HALMA: Humanlike Abstraction Learning Meets Affordance in Rapid Problem Solving

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Generalization in Human Minds

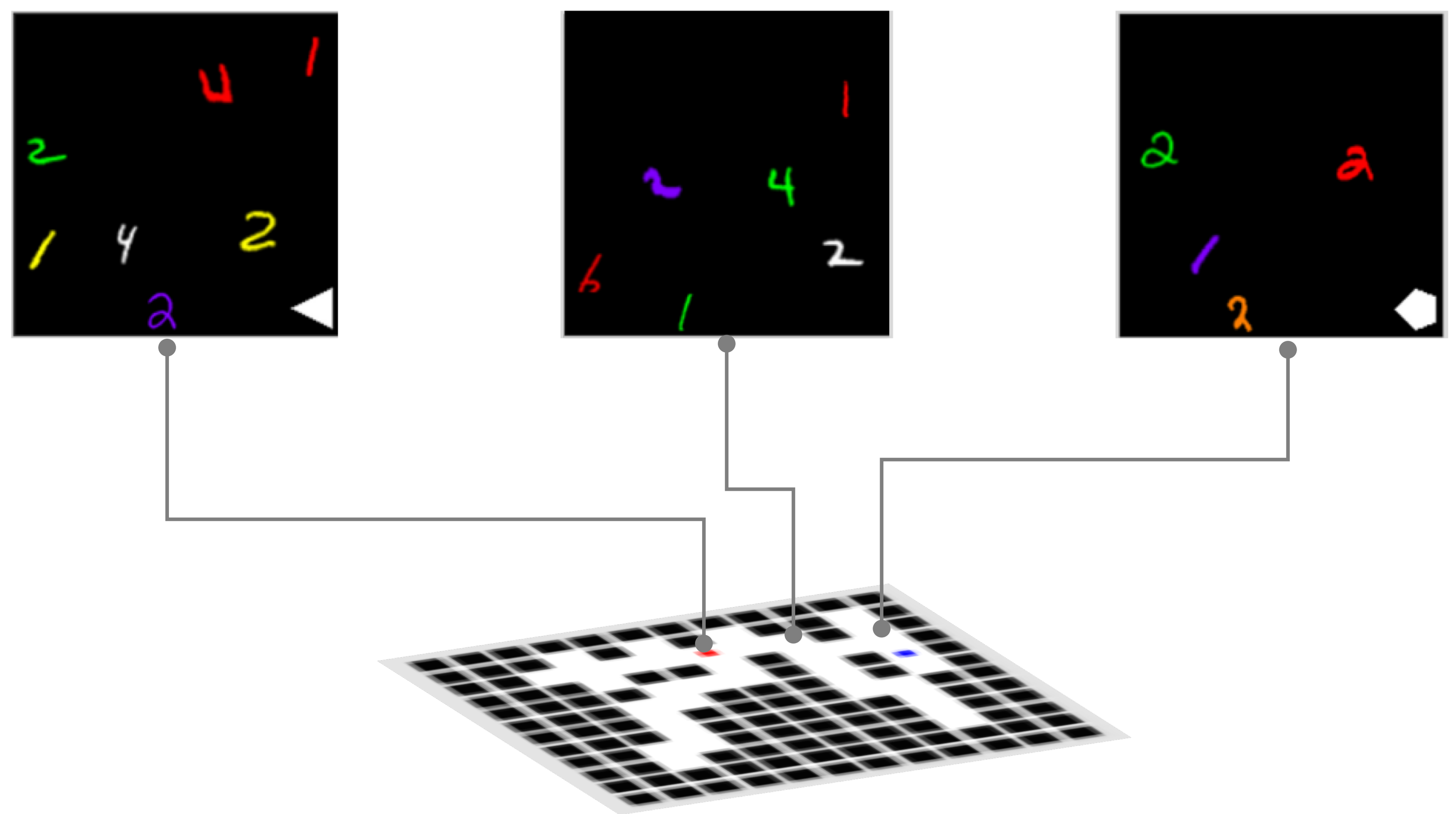
When presented with an object in visual scenes, humans understand

- *semantics*, i.e. what it is in terms of classification,
- *affordances*, i.e. what can be done with it in terms of task solving.

