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Holographic Declarative Memory:

A Scalable Memory Module for ACT-R

- Holographic Declarative Memory (**HDM**) is a new module for ACT-R, implemented for Python ACT-R (Stewart & West, 2006).
- HDM is an alternative to ACT-R's Declarative Memory (**DM**).
- HDM replaces DM's symbols with *holographic vectors* (Plate, 1995) and implements a holographic theory of memory based on **DSHM** (Rutledge-Taylor, Kelly, West, & Pyke, 2014) and **BEAGLE** (Jones & Mewhort, 2007).

Holographic Declarative Memory

Architectures

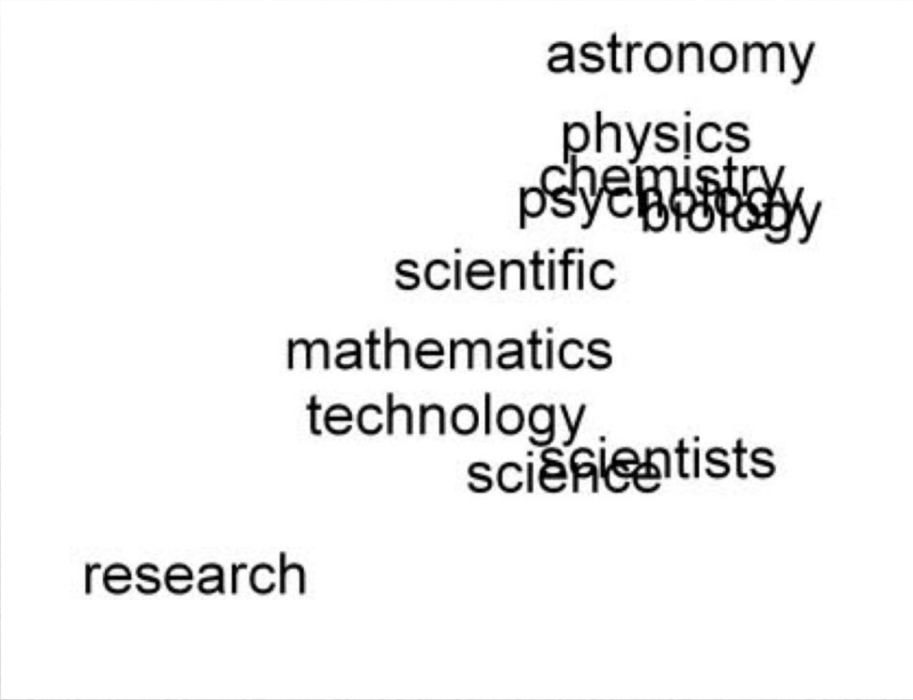
- Symbolic Architectures (e.g., ACT-R DM)
  - concepts and relations between concepts represented as text
  - lists of slot-value pairs
  - **“name:cat type:animal look:furry”**

- Vector Symbolic Architectures (e.g. HDM)
  - concepts and relations between concepts represented as vectors
  - **“name:cat type:animal look:furry”**
  - **= [0.0916, 0.5175,-0.8271, 0.1983, 0.0197 …]**

- Connectionist / Neural Network Architectures
  - neurons and neural connectivity represented by vectors of patterns of activation and matrices of connection weights

Vector space

- Vectors can be understood as describing coordinates in a high-dimensional space
- Points close in space have similar meaning
- Allows for shades of meaning and partial matching



Why use holographic vectors?

- Holographic vectors retain the expressive power of symbols
  - Compactly store complicated, recursive relations between ideas
- Holographic vectors have a similarity metric, allowing for…
  - Shades of meaning and fuzzy / partial matching
  - Lossy compression for modeling forgetting
  - Fault tolerance
- HDM can enhance ACT-R’s ability to:
  - Scale to big data / model long-term learning
  - Learn association strengths from experience
  - Provide a bridge to neural realization

- Holographic models of memory in the literature

- Case Study: The Fan Effect
  - What is the fan effect?
  - The ACT-R DM model of the fan effect
  - The HDM model of the fan effect

- Results: How does DM and HDM compare?
- Analysis: Why does HDM work?
- Conclusions / future work

