Multi-Agent Framework for Human User Simulation

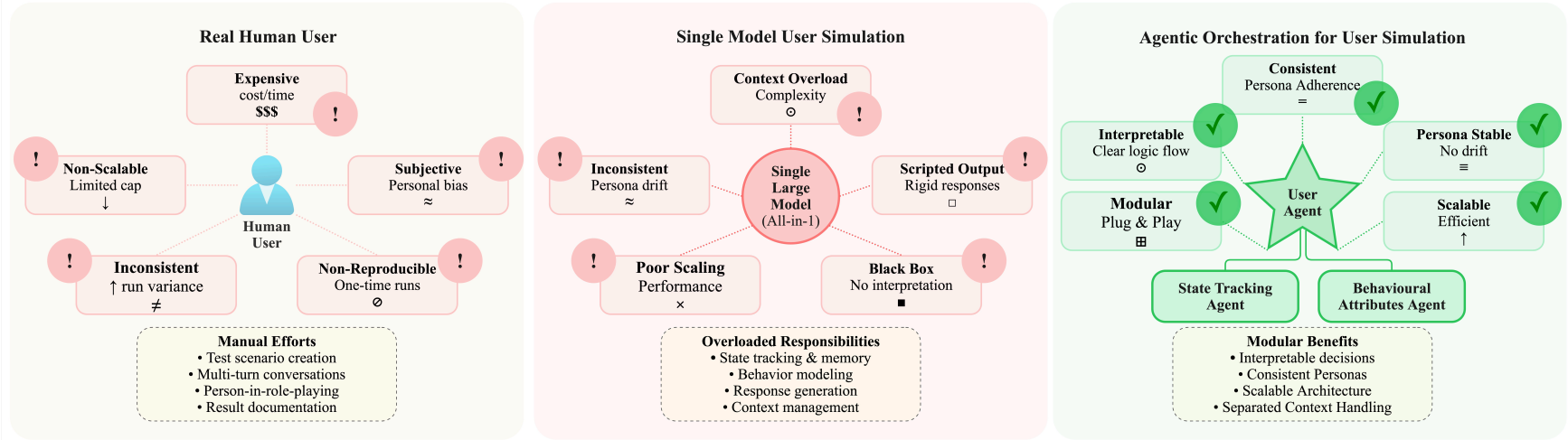
in Interactive Conversational AI Systems

A Novel Approach to Testing Conversational AI at Scale →

Read the Full Paper

9/5/2025

The Challenge



Testing conversational AI at scale is difficult

- Need realistic, diverse user interactions
- Complex behavioral patterns across personas
- Multi-turn conversation dynamics

Current approaches fall short

- Static test sets miss dynamic nature
- Human evaluators: expensive & hard to scale
- Single LLM: lacks behavioral diversity

Our Solution

Multi-Agent Orchestration

🤖

User

Primary orchestrator

Generates contextually appropriate responses based on input messages, state, and attributes

📊

State Tracking

Structured task state

Maintains current progress and target goals throughout the conversation

🎭

Message Attributes

Behavioral control

Controls mood, execution style, and exploration patterns

Agentic Setup Methodology

User Response Generation

$$r_t = f_{user}(m_t, s_t, a_t)$$

- r_t = response at turn t
- m_t = input message
- s_t = task state
- a_t = behavioral attributes

State Tracking

$$s_t = f_{stateTracking}(input\_message)$$

$$= \{\mathcal{T}_{current}, \mathcal{T}_{target}\}$$

- $\mathcal{T}_{current}$ = confirmed task items
- $\mathcal{T}_{target}$ = desired final state

