Information-Theoretic Analysis of a Minimally-Cognitive Agent
The Relational Categorization Tasks

Cue Stage

Probe Stage

$\bar{z}_{\text{probe}} < \bar{z}_{\text{cue}}$

$\bar{z}_{\text{probe}} > \bar{z}_{\text{cue}}$
A Framework for Information-Theoretic Analysis

$x_i$

$X_t$

$S1$

$S7$

$N1$

$N3$

$M1$

$M2$

$X$

$t_1$

$t_2$

$t_3$
Information About Stimulus Features

![Diagram showing stimulus features and output over time.](image-url)
Extracting the Data

(20, 20)

\[
\begin{array}{cccc}
0 & <S1> & \cdots & <N1> \\
\vdots & \vdots & \ddots & \vdots \\
62.1 & <S1> & \cdots & <N1> \\
\vdots & \vdots & \ddots & \vdots \\
146.7 & <S1> & \cdots & <N1> \\
\vdots & \vdots & \ddots & \vdots \\
\end{array}
\]

\{20, <N1>\}

\{50, <N1>\}

(50, 20)

\[
\begin{array}{cccc}
0 & <S1> & \cdots & <N1> \\
\vdots & \vdots & \ddots & \vdots \\
62.1 & <S1> & \cdots & <N1> \\
\vdots & \vdots & \ddots & \vdots \\
146.7 & <S1> & \cdots & <N1> \\
\end{array}
\]
Computing the Distributions

\{20, <N1>\} \ldots \{50, <N1>\}

Interpolate

\begin{align*}
& \text{\textbf{o}_1} \\
& \text{\textbf{Z}_{\text{cue}}} \\
& p(\text{\textbf{o}_1}) \\
& p(\text{\textbf{Z}_{\text{cue}}}) \\
& p(\text{\textbf{Z}_{\text{cue}}, \text{\textbf{o}_1}})
\end{align*}
Computing Mutual Information

\[ I(Z_{\text{cue}}; O_1) = \sum_{i=1}^{N_Z} \sum_{j=1}^{N_O} p([Z_{\text{cue}}]_i, [O_1]_j) \log \frac{p([Z_{\text{cue}}]_i, [O_1]_j)}{p([Z_{\text{cue}}]_i) p([O_1]_j)} \]

\[ \frac{I(Z_{\text{cue}}; O_1)}{H(Z_{\text{cue}})} \approx 0.828 \]
Passive Agent
Cue Stage Information Flow

- \( I(Z_{\text{cue}}; S_i) \)
- \( I(Z_{\text{cue}}; X) \)
- Graphs showing the information flow over time for different cues and conditions.
Cue Stage Information Flow

Specific Information

Information Gain

Information Transfer

$I_T(Z_{\text{cue}} = z; S_{3/5} \rightarrow O_3)$

$I_T(Z_{\text{cue}} = z; S_{2/6} \rightarrow O_3)$

$I_T(Z_{\text{cue}} = z; S_{1/7} \rightarrow O_3)$

$I_G(Z_{\text{cue}} = z; O_3)$

$I_K(Z_{\text{cue}} = z; O_3)$
motor neuron and subsequently flows to plots we see that relative size information first builds up in formation transfer from nation of the agent's catch/avoid response. Indeed, calculating the information transfer from the high amount of information that ends up in suggests a direct transfer of relative size information along the path up of relative size information in by a similar pattern for the agent's horizontal position (Figure 7.8). This sequential build-up of relative size information accumulates in N1 (Figure 7.8). This sequential build-up of relative size information ultimately drives the agent's behavioral response. In particular, shortly after relative size information accumulates in N1 (Figure 7.8), the transfer of relative size information from the right motor neuron (Figure 7.8) confirms that this is the case, with a high amount of transfer where it is reflected in the agent's behavior. In the right motor neuron (Figure 7.8), the transfer of relative size information from X is the information-theoretic manifestation of the agent's catch/avoid response. In particular, shortly after relative size information accumulates in N1 (Figure 7.8), the transfer of relative size information ultimately drives the agent's behavioral response. In particular, shortly after relative size information accumulates in N1 (Figure 7.8), the transfer of relative size information ultimately drives the agent's behavioral response. In particular, shortly after relative size information accumulates in N1 (Figure 7.8), the transfer of relative size information ultimately drives the agent's behavioral response.
A Puzzle

[Graph showing three lines labeled N1, N2, and N3 over time (t) with question mark indicating uncertainty.

\[ I(R; O_t) \]
Active Agent
Active Agents: Cue Stage Information Flow

Where is Cue Size Stored?

Information Offloading
Active Agents: Probe Stage Information Flow

How is Probe Size Extracted?

Information Self-Structuring
Information Self-Structuring

7. Information Dynamics of Embodied Relational Categorization

Figure 7.12: Self-structuring of relative size information. The flow of relative size information for all sensors (gray lines) and the horizontal position (red line) of the (a) active and (b) passive agents.

About $F$ to flow along the path $N_1 ! M ! X ! S$ and influence the sensors. Thus, in this instance, the benefits of information self-structuring are clearly demonstrated, with the active agent able to circumvent considerable cognitive demands simply by moving its body.

7.4 Discussion

One of the primary strengths of our information dynamics approach is that it applies naturally to situated and embodied aspects of behavior. As demonstrated in the previous section, techniques for analyzing information dynamics apply just as readily to bodily and environmental variables as they do to sensory and neural ones, and thus can be used to investigate interactions that span the brain-body and body-environment boundaries. In future work, we plan to apply these techniques to analyze other agents that exhibit interestingly embodied and extended solutions to cognitive tasks. For example, a previously evolved feature categorization agent $^{17}$ was found to repeatedly scan falling objects before deciding to catch or avoid them. We plan to investigate what benefits this scanning...
Through the Lens of Information Theory

Informational Explanation

Information Theory