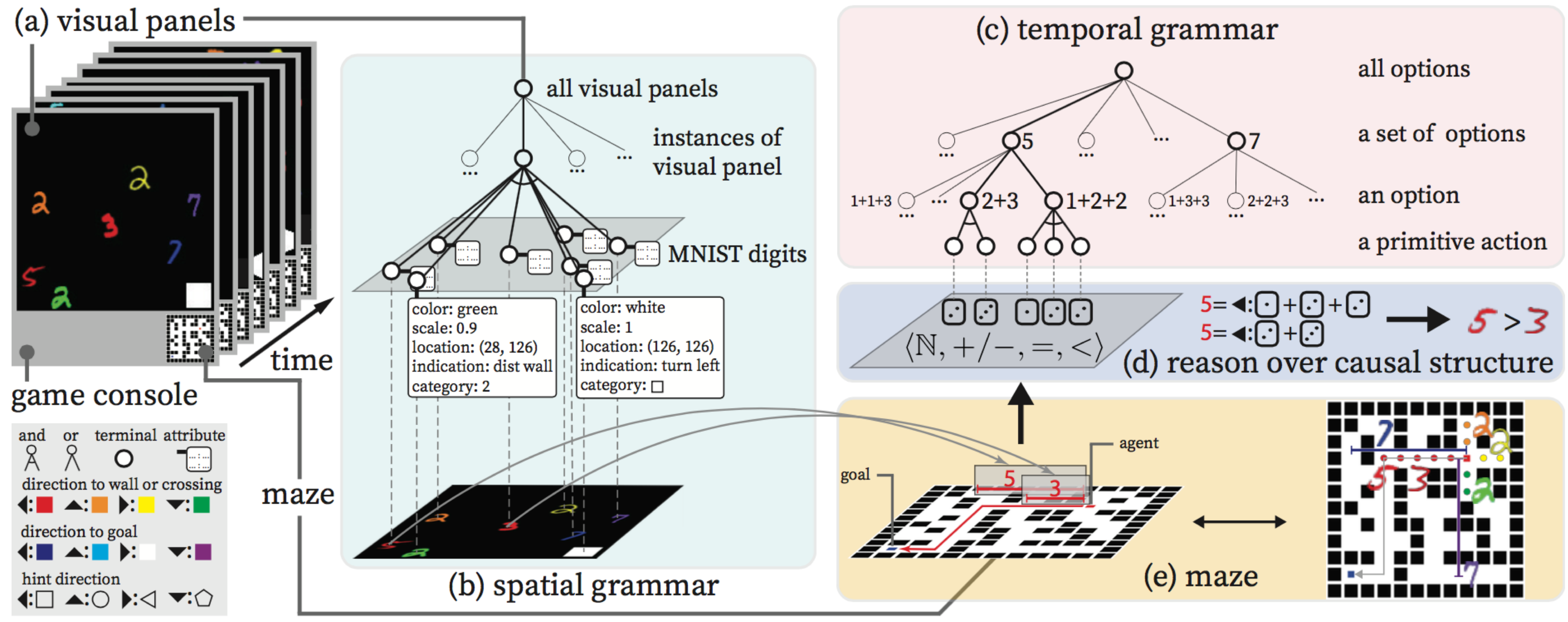
Once these concepts are understood, humans generalize them to similar contexts to form strategies for rapid problem-solving.

The HALMA Domain

- Imagine you are in a dark space where you can see almost nothing. The only things you can see are colored digits and some geometric symbols.
- You can make some moves to instantly transit around the dark space. Each move consists of a direction and then a sequence of numbers.
- A move can be either affordable or not, depending on the maze structures of the dark spaces.

