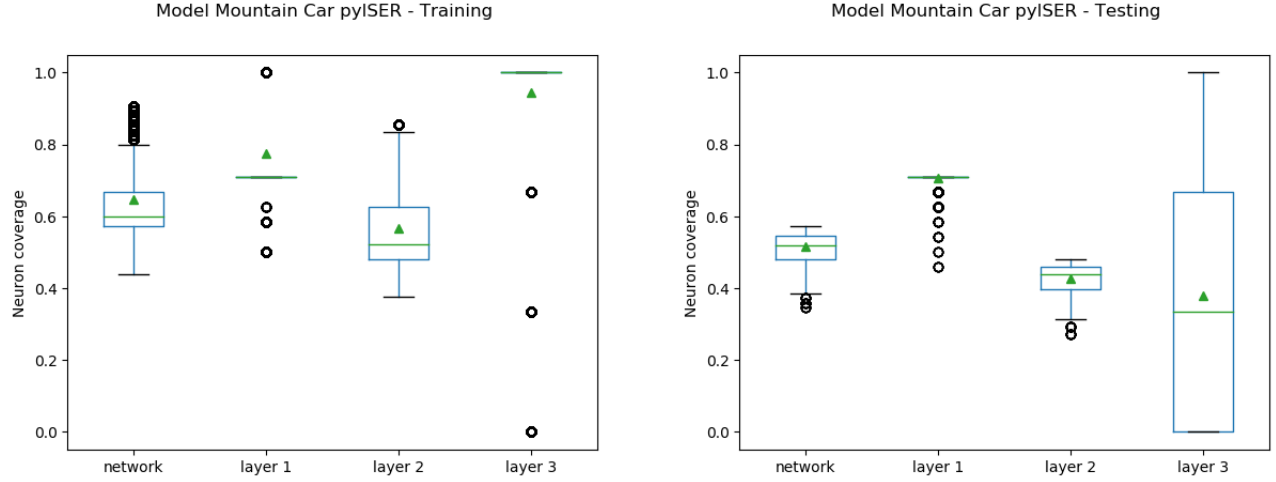


Figure 22. Distribution of cumulative coverage for pylSER model during training and testing phase on MC

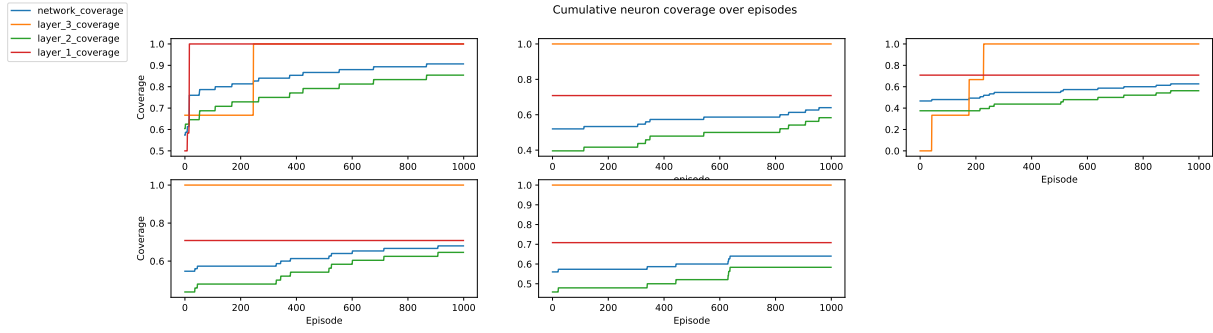


Figure 23. CNC and CNCL over episodes for pylSER model during training phase on MC

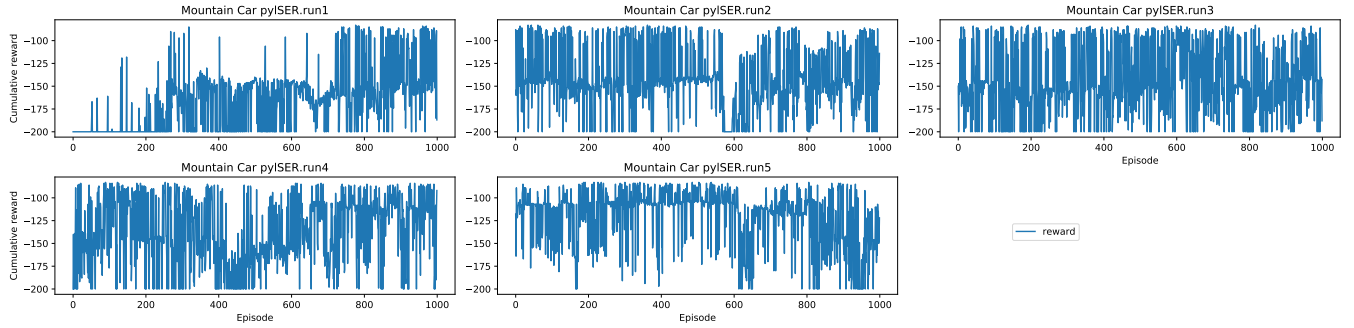


Figure 24. Cumulative reward over episodes for pylSER model during training phase on MC

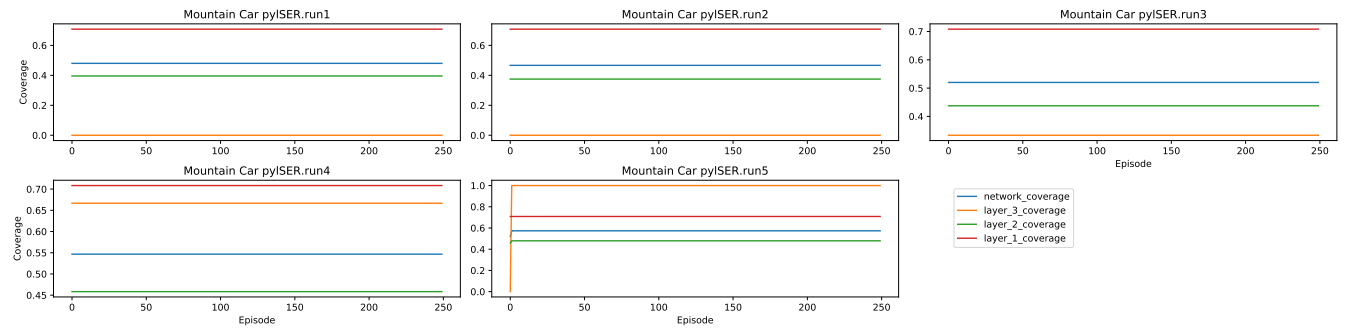


Figure 25. CNC and CNCL over episodes for pylSER model during testing phase on MC

THE MOUNTAIN CAR PROBLEM WITH CONTINUOUS REWARD

branavg model

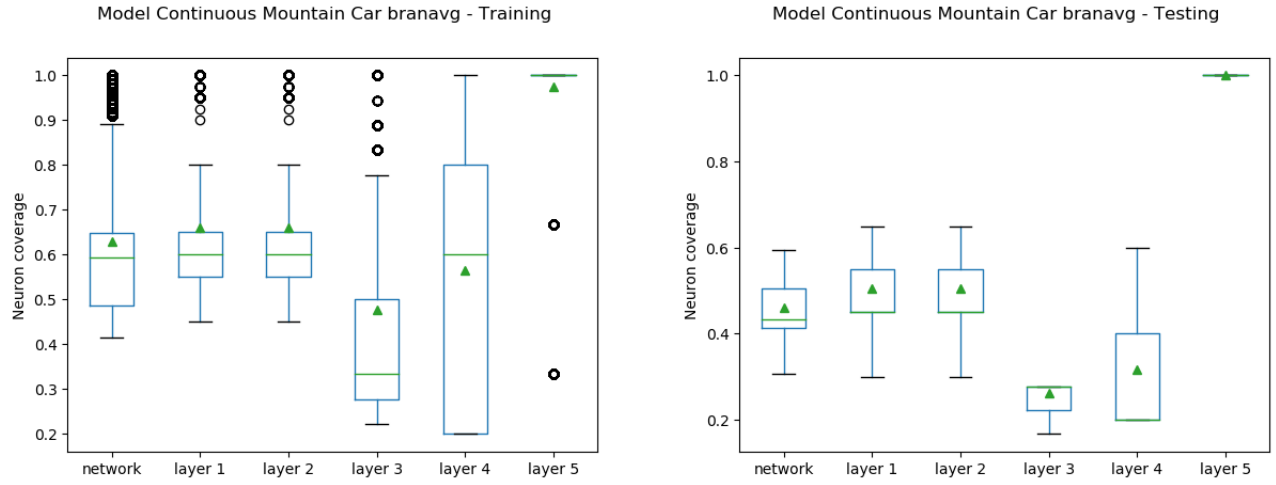


Figure 26. Distribution of cumulative coverage for branavg model during training and testing phase on MC with continuous reward

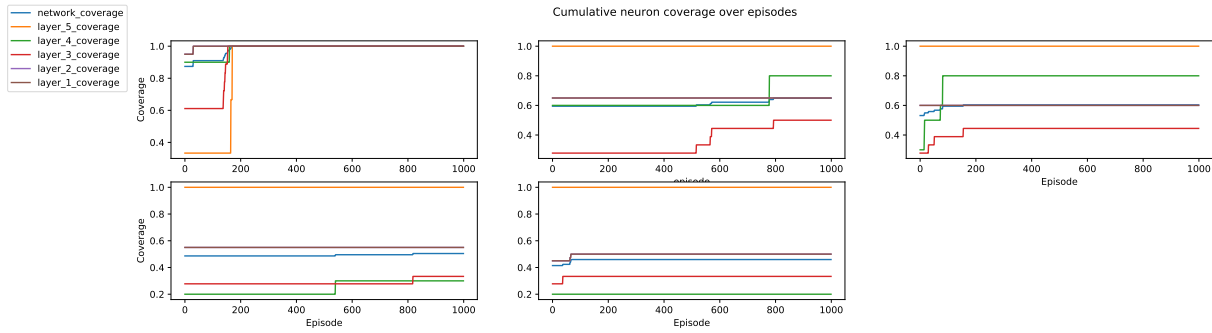


Figure 27. CNC and CNCL over episodes for branavg model during training phase on MC with continuous reward

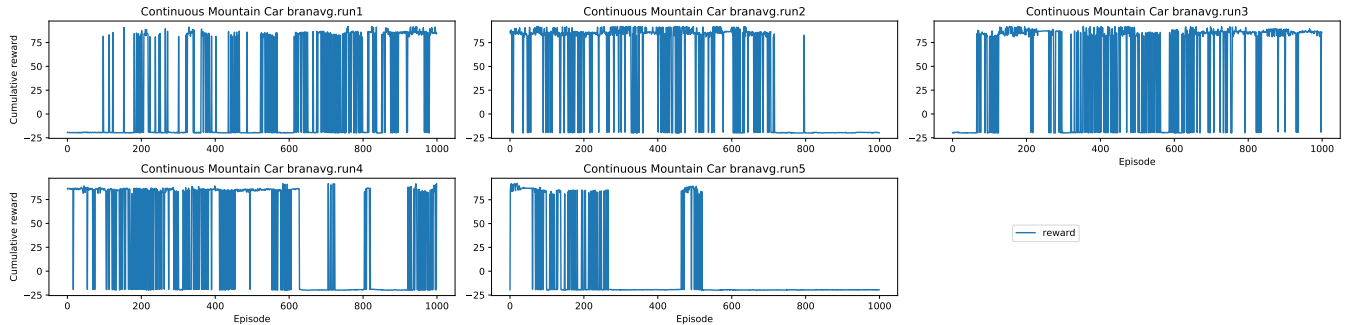


Figure 28. Cumulative reward over episodes for branavg model during training phase on MC with continuous reward

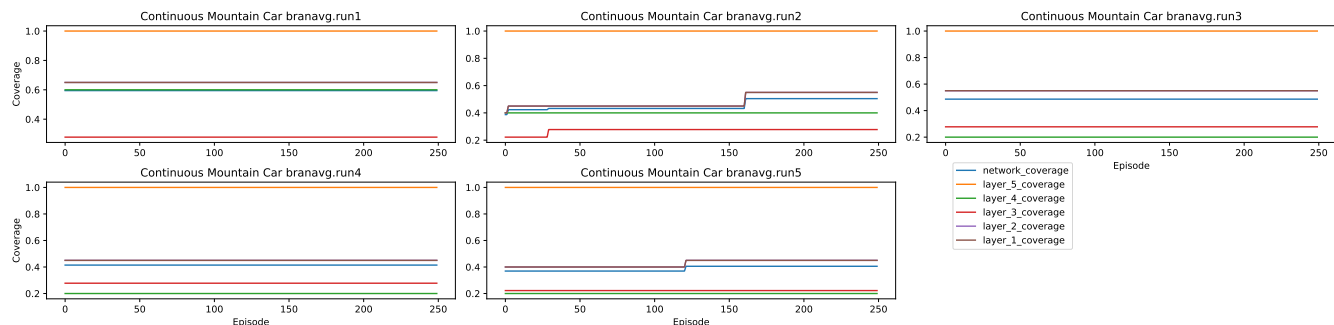


Figure 29. CNC and CNCL over episodes for branavg model during testing phase on MC with continuous reward