Message Attributes

$$a_t = f_{msgAttrGen}(p_{bio}, s_t)$$

$$a_t = \{mood\_tone, task\_execution\_style,$$

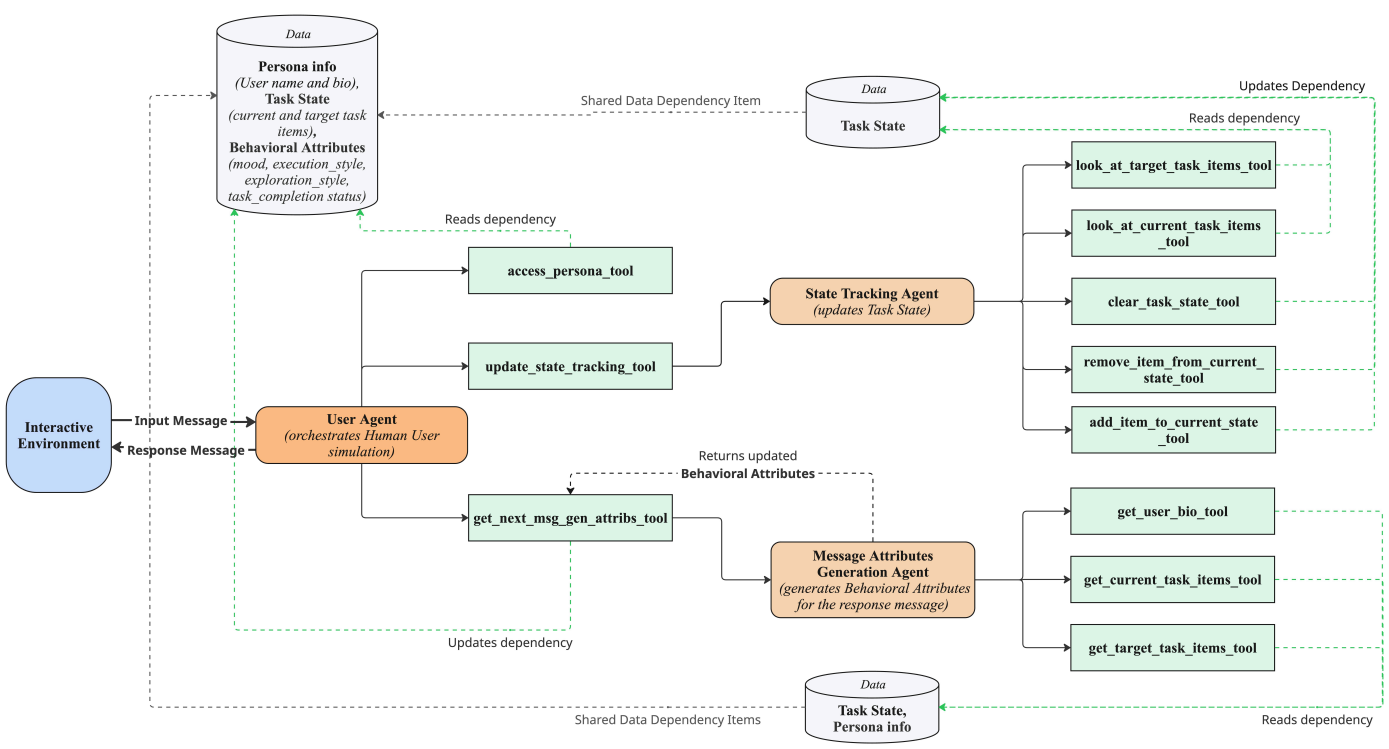
$$exploration\_style, task\_completion\_status\}$$

- p_{bio} = persona biography
- $mood\_tone$ ∈{casual, frustrated, confused, enthusiastic}
- $task\_execution\_style$ ∈{one-by-one, all-at-once}
- $exploration\_style$ ∈{explores, does-not-explore}
- $task\_completion\_status$ ∈{complete, incomplete}

Exit Gating

$$task\_completion\_status = \begin{cases} complete & \text{if } \mathcal{T}_{current} \supseteq \mathcal{T}_{target} \\ incomplete & \text{otherwise} \end{cases}$$

System Architecture



Validation Domain

Restaurant Guest Ordering

Why restaurant ordering?

✅ **Task Complexity**

- Multi-turn conversations
- Menu navigation
- Customization handling

✅ **State Management**

- Multiple items with modifiers
- Order building process
- Clarification handling

✅ **Behavioral Diversity**

- Different foodie personas
- Ordering styles
- Emotional responses

Dataset

📊 **20** diverse guest personas

🍽️ **50+** menu items with customizations

🧪 **60** test cases (3 per persona)

Implementation

- **Framework**: Pydantic AI with GPT-4o
- **Tools**: Type-safe definitions
- **Logging**: Comprehensive tracking

Ordering System

- LLM-based (GPT-4o) restaurant interface
- Natural language processing
- Menu knowledge & clarification handling
- Independent of guest simulation

Evaluation Metrics (1/2)

Persona Adherence Score (PAS)

$$PAS = \frac{1}{N}\sum_{i=1}^{N} MS_i$$

$$MS_i = \sum_{j=1}^{4} w_j \cdot C_j$$

- N = number of messages
- Equal weights $w_j = 0.25$ for:
  - Exploration style, mood tone
  - Task execution, completion status

Behavioral Variance Score (BVS)

$$TR_d = \frac{1}{M-1}\sum_{i=2}^{M} \mathbb{I}(state_i^d \neq state_{i-1}^d)$$

$$TR_{avg} = \frac{TR_{task\_execution\_style} + TR_{exploration\_style} + TR_{mood\_tone}}{3}$$

$$BVS = \begin{cases} \frac{TR_{avg}}{0.2} & \text{if } TR_{avg} \leq 0.2 \\ 1 - \frac{TR_{avg} - 0.2}{0.8} & \text{if } TR_{avg} > 0.2 \end{cases}$$

- TR_d = transition rate for behavioral dimension d
- Optimal at 20% transition rate

Task Restriction Adherence (TRA)

$$TRA = \frac{2 \cdot Precision \cdot Recall}{Precision + Recall}$$

$$Precision = \frac{|C \cap T|}{|C|}, Recall = \frac{|C \cap T|}{|T|}$$

- T = normalized target items
- C = normalized current state items

Decision Explainability Index (DEI)

$$DEI = \begin{cases} 0 & \text{No tools} \\ \min(0.2, \frac{ED}{N} \times 0.2) & \text{Basic tools} \\ \min(0.5, \frac{ED}{N} \times 0.5) & \text{Basic + 1 agent} \\ \min(1.0, \frac{ED}{2N}) & \text{Full system} \end{cases}$$