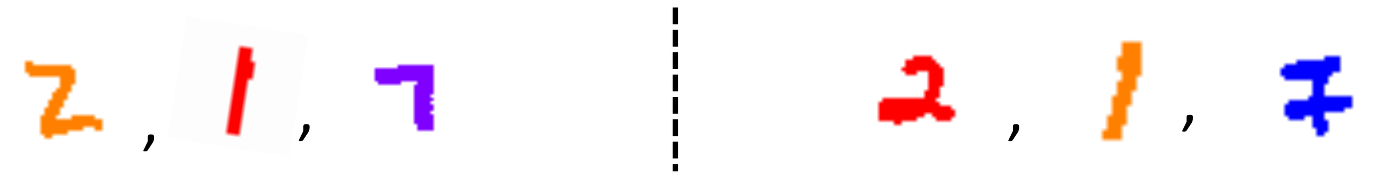


The Structured Distributions of HALMA

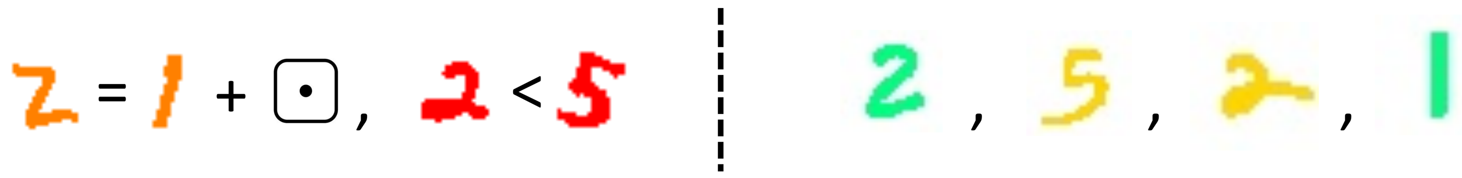


Systematic Generalization Splits at Three Levels

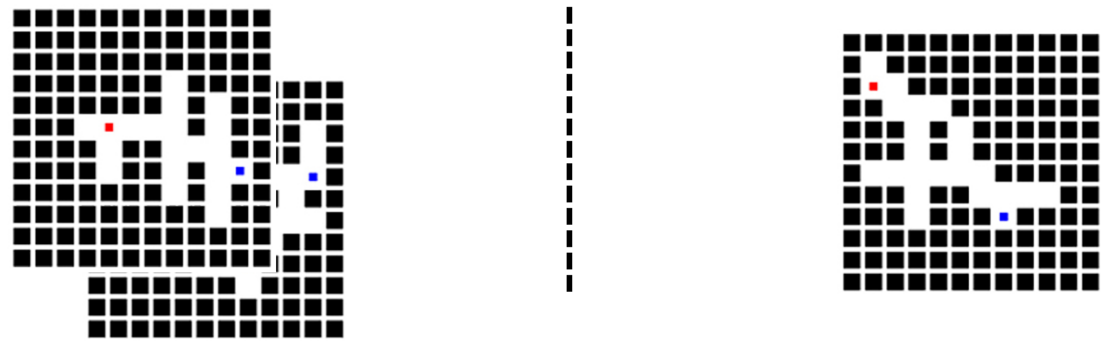
- *Perceptual Generalization*



- *Conceptual Generalization*