Harshitandro model

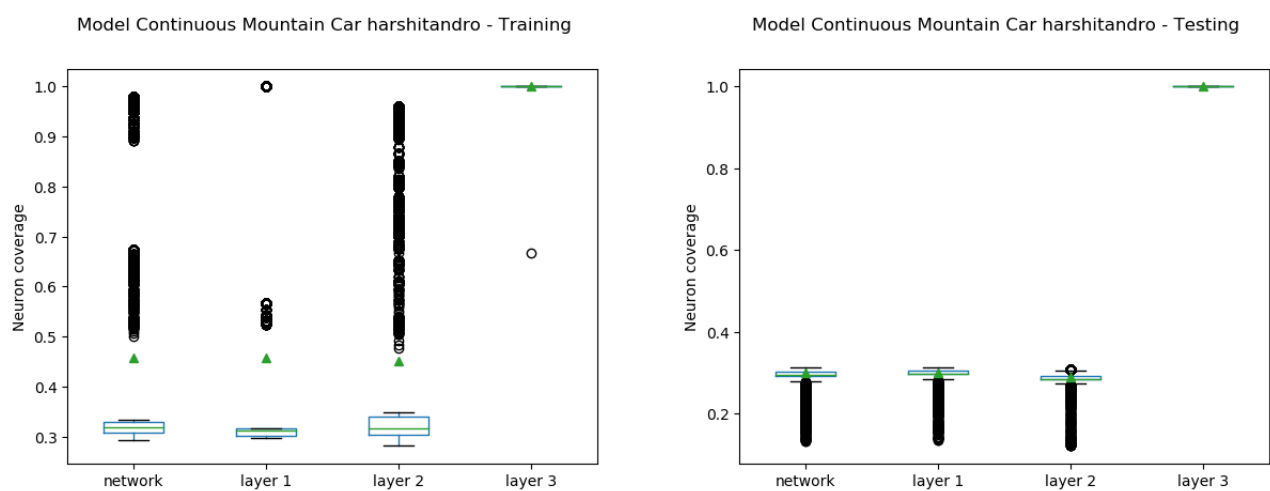


Figure 30. Distribution of cumulative coverage for harshitandro model during training and testing phase on MC with continuous reward

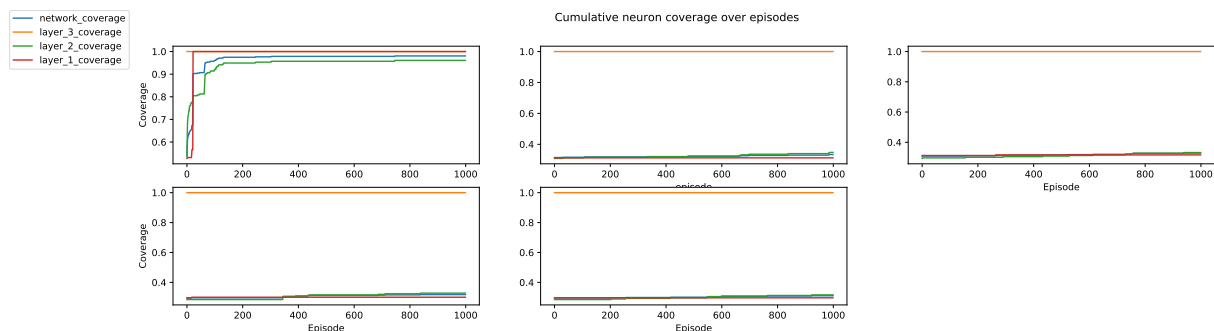


Figure 31. CNC and CNCL over episodes for harshitandro model during training phase on MC with continuous reward

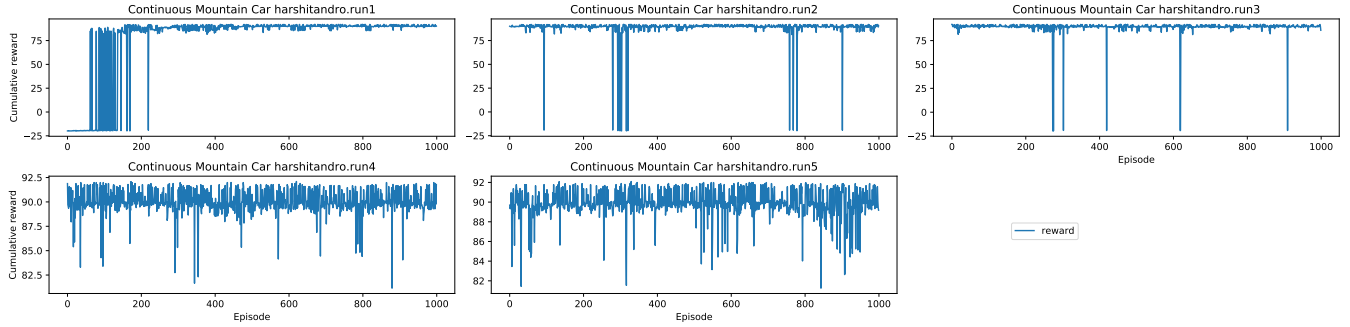


Figure 32. Cumulative reward over episodes for harshitandro model during training phase on MC with continuous reward

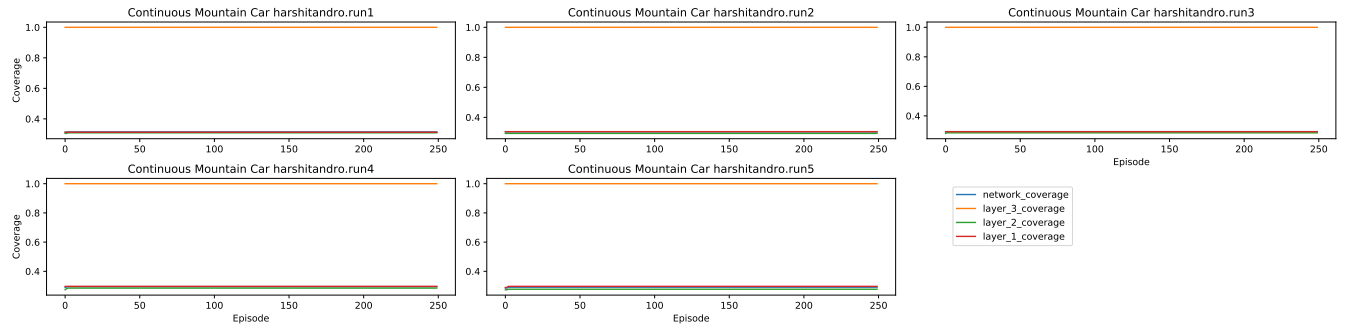


Figure 33. CNC and CNCL over episodes for harshitandro model during testing phase on MC with continuous reward

Kxl4126 model

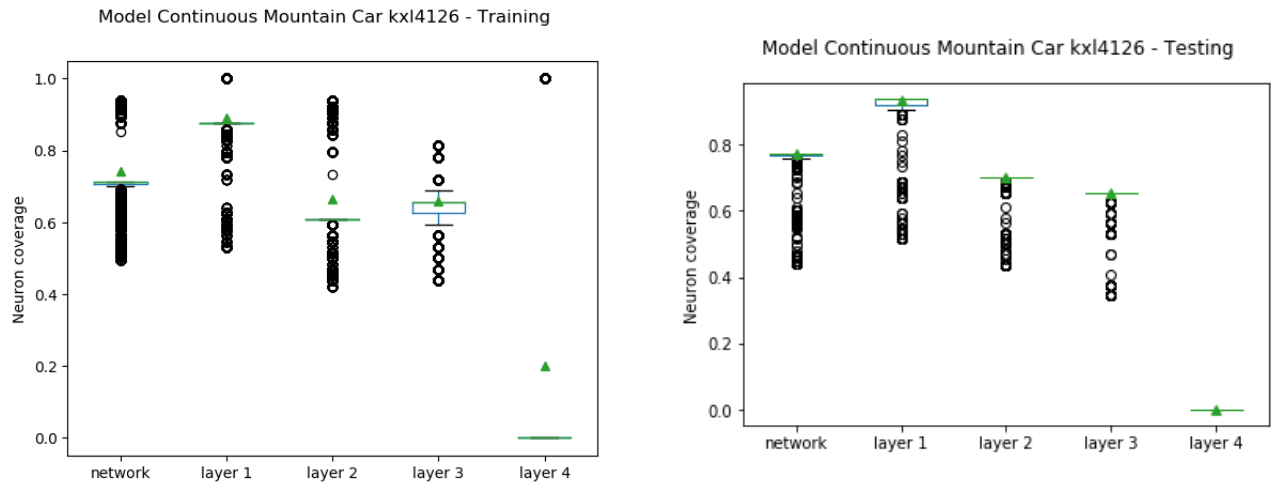


Figure 34. Distribution of cumulative coverage for kxl4126 model during training and testing phase on MC with continuous reward

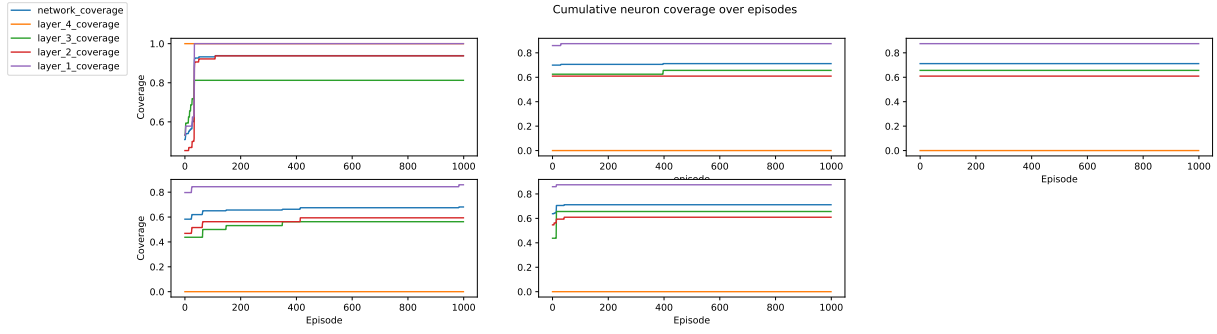


Figure 35. CNC and CNCL over episodes for kxl4126 model during training phase on MC with continuous reward

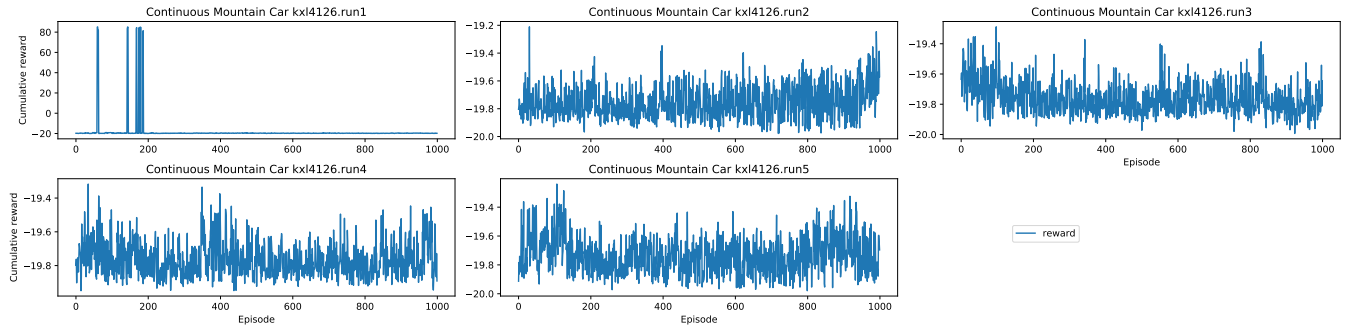


Figure 36. Cumulative reward over episodes for kxl4126 model during training phase on MC with continuous reward