- ED = explained decisions, N = messages

Evaluation Metrics (2/2) - Composite Score

Composite Realism & Reliability Score (CRRS)

$$CRRS = 0.25 \cdot PAS + 0.20 \cdot BVS$$

$$+0.35 \cdot TRA + 0.20 \cdot DEI$$

Unified score for overall simulation quality

Weight Distribution

- **TRA (35%)**: Primary task completion metric
- **PAS (25%)**: Persona consistency
- **BVS (20%)**: Natural behavioral variation
- **DEI (20%)**: System validation & explainability

Task completion gets highest weight as it's critical for simulation success

Metric Ranges & Interpretation

All metrics normalized to 0, 1 range:

- **PAS**: 1 = perfect persona adherence
- **BVS**: 1 = optimal variance (20% transitions)
- **TRA**: 1 = perfect F1 score for task items
- **DEI**: 1 = full explainability with tools
- **CRRS**: 1 = perfect overall simulation

Performance Targets

- **CRRS > 0.8**: Excellent simulation quality
- **CRRS 0.6-0.8**: Good simulation quality
- **CRRS < 0.6**: Needs improvement

Ablation Study Design

Configuration	Order Tracking	Message Attributes	Architecture
Config 1 (Baseline)	❌	❌	Single LLM
Config 2 (User Only)	❌	❌	Single Agent
Config 3 (User + ST)	✅	❌	Two Agents
Config 4 (User + MAG)	❌	✅	Two Agents
Config 5 (Full System)	✅	✅	Three Agents

Testing contribution of each component systematically

Results: Performance & Statistical Significance

Performance Metrics

Config	PAS	BVS	TRA	DEI	CRRS
1	0.589	0.218	0.608	0.000	0.404
2	0.585	0.485	0.582	0.200	0.487
3	0.554	0.689	**0.785**	0.498	0.651
4	**0.661**	0.000	0.602	0.432	0.462
5	0.706	**0.839**	**0.785**	**0.994**	**0.818**

🎯 **Full Multi-Agent System Achieves 102.6% Improvement**

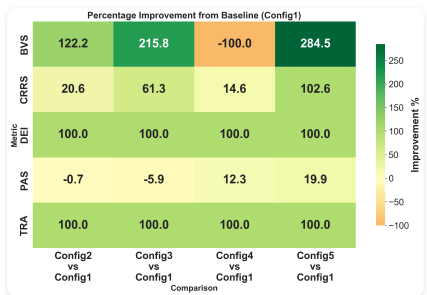
CRRS score doubles from 0.404 (baseline) to 0.818 (full system)

Statistical Significance

(Baseline vs Full System)

Metric	Δ	p-value
PAS	+20%	0.004**
BVS	+285%	<0.001***
TRA	+29%	0.005**
DEI	+100%	<0.001***
CRRS	+103%	<0.001***

** p < 0.01, *** p < 0.001



✅ All metrics significant (p < 0.01)

Key Findings

🔗 Component Synergy

- Config 3 (State only): High TRA, low PAS
- Config 4 (Attrs only): High PAS, zero BVS
- **Config 5 (Full): Best across all metrics**

> Neither sub-agent alone achieves optimal performance

🤖 Behavioral Rigidity

- Pure behavioral control without state awareness
- Results in robotic, templated interactions
- **BVS = 0 for Config 4**

> State awareness is critical for natural variance

💰 Cost-Performance Trade-off

Config	Avg Tokens	Latency (s)	CRRS
Baseline	6,618	5.08	0.404
Full System	14,789	23.16	**0.818**

2.2x tokens for 2x performance improvement

Limitations, Ethics, Future Work & Applications

Current Limitations

- 📈 High computational cost (124% more tokens)
- 🔧 Domain-specific engineering required
- 🌐 English-only validation
- 🧠 Lacks complex behaviors

Ethical Considerations

- 🔍 Maintain transparency
- ⚖️ Avoid bias perpetuation
- 🚫 No impersonation without consent
- 🛡️ Responsible deployment

Future Directions

🔄 Adaptive Evolution
Dynamic behavioral adjustment

🤹 Multi-Modal
Voice, gesture, emotional tracking

🌍 Cross-Domain
Healthcare, education, travel

⚡ Optimization
Caching, selective invocation

Applications

Testing & QA

- Automated conversation testing
- Edge case discovery
- Performance benchmarking

Broader Domains

- 🗣️ Voice assistants
- 💬 Chatbots & virtual agents
- 🏥 Healthcare interfaces
- 🛍️ E-commerce platforms
- 📚 Educational tools
- 💼 Business automation

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Code & Data Availability

Implementation code, test datasets, and evaluation scripts available at:
`https://github.toasttab.com/hareeshkarthik-toast/agentic-human-guest-simulation-for-ordering`