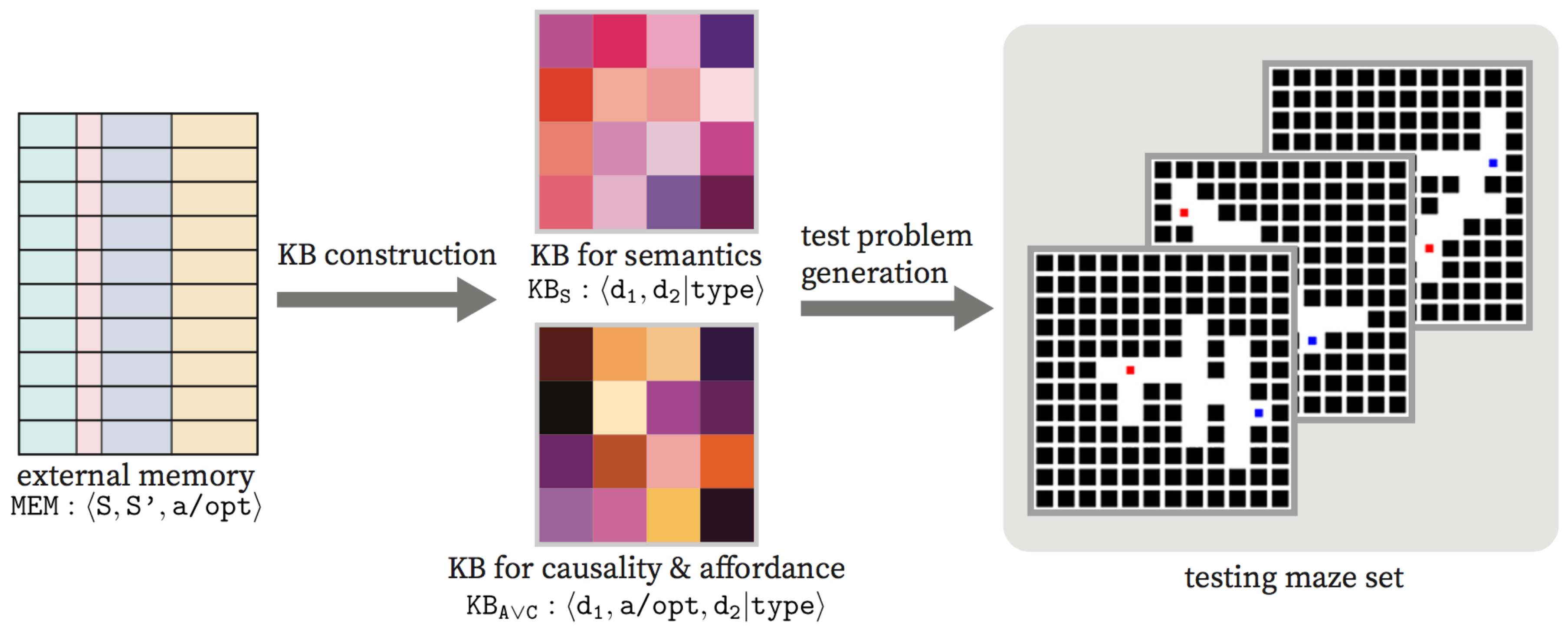


- *Algorithmic Generalization*



$$\mathbb{E}_{\zeta}\left[\sum_{i=0}^{N} \gamma^{\sum_{j=0}^{i-1} \mathrm{len}(\tau_j)} \sum_{t=0}^{\mathrm{len}(\tau_i)-1} \gamma^t R(s_{\tau_i,t}, a_{\tau_i,t})\right].$$