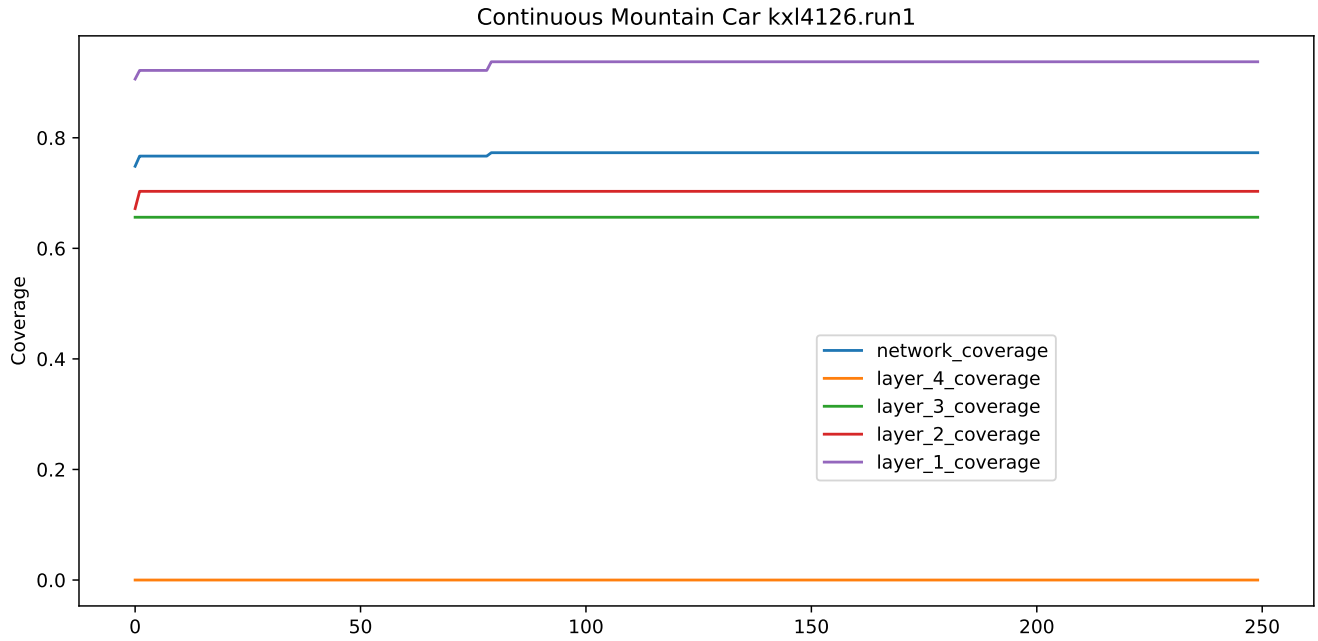


Figure 37. CNC and CNCL over episodes for kxl4126 model during testing phase on MC with continuous reward

MLnewlifer model

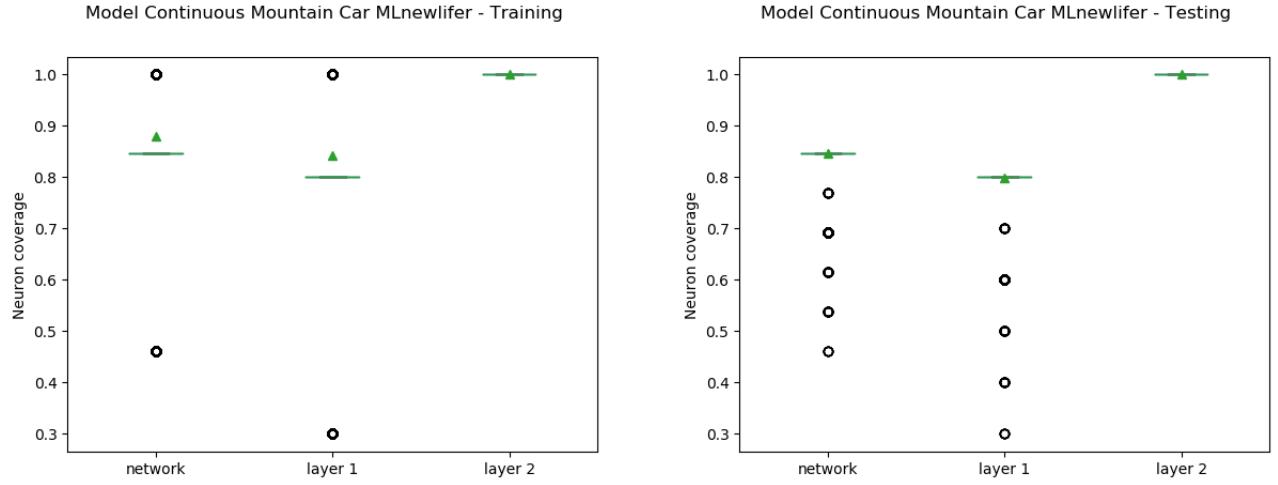


Figure 38. Distribution of cumulative coverage for MLnewlifer model during training and testing phase on MC with continuous reward

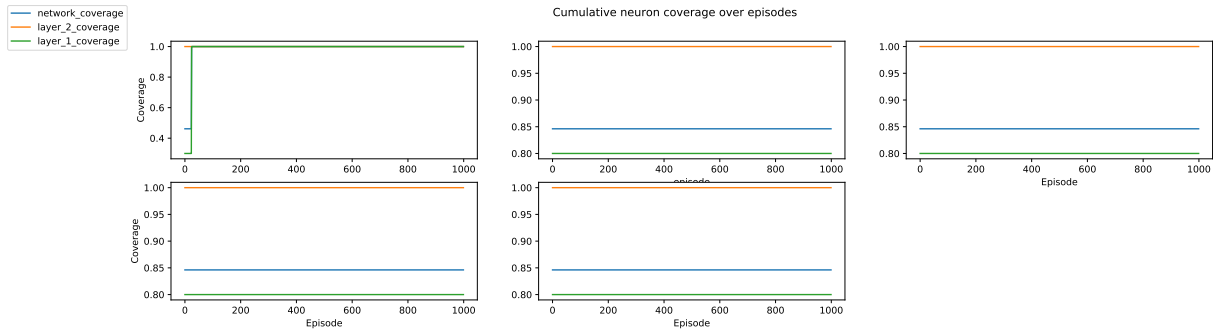


Figure 39. CNC and CNCL over episodes for MLnewlifer model during training phase on MC with continuous reward

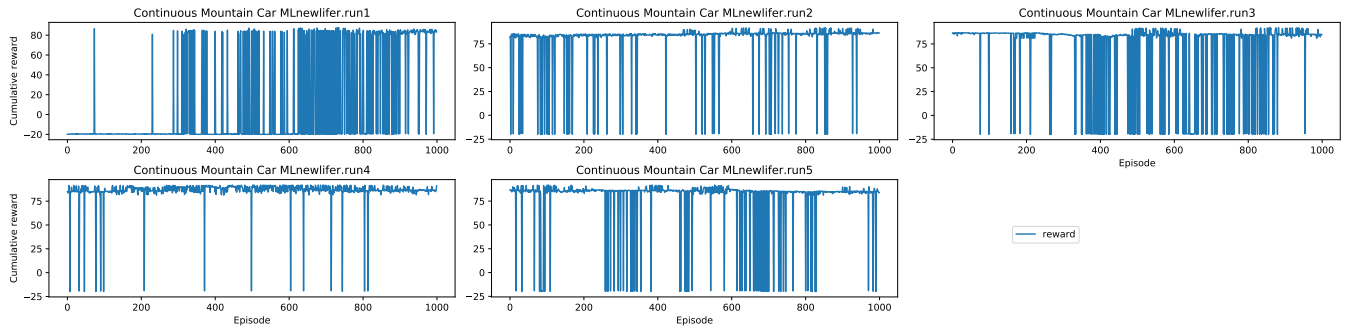


Figure 40. Cumulative reward over episodes for MLnewlifer model during training phase on MC with continuous reward

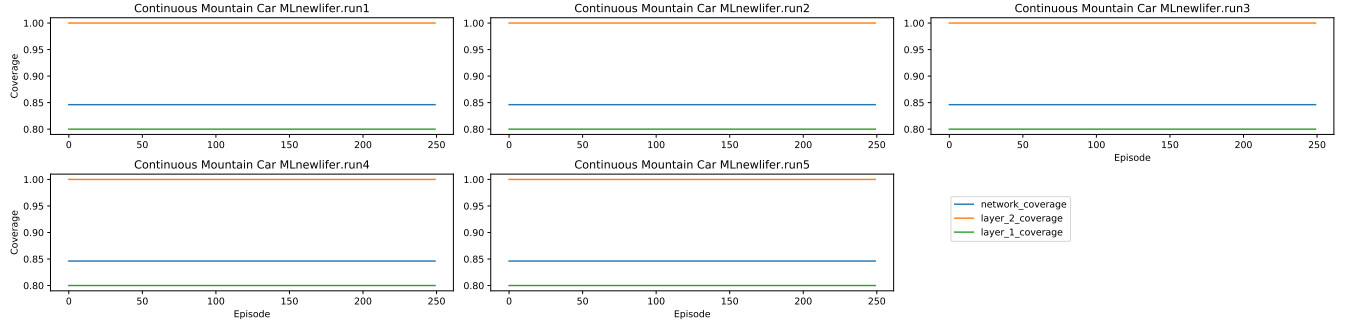


Figure 41. CNC and CNCL over episodes for MLnewlifer model during testing phase on MC with continuous reward

PylSER model

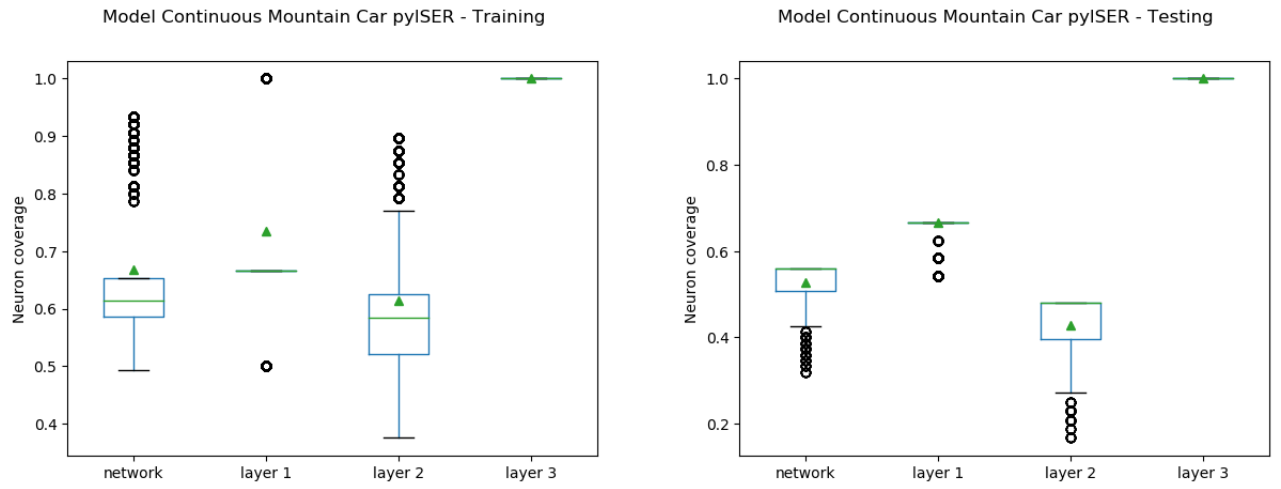


Figure 42. Distribution of cumulative coverage for pylSER model during training and testing phase on MC with continuous reward

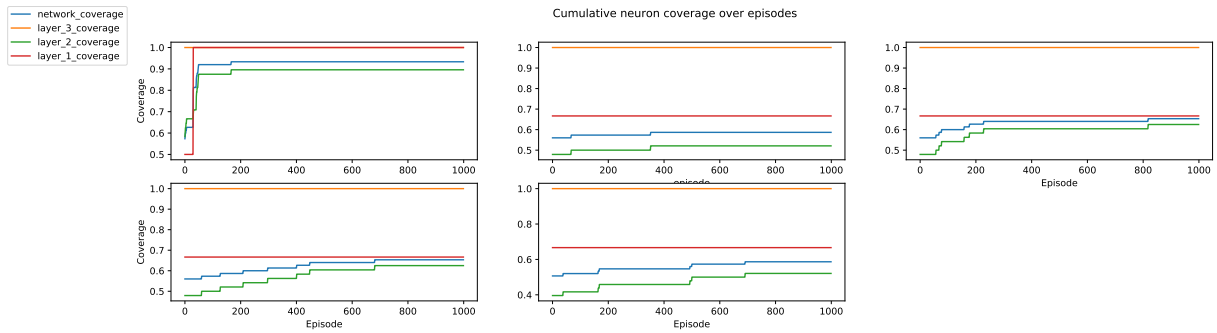


Figure 43. CNC and CNCL over episodes for pylSER model during training phase on MC with continuous reward

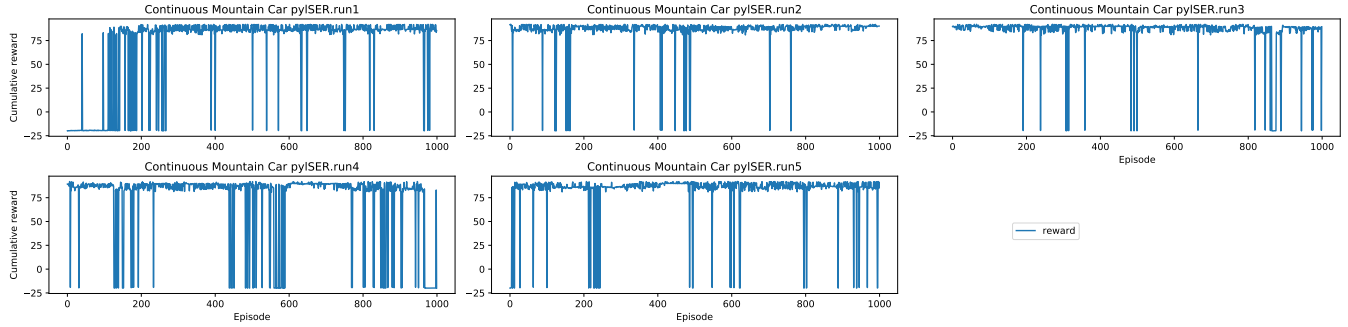


Figure 44. Cumulative reward over episodes for pylSER model during training phase on MC with continuous reward

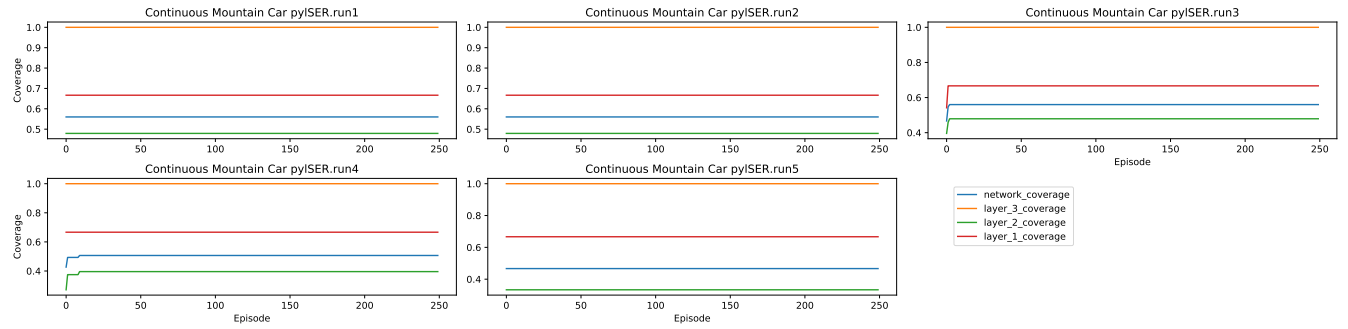


Figure 45. CNC and CNCL over episodes for pylSER model during testing phase on MC with continuous reward

THE CARTPOLE PROBLEM

CFOnHeart model

Input	Input Shape: (4)
Layer 1	Layer Shape: (128)
Layer 2	Layer Shape: (128)
Layer 3	Layer Shape: (2)

Figure 46. Network architecture of CFOnHeart model

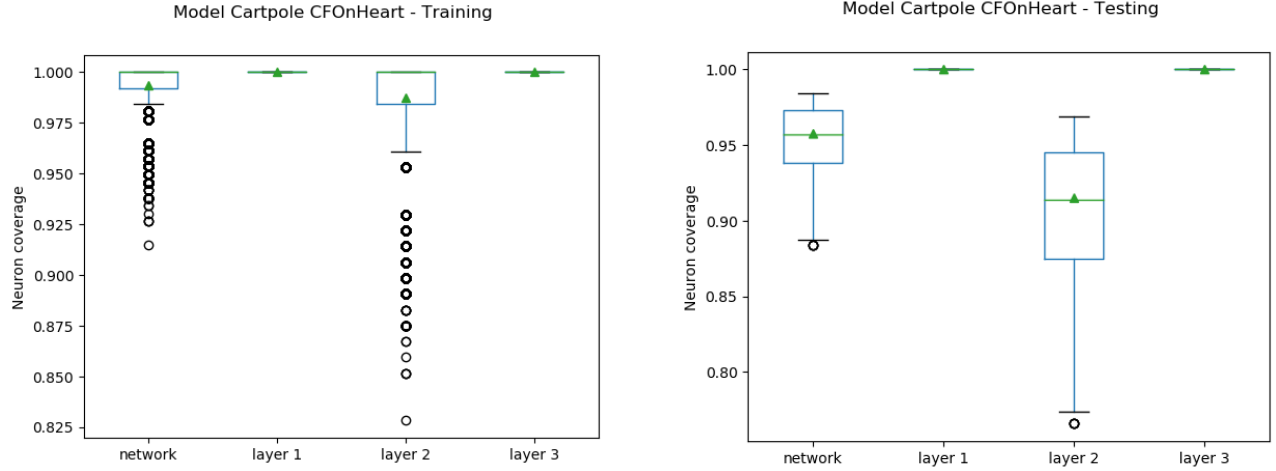


Figure 47. Distribution of cumulative coverage for CFOnHeart model during training and testing phase on CP

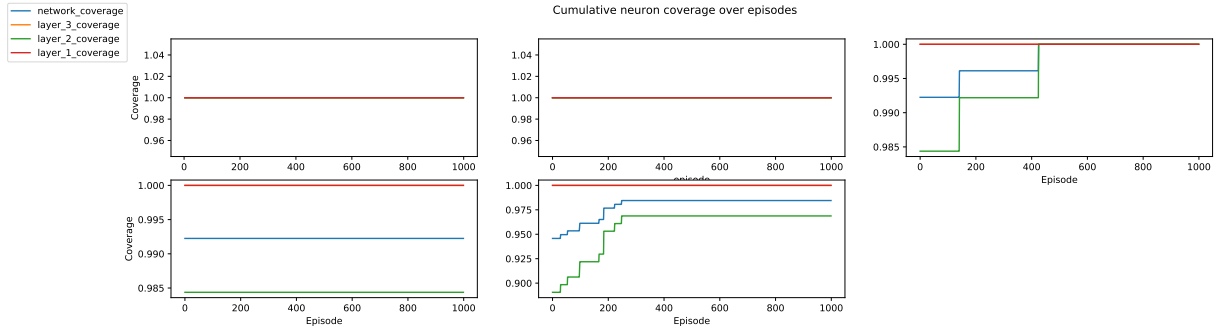


Figure 48. CNC and CNCL over episodes for CFOnHeart model during training phase on CP

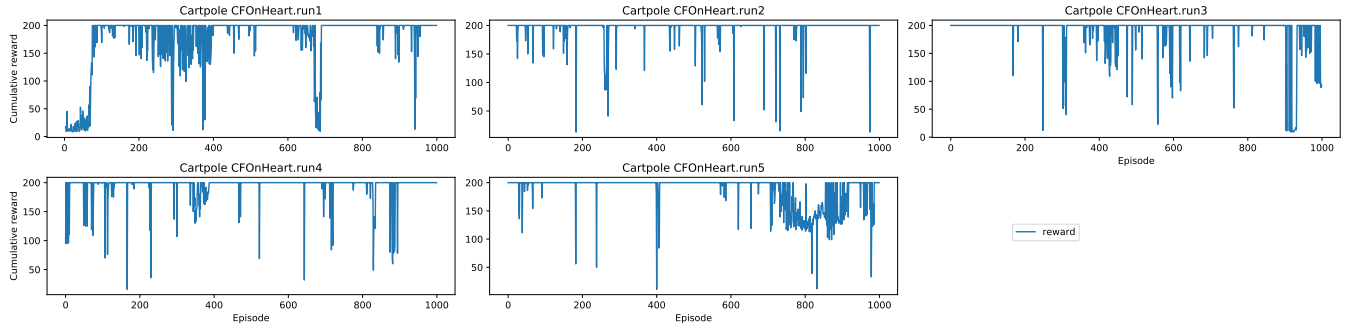


Figure 49. Cumulative reward over episodes for CFOnHeart model during training phase on CP

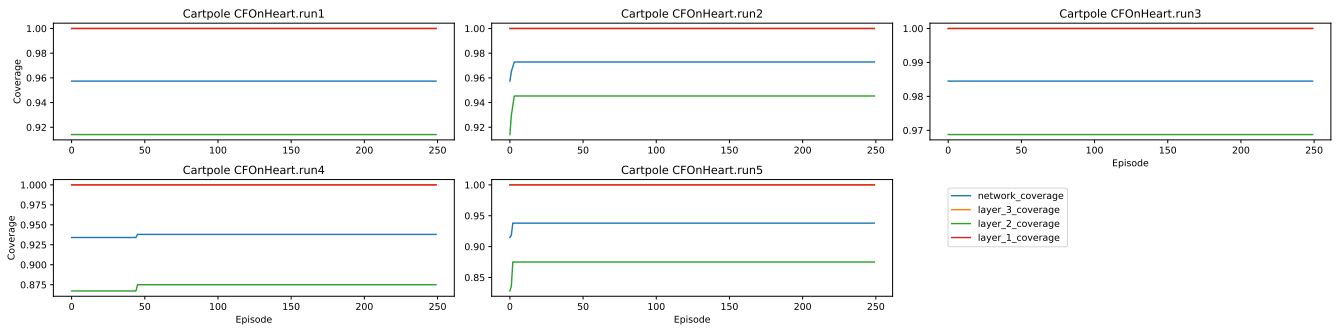


Figure 50. CNC and CNCL over episodes for CFOnHeart model during testing phase on CP

Input	Input Shape: (4)
Layer 1	Layer Shape: (24)
Layer 2	Layer Shape: (24)
Layer 3	Layer Shape: 2

Figure 51. Network architecture of gsurma model

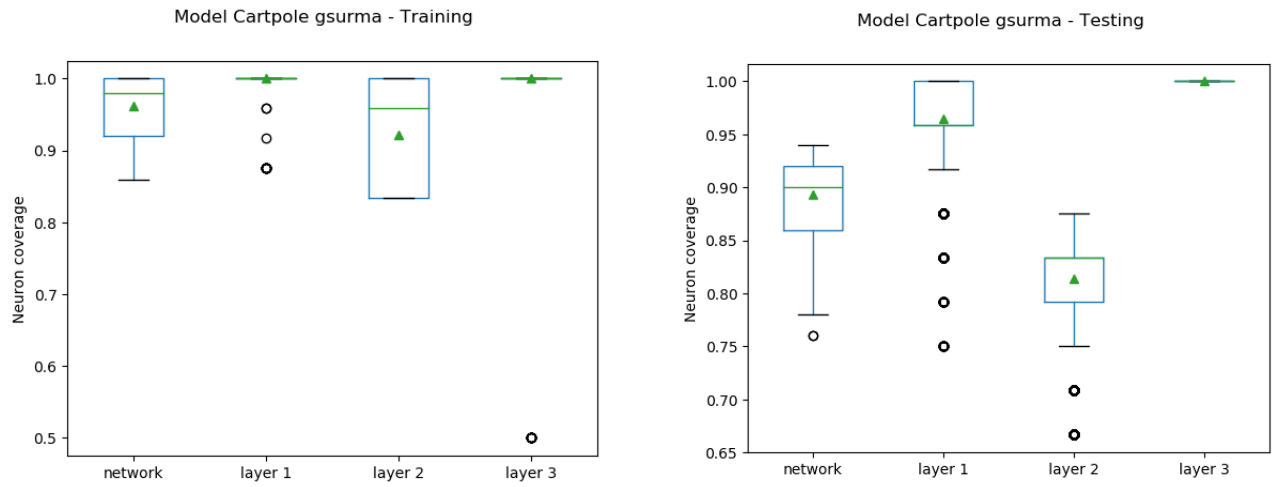


Figure 52. Distribution of cumulative coverage for gsurma model during training and testing phase on CP

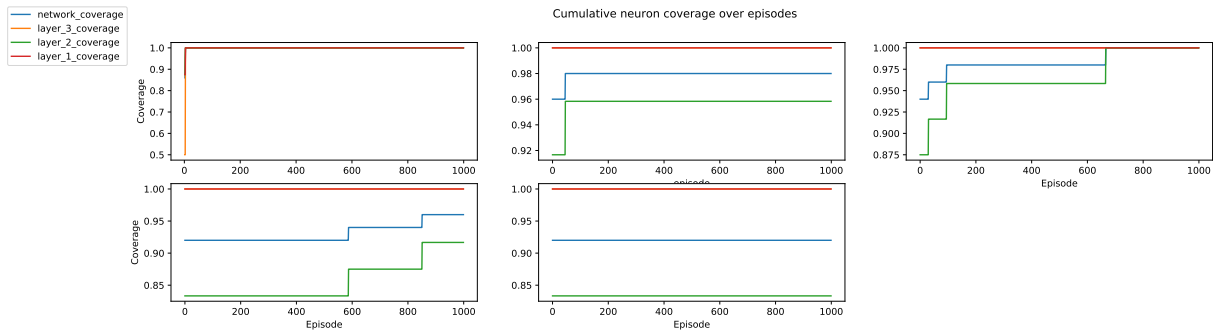


Figure 53. CNC and CNCL over episodes for gsurma model during training phase on CP