Dynamically Generated Tests for OOD Assessment



Benchmarking Deep RL Agents for OOD Generalization

	Test Type & Examples	%	SYMBOLIC (max_opt_len=5) MLP	LSTM	TRAN	TRAN+LSTM	VISUAL (max_opt_len=1) CNN+MLP	CNN+TRAN	SPACE
T	Training problems	$\rho_a \uparrow$	94.78±4.11	87.88±2.14	85.43±6.77	86.95±3.09	85.61±7.22	89.71±2.61	83.55±2.65
		$\rho_g \uparrow$	99.23±0.63	57.22±3.07	93.85±1.26	72.33±5.79	75.76±4.77	58.33±4.19	16.33±0.94
		$\rho_p \uparrow$	71.67±1.73	50.91±3.54	67.89±0.63	63.97±5.84	63.77±2.68	35.31±3.00	12.02±1.17
RT	Random split	$\rho_a \uparrow$	62.98±1.52	76.09±2.10	65.15±4.45	62.31±2.90	13.30±2.30	43.09±7.92	41.62±1.20
		$\rho_g \uparrow$	51.00±2.21	57.78±3.49	82.82±0.96	54.00±2.94	7.58±0.43	14.00±4.24	3.67±0.47
		$\rho_p \uparrow$	54.91±2.85	45.15±1.46	58.07±1.01	40.13±2.52	5.09±1.17	8.33±1.96	2.66±0.19
ST	⟨3, 5, 1, 7⟩ ∈ MEM,	$\rho_g \uparrow$	55.00±7.07	50.00±8.16	41.67±8.50	66.67±13.12	0.00±0.00	0.00±0.00	0.00±0.00
	test ⟨3, 5, 4, 2⟩ ∉ MEM.	$\rho_p \uparrow$	19.90±2.18	24.02±7.20	16.34±3.90	35.74±5.85	0.00±0.00	0.00±0.00	0.00±0.00
	3 < 5 ∈ KB$_S$,	$\rho_g \uparrow$	25.00±8.16	63.33±6.24	43.33±6.23	78.33±2.36	0.00±0.00	0.00±0.00	0.00±0.00
	test ⟨3, 5⟩ ∉ KB$_S$.	$\rho_p \uparrow$	7.37±2.33	26.31±2.34	12.22±1.83	34.79±4.25	0.00±0.00	0.00±0.00	0.00±0.00
AfT	5 = 3 + ◀ : ⚁ ∈ KB$_{AVC}$,	$\rho_g \uparrow$	41.67±2.36	60.00±10.80	36.67±8.50	58.33±10.27	0.00±0.00	0.00±0.00	0.00±0.00
	test ⟨3, 5⟩ ∉ KB$_S$.	$\rho_p \uparrow$	15.10±0.35	28.91±7.62	14.01±3.75	27.11±2.12	0.00±0.00	0.00±0.00	0.00±0.00
	{5 = ▲ : ⚁ + ⚂, 3 = ▲ : ⚂}	$\rho_g \uparrow$	31.67±8.50	45.00±10.80	43.33±6.24	71.67±6.24	0.00±0.00	0.00±0.00	0.00±0.00
	⊂ KB$_{AVC}$, test ⟨3, 5⟩ ∉ KB$_S$.	$\rho_p \uparrow$	11.68±3.34	17.15±5.82	17.86±3.02	35.40±3.71	0.00±0.00	0.00±0.00	0.00±0.00
	5 = 3 + ▲ : ⚁ ∈ KB$_{AVC}$,	$\rho_g \uparrow$	6.67±2.36	100.00±0.00	25.00±0.00	-	0.00±0.00	0.00±0.00	0.00±0.00
	test ⟨3, 5⟩ ∉ KB$_S$.	$\rho_p \uparrow$	1.48±0.52	51.86±0.18	5.83±0.24	-	0.00±0.00	0.00±0.00	0.00±0.00
	{5 = ▶ : ⚁ + ⚂, 3 = ▼ : ⚂}	$\rho_g \uparrow$	0.00±0.00	86.67±9.43	50.00±0.00	-	0.00±0.00	0.00±0.00	0.00±0.00
	⊂ KB$_{AVC}$, test ⟨3, 5⟩ ∉ KB$_S$.	$\rho_p \uparrow$	0.00±0.00	29.89±2.18	10.00±0.00	-	0.00±0.00	0.00±0.00	0.00±0.00
AnT	{3 < 4, 4 < 5, 3 < 5, 6 < 7, 7 < 8} ⊂ KB$_{ST \vee AfT}$,	$\rho_g \uparrow$	35.00±7.07	48.33±4.71	41.67±2.36	41.67±13.12	0.00±0.00	-	0.00±0.00
	test ⟨6, 8⟩ ∉ KB$_{ST \vee AfT}$.	$\rho_p \uparrow$	12.19±1.84	21.84±0.53	14.45±1.66	22.03±6.64	0.00±0.00	-	0.00±0.00