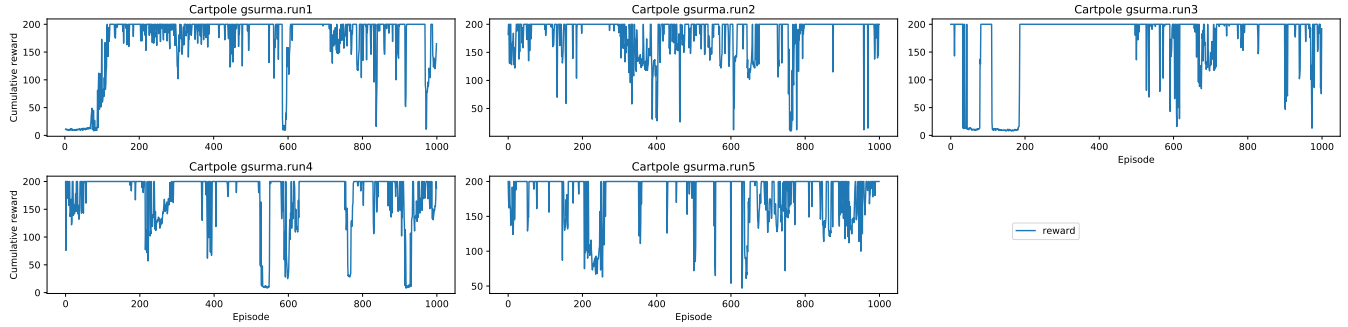


Figure 54. Cumulative reward over episodes for gsurma model during training phase on CP

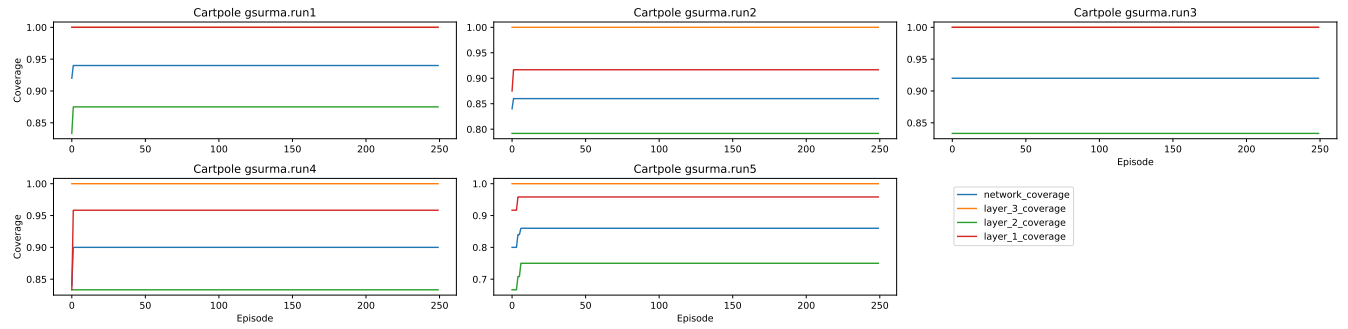


Figure 55. CNC and CNCL over episodes for gsurma model during testing phase on CP

Harshitandro model

Input	Input Shape: (4)
Layer 1	Layer Shape: (256)
Layer 2	Layer Shape: (256)
Layer 3	Layer Shape: 2

Figure 56. Network architecture of harshitandro model

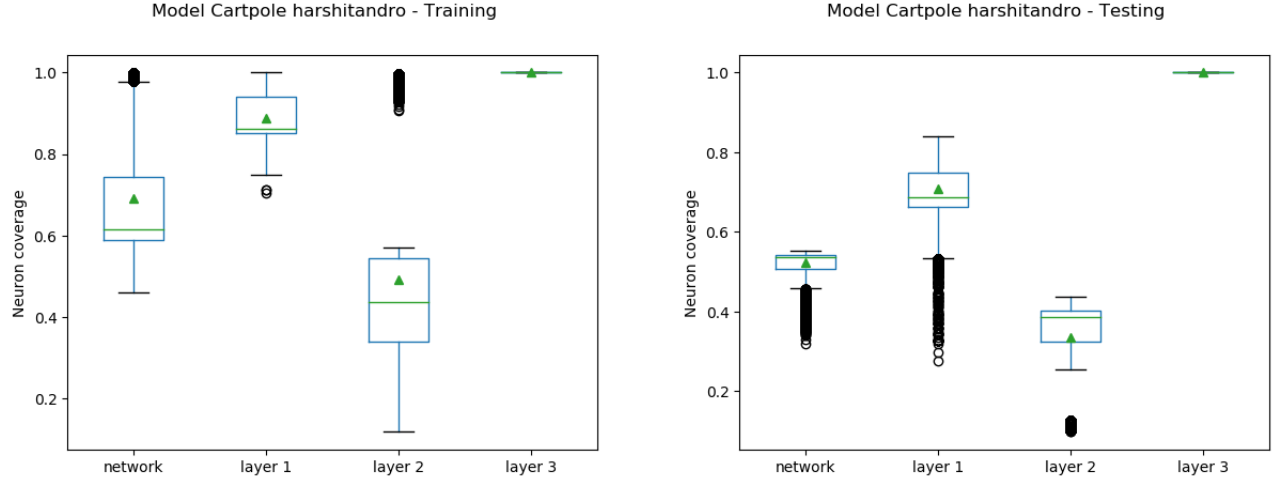


Figure 57. Distribution of cumulative coverage for harshitandro model during training and testing phase on CP

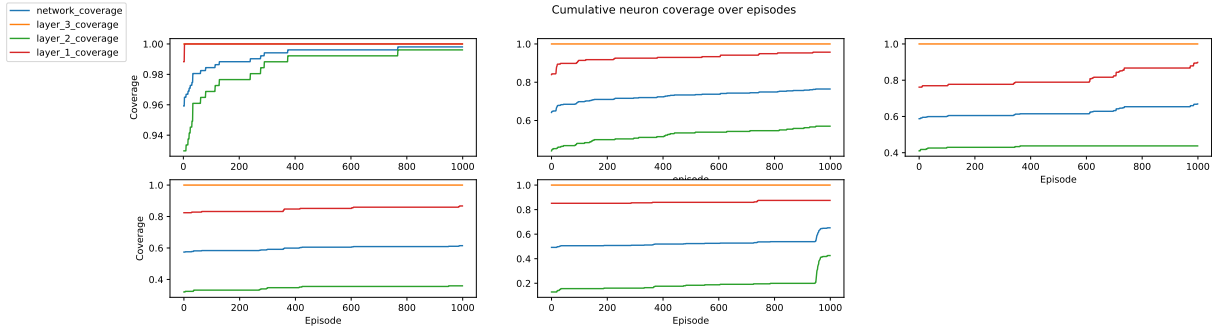


Figure 58. CNC and CNCL over episodes for harshitandro model during training phase on CP

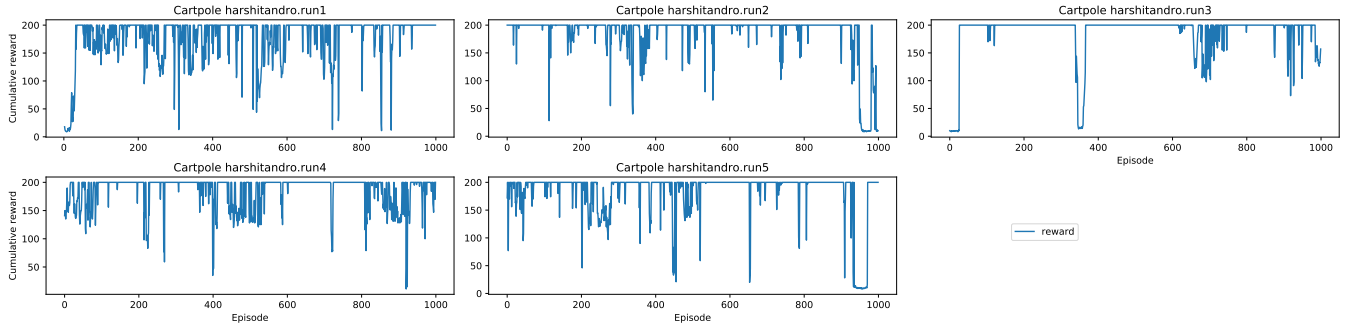


Figure 59. Cumulative reward over episodes for harshitandro model during training phase on CP

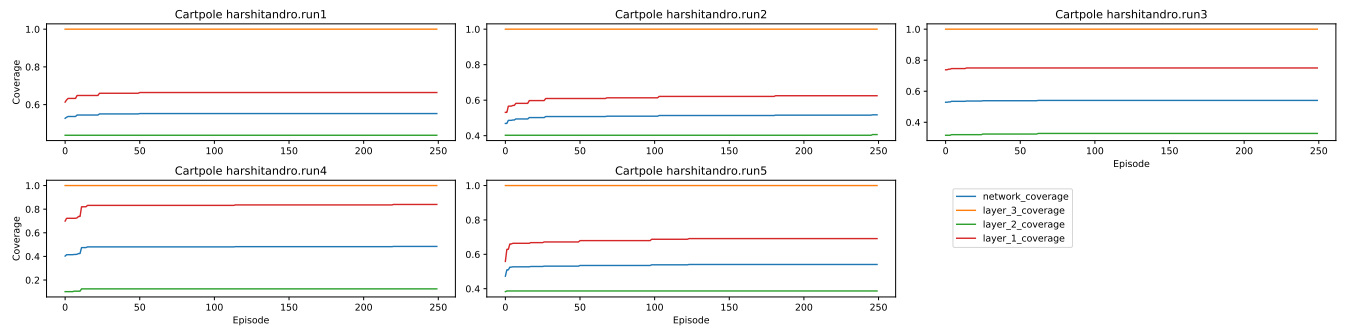


Figure 60. CNC and CNCL over episodes for harshitandro model during testing phase on CP

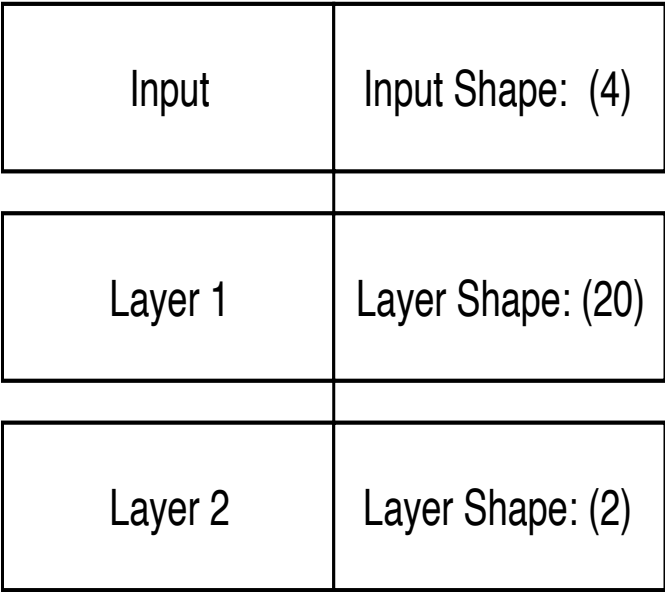


Figure 61. Network architecture of junliangliu model

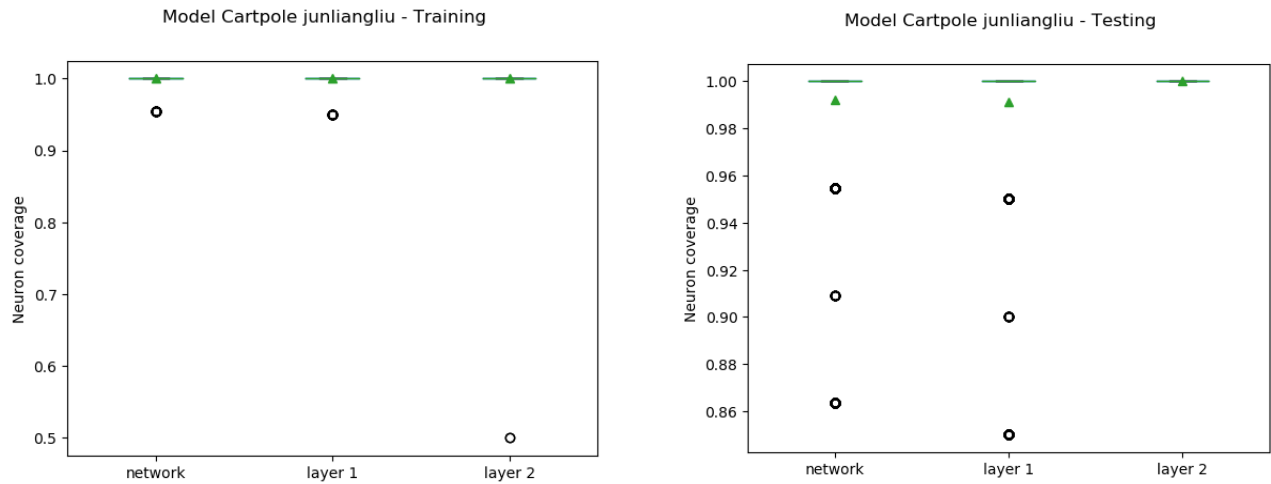


Figure 62. Distribution of cumulative coverage for junliangliu model during training and testing phase on CP

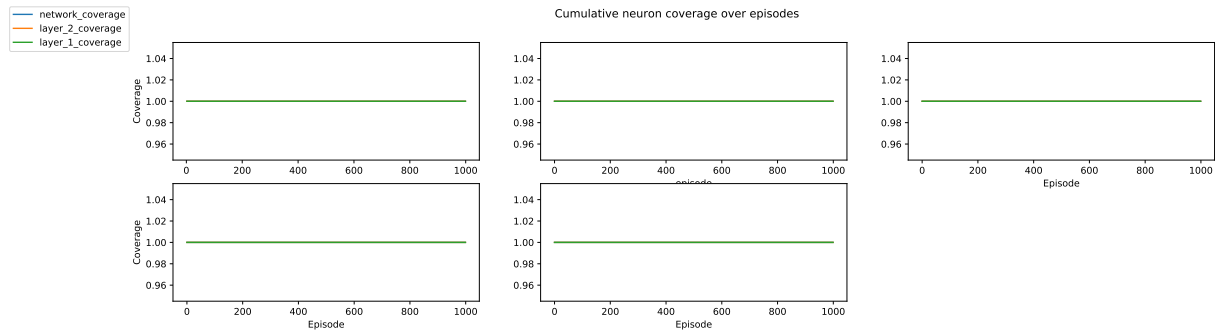


Figure 63. CNC and CNCL over episodes for junliangliu model during training phase on CP

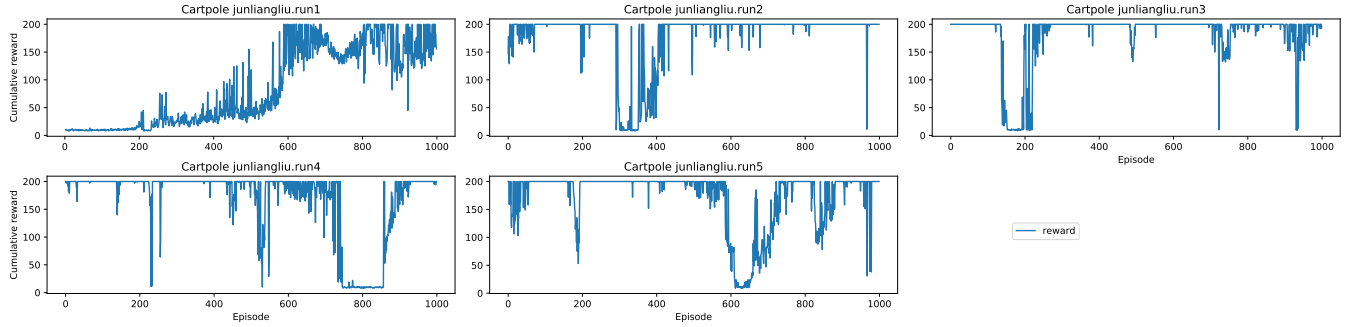


Figure 64. Cumulative reward over episodes for junliangliu model during training phase on CP

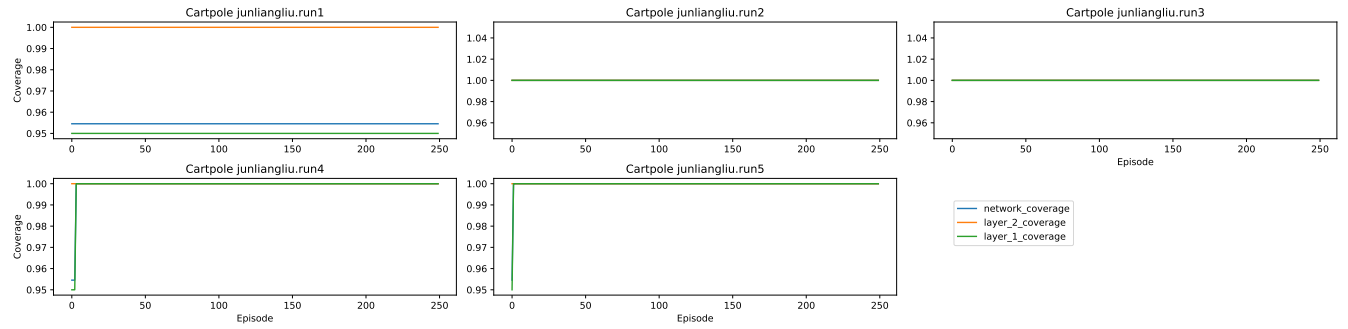


Figure 65. CNC and CNCL over episodes for junliangliu model during testing phase on CP

Z0m6ie model

Input	Input Shape: (4)
Layer 1	Layer Shape: (20)
Layer 2	Layer Shape: (20)
Layer 3	Layer Shape: (2)

Figure 66. Network architecture of Z0m6ie model

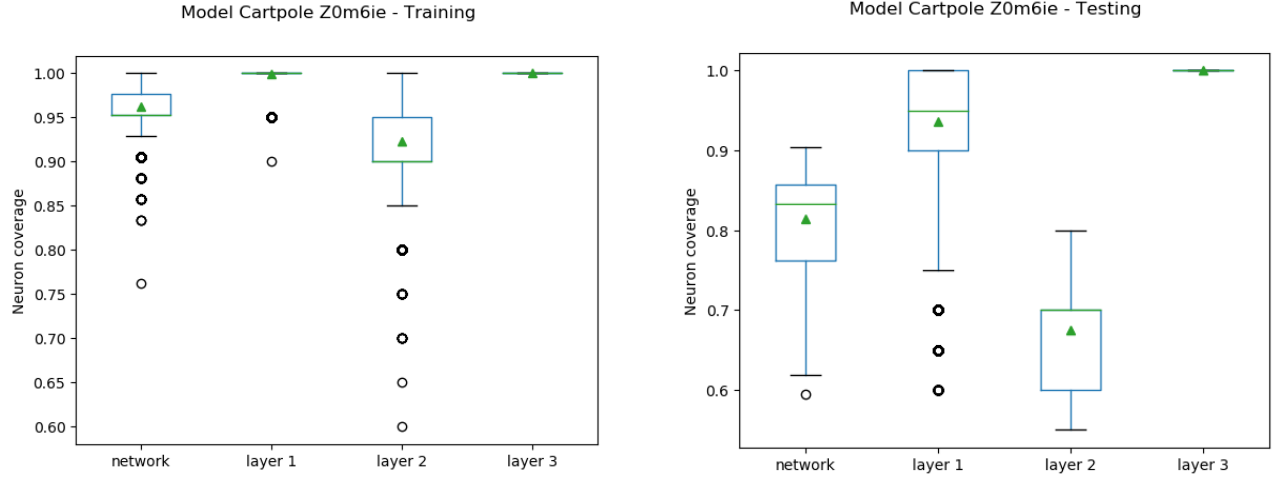


Figure 67. Distribution of cumulative coverage for Z0m6ie model during training and testing phase on CP

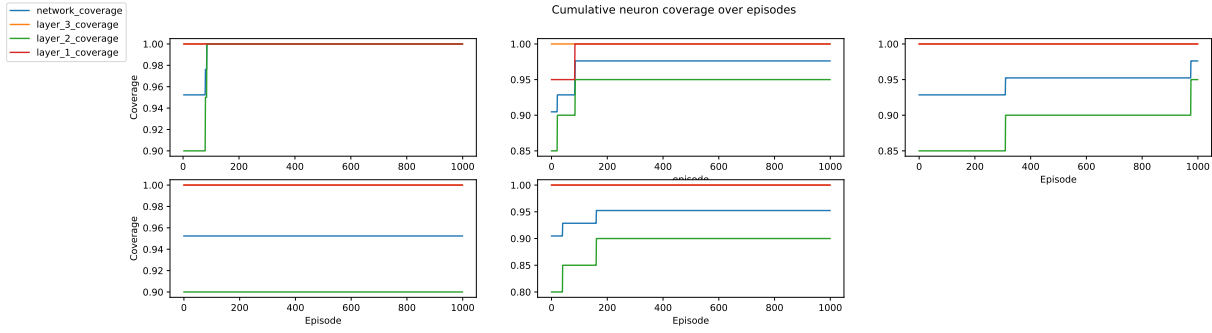


Figure 68. CNC and CNCL over episodes for Z0m6ie model during training phase on CP

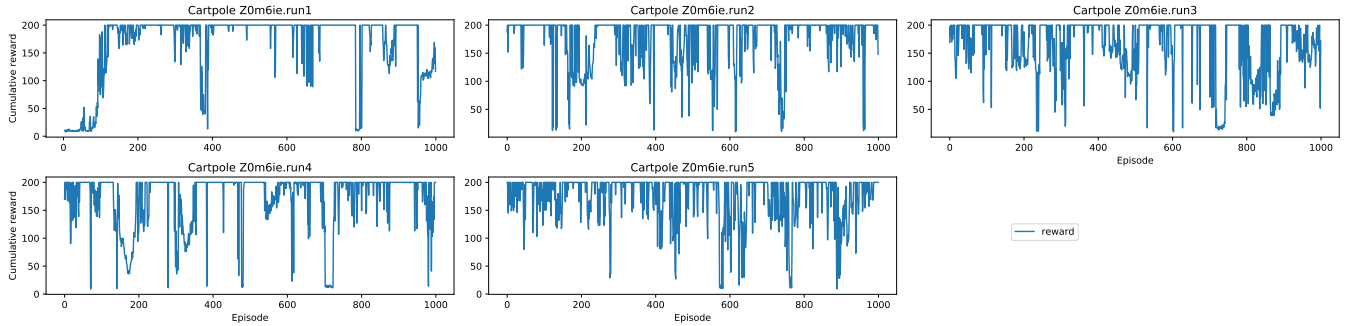


Figure 69. Cumulative reward over episodes for Z0m6ie model during training phase on CP

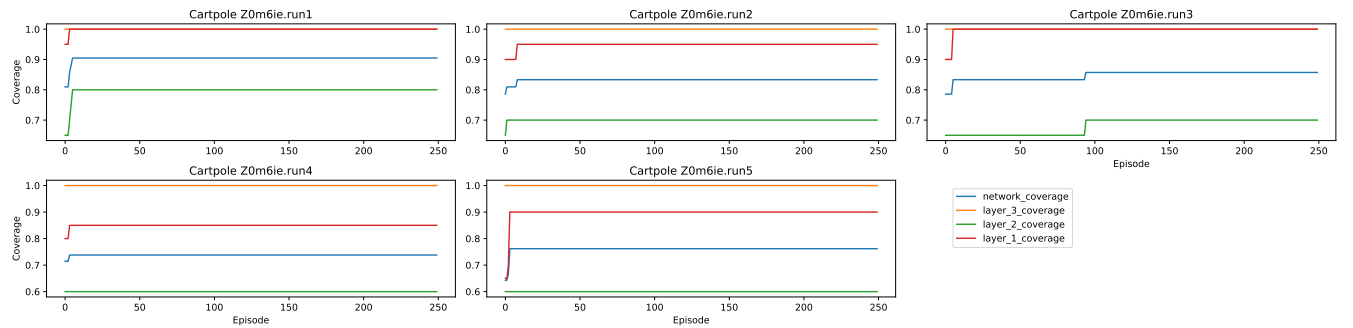


Figure 70. CNC and CNCL over episodes for Z0m6ie model during testing phase on CP

THE SUPER MARIO BROS. GAME

SMB1 model

Input	Input Shape: (84,84,4)
Layer 1 <i>Conv2D</i>	Layer Shape: (39,39,32)
Layer 2 <i>Conv2D</i>	Layer Shape: (18,18,64)
Layer 3 <i>Conv2D</i>	Layer Shape: (7,7,64)
Layer 4 <i>Dense</i>	Layer Shape: (512)
Layer 6 <i>Dense</i>	Layer Shape: (18)

Figure 71. Network architecture of smb1 model

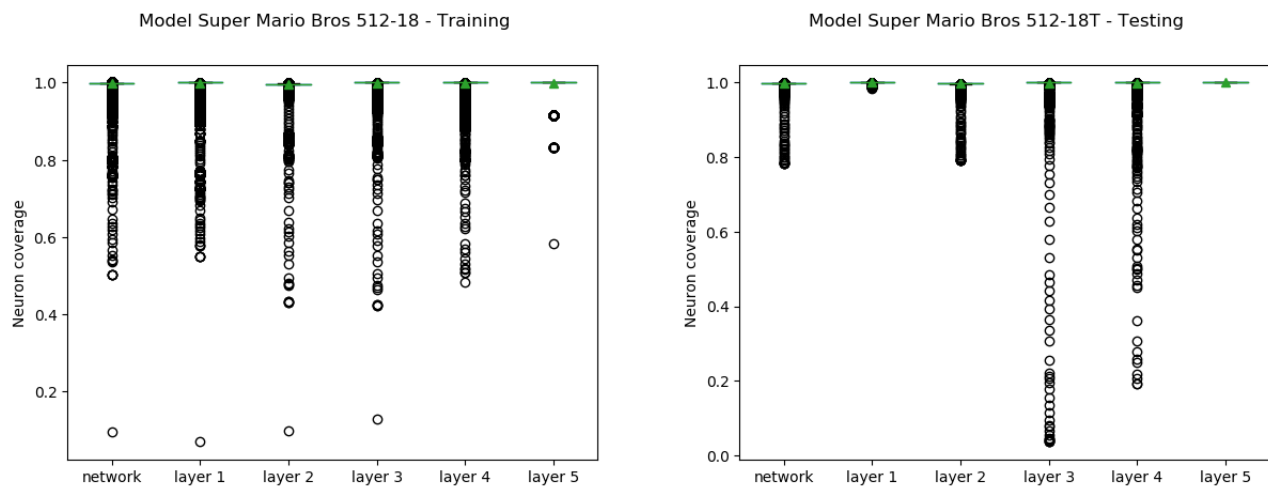


Figure 72. Distribution of cumulative coverage for smb1 model during training and testing phase on SMB