Ablation on Data Volume and Movement Complexity

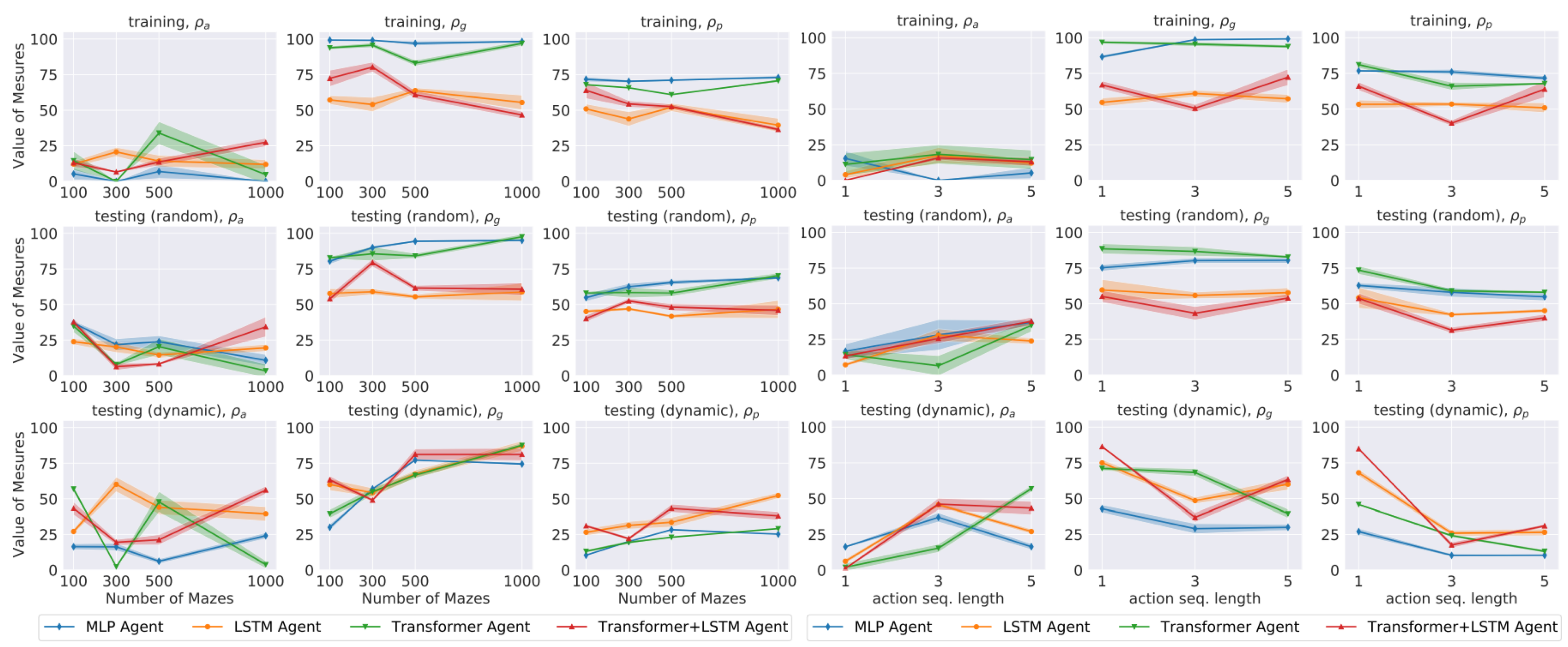


Figure S14: Ablation study of different number of training mazes.

Figure S15: Ablation study of different max_opt_len (symbolic observations).