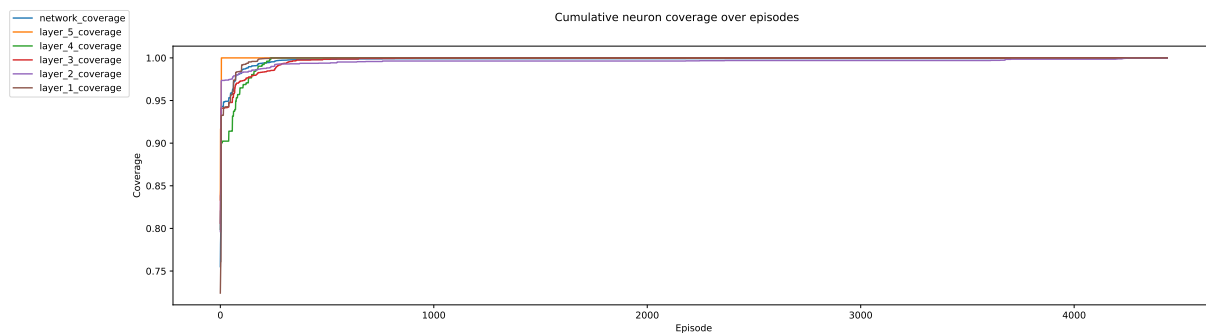


Figure 73. CNC and CNCL over episodes for smb1 model during training phase on SMB

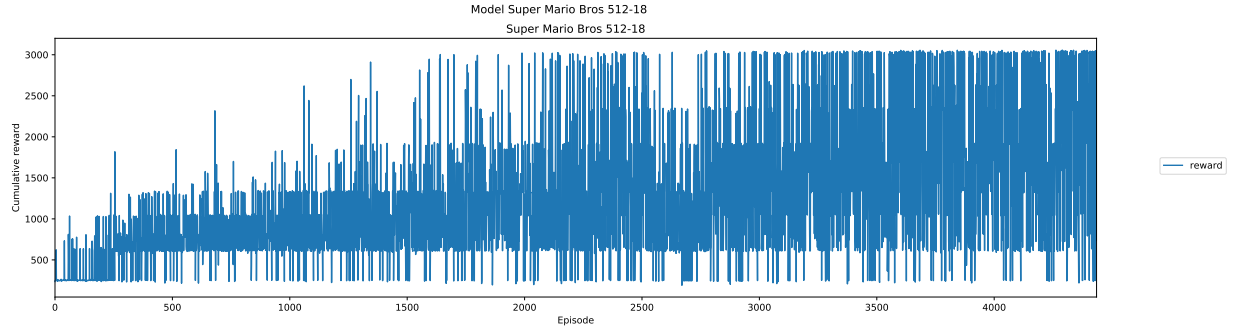


Figure 74. Cumulative reward over episodes for smb1 model during training phase on SMB

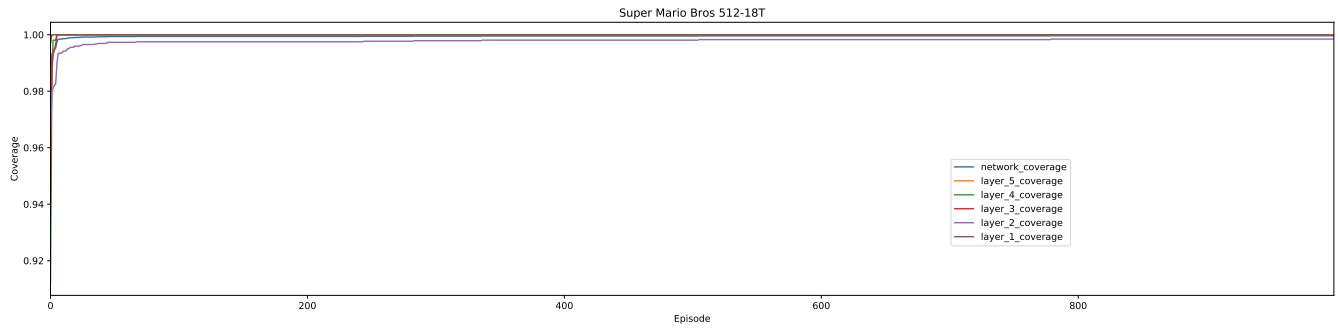


Figure 75. CNC and CNCL over episodes for smb1 model during testing phase on SMB

SMB2 model

Input	Input Shape: (84,84,4)
Layer 1 <i>Conv2D</i>	Layer Shape: (39,39,32)
Layer 2 <i>Conv2D</i>	Layer Shape: (18,18,64)
Layer 3 <i>Conv2D</i>	Layer Shape: (7,7,64)
Layer 4 <i>Dense</i>	Layer Shape: (1024)
Layer 6 <i>Dense</i>	Layer Shape: (18)

Figure 76. Network architecture of smb2 model

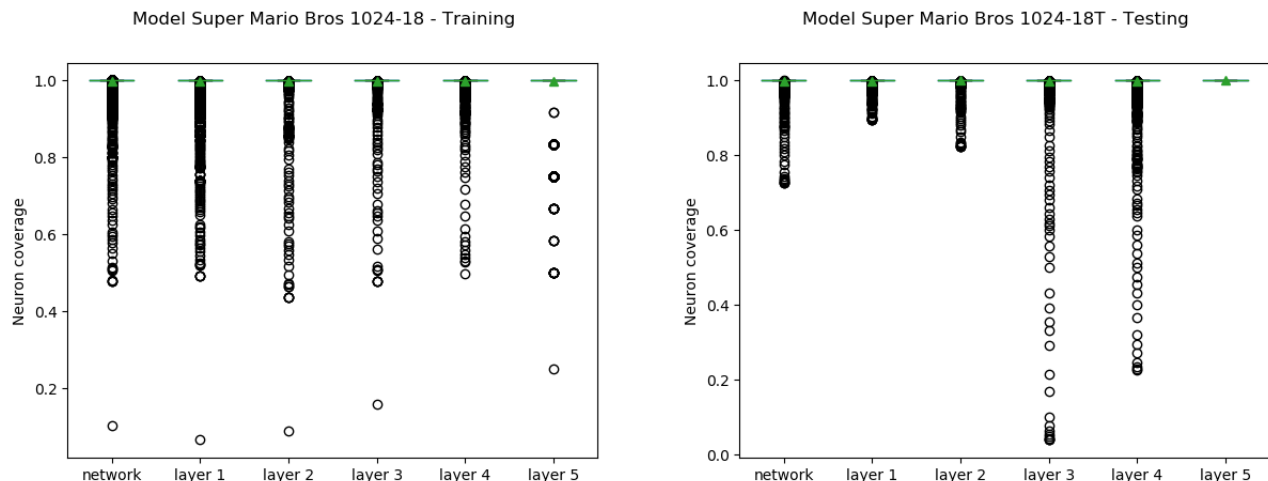


Figure 77. Distribution of cumulative coverage for smb2 model during training and testing phase on SMB

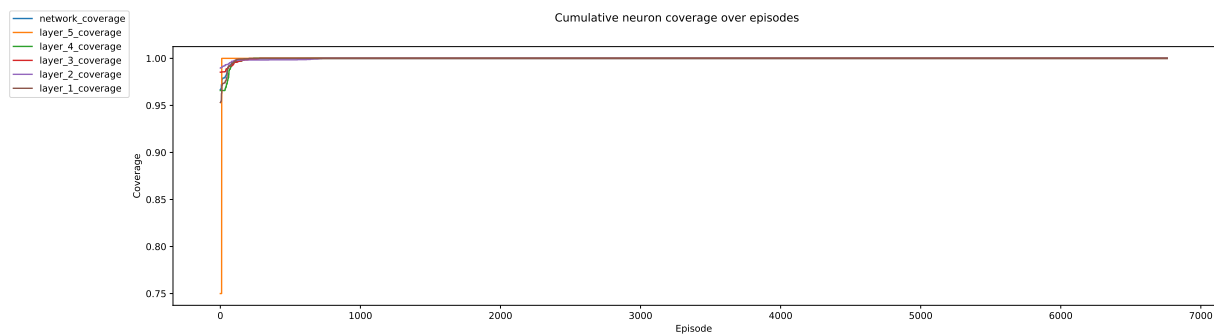


Figure 78. CNC and CNCL over episodes for smb2 model during training phase on SMB

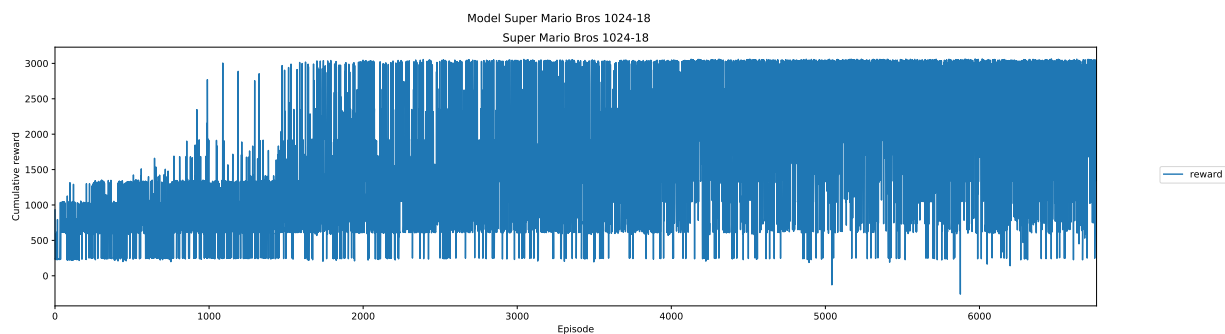


Figure 79. Cumulative reward over episodes for smb2 model during training phase on SMB

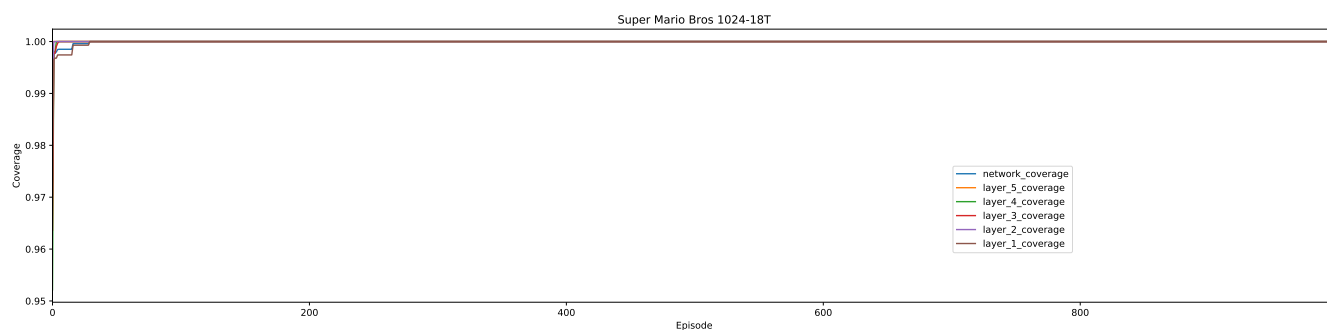


Figure 80. CNC and CNCL over episodes for smb2 model during testing phase on SMB

SMB3 model

Input	Input Shape: (84,84,4)
Layer 1 <i>Conv2D</i>	Layer Shape: (39,39,32)
Layer 2 <i>Conv2D</i>	Layer Shape: (18,18,64)
Layer 3 <i>Conv2D</i>	Layer Shape: (7,7,64)
Layer 4 <i>Dense</i>	Layer Shape: (1024)
Layer 5 <i>Dense</i>	Layer Shape: (512)
Layer 6 <i>Dense</i>	Layer Shape: (18)

Figure 81. Network architecture of smb3 model

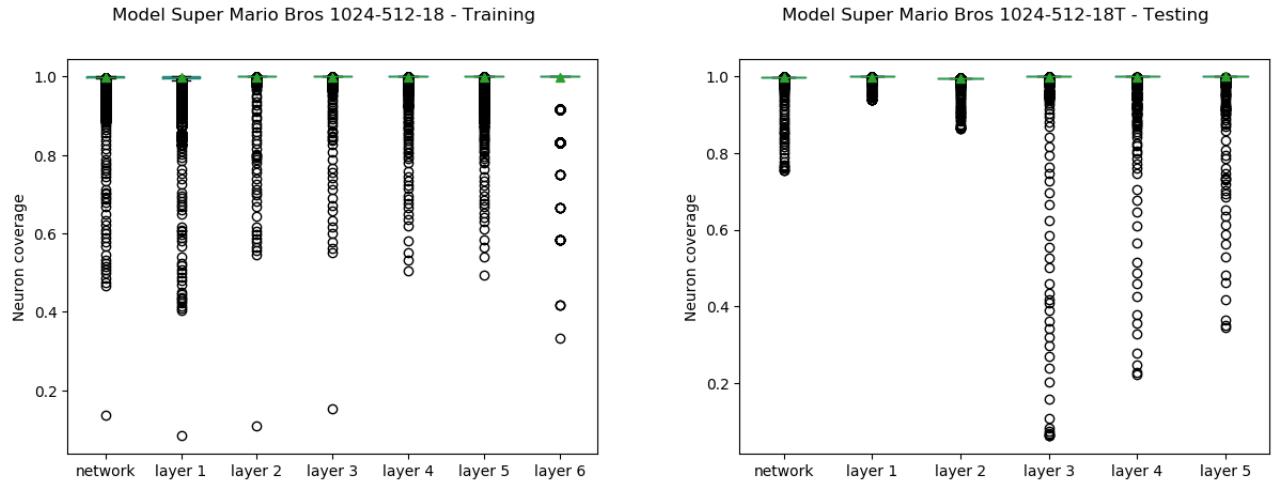


Figure 82. Distribution of cumulative coverage for smb3 model during training and testing phase on SMB

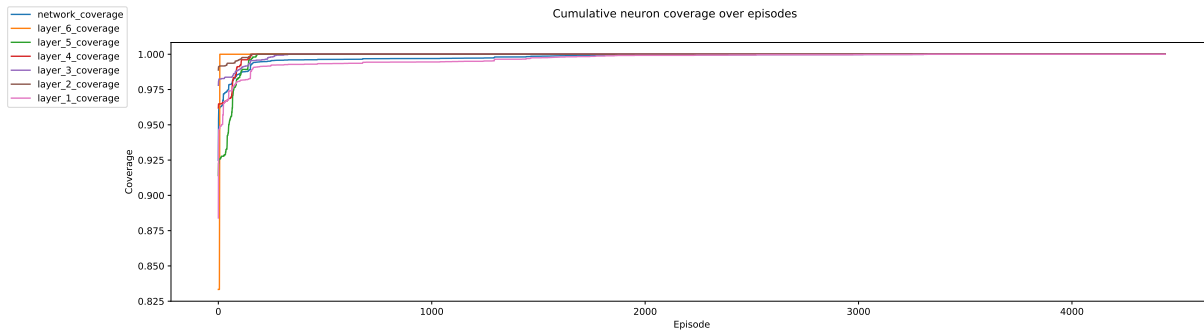


Figure 83. CNC and CNCL over episodes for smb3 model during training phase on SMB

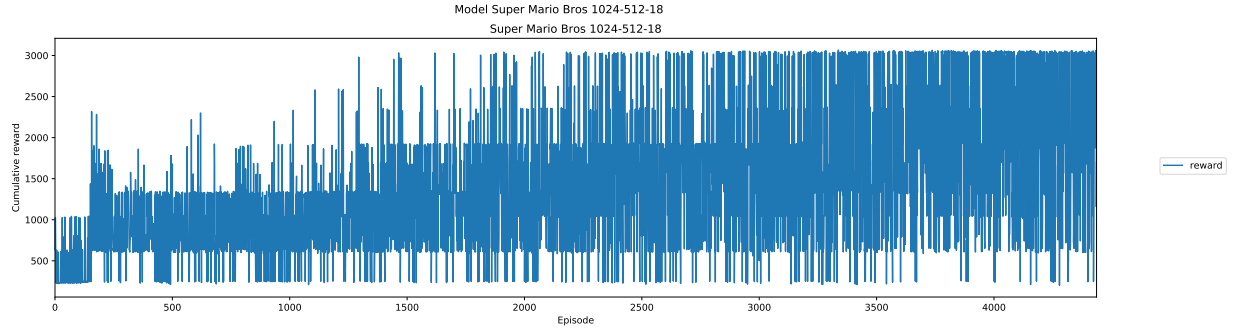


Figure 84. Cumulative reward over episodes for smb3 model during training phase on SMB

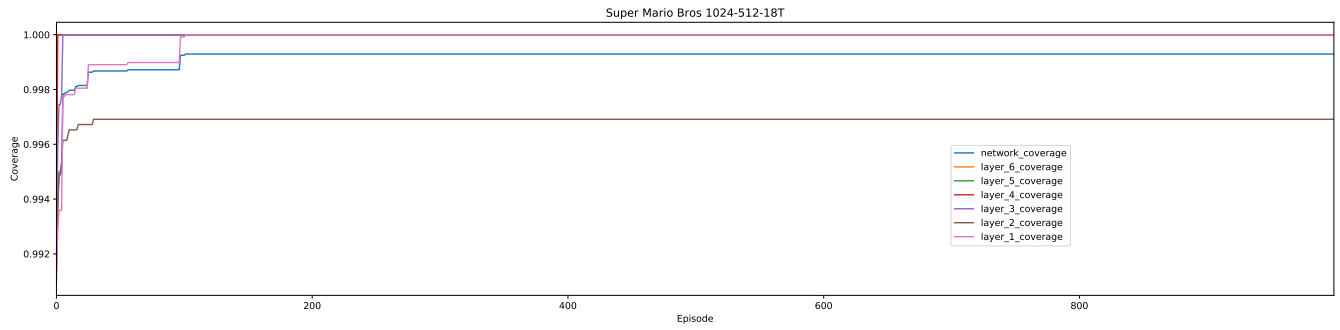


Figure 85. CNC and CNCL over episodes for smb3 model during testing phase on SMB

SMB₄ model

Input	Input Shape: (84,84,4)
Layer 1 <i>Conv2D</i>	Layer Shape: (39,39,32)
Layer 2 <i>Conv2D</i>	Layer Shape: (18,18,64)
Layer 3 <i>Conv2D</i>	Layer Shape: (7,7,64)
Layer 4 <i>Dense</i>	Layer Shape: (1024)
Layer 5 <i>Dense</i>	Layer Shape: (1024)
Layer 6 <i>Dense</i>	Layer Shape: (18)

Figure 86. Network architecture of smb4 model

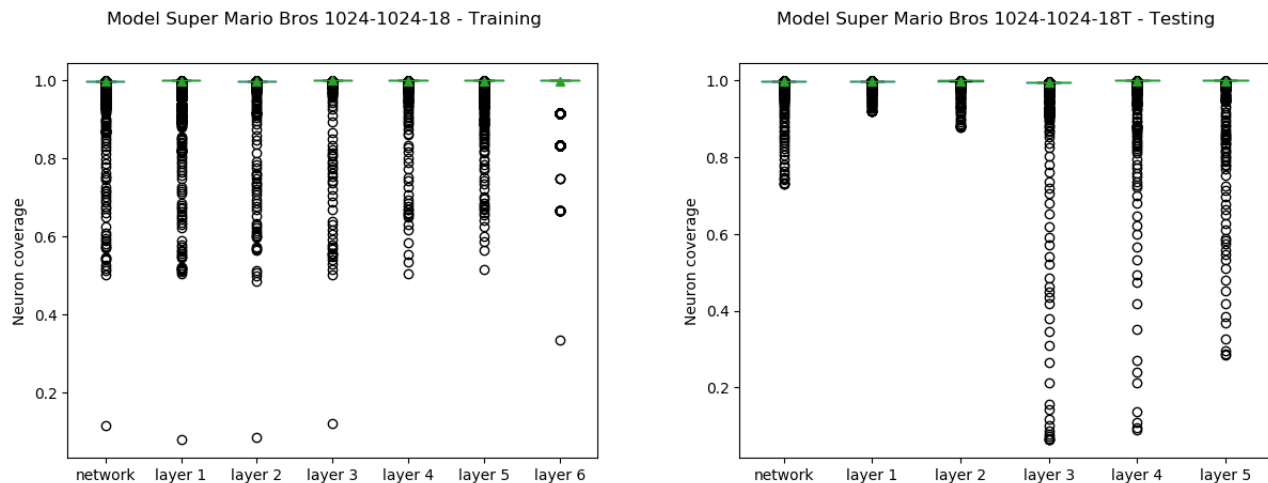


Figure 87. Distribution of cumulative coverage for smb4 model during training and testing phase on SMB

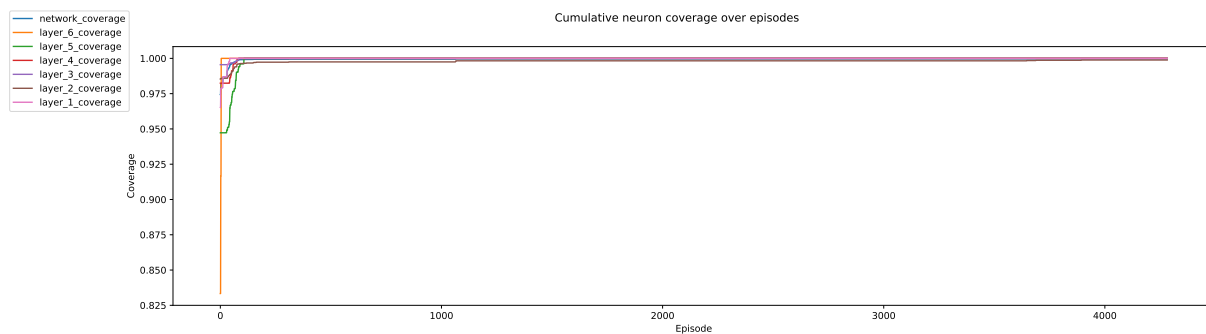


Figure 88. CNC and CNCL over episodes for smb4 model during training phase on SMB

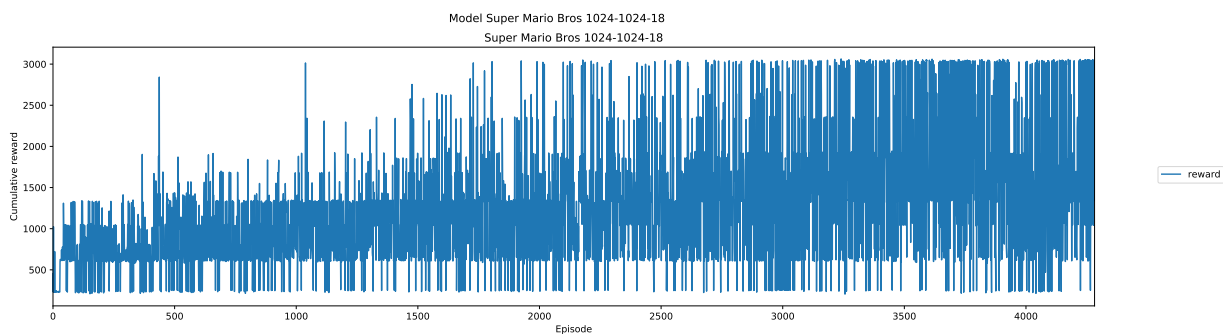


Figure 89. Cumulative reward over episodes for smb4 model during training phase on SMB

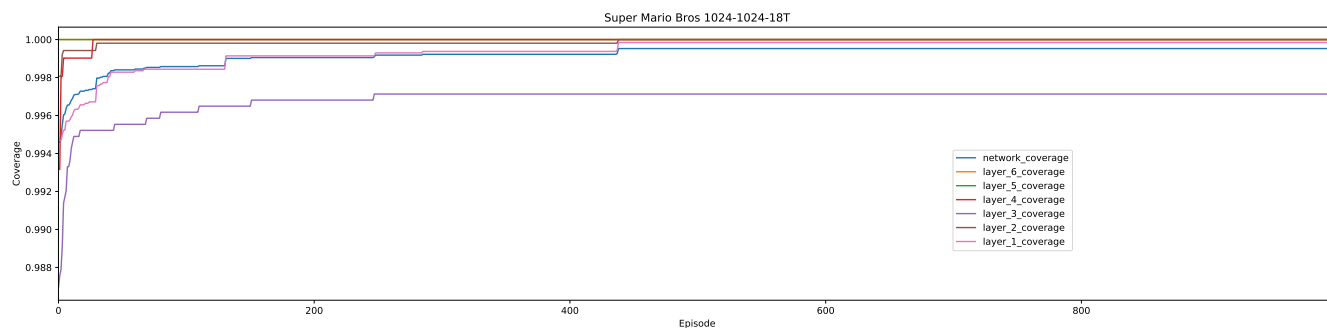


Figure 90. CNC and CNCL over episodes for smb4 model during testing phase on SMB