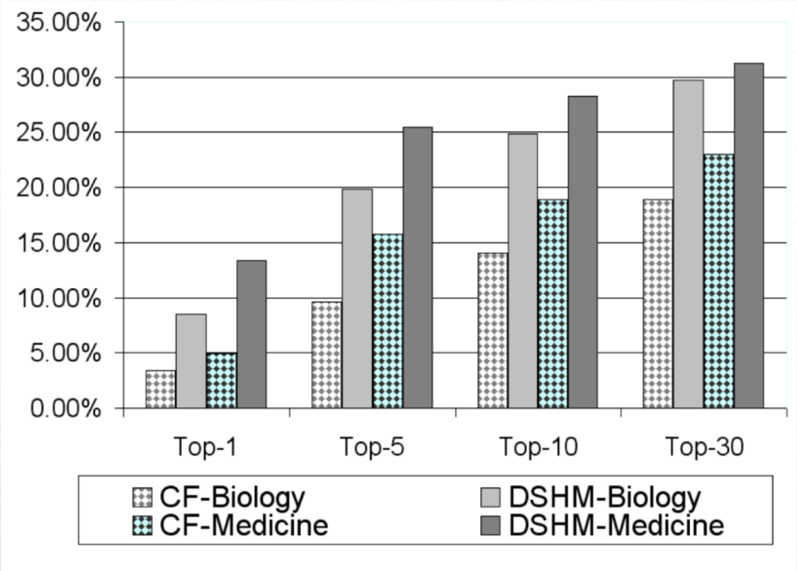
In what follows …

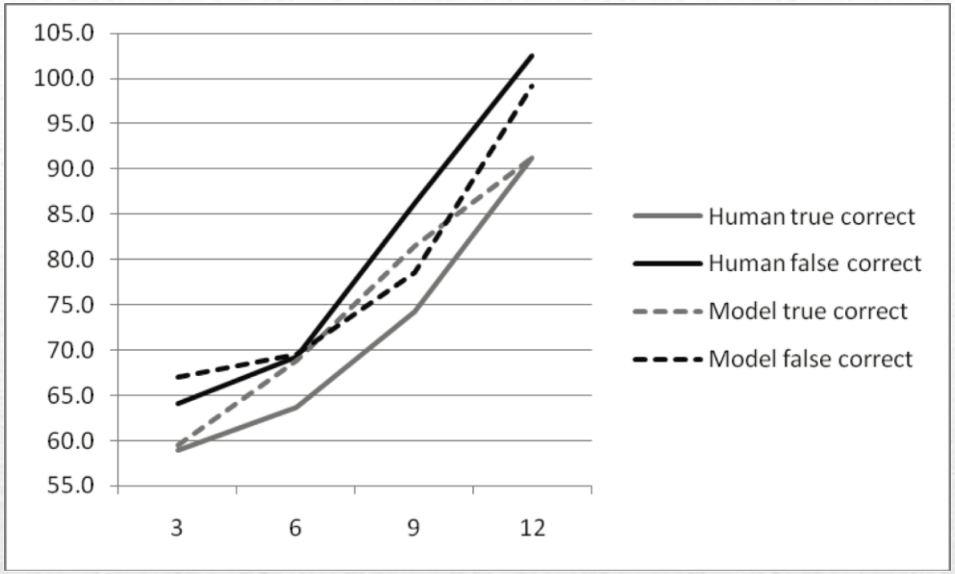
- Explain and predict a variety of human **memory** phenomena
  - **Fan** effect (Rutledge-Taylor et al., 2014)
  - **Serial recall** and **free recall** of lists (Franklin & Mewhort, 2015)
  - **Implicit** learning (Jamieson & Mewhort, 2011)
- **Analogical reasoning**
  - (Plate, 2000; Eliasmith & Thagard, 2001)
- Simple **problem-solving** tasks
  - (Eliasmith, 2013; Rutledge-Taylor et al., 2014)
- **SPAUN**, the world's largest functional **brain model**
  - (Eliasmith, 2013)
- **BEAGLE**, a model of learning **word meaning** from a corpus
  - (Jones & Mewhort, 2007)

Holographic memory in the literature

BEAGLE
(Jones & Mewhort, 2007)

- Takes a corpus as input
- Produces a set of vectors representing word meaning
- Similarities between vectors produce clusters of topic and part of speech
- Vector similarities predict semantic priming data





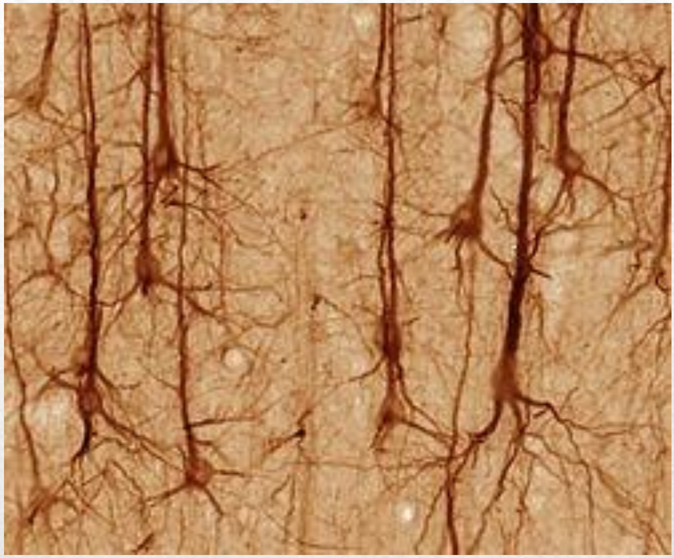
- Applies BEAGLE to non-lingusitic stimuli
- Models two-term and three-term fan effect
- Models rock-paper-scissors play
- Effective recommender system for movies or research papers

DSHM (Rutledge-Taylor et al., 2014)

- **ACT-R** describes mental processes and **brain areas** associated with them, but does not address the question of how those mental processes are carried out at the neural level.

- **Holographic vectors** can be implemented in realistic neural models.

- **HDM** can be straightforwardly implemented in the **Neural Engineering Framework** (Eliasmith, 2013), a theory of neuro-computation.



Neural realization (Eliasmith, 2013)

- “the **hippy** is in the **park**”
- “the **hippy** is in the **bank**”

fan(**hippy**) = 3

- “the **hippy** is in the **store**”

fan(**store**) = 2

- “the **officer** is in the **store**”

fan(**officer**) = 1

Fan Effect (Anderson, 1974)

Fan Effect (Anderson, 1974)

- participants are **slower** to recognize or reject sentences that contain concepts that have a **higher** *fan.*

- **availability** of information in memory with respect to a cue is related to the **probability** of that piece of information conditional on the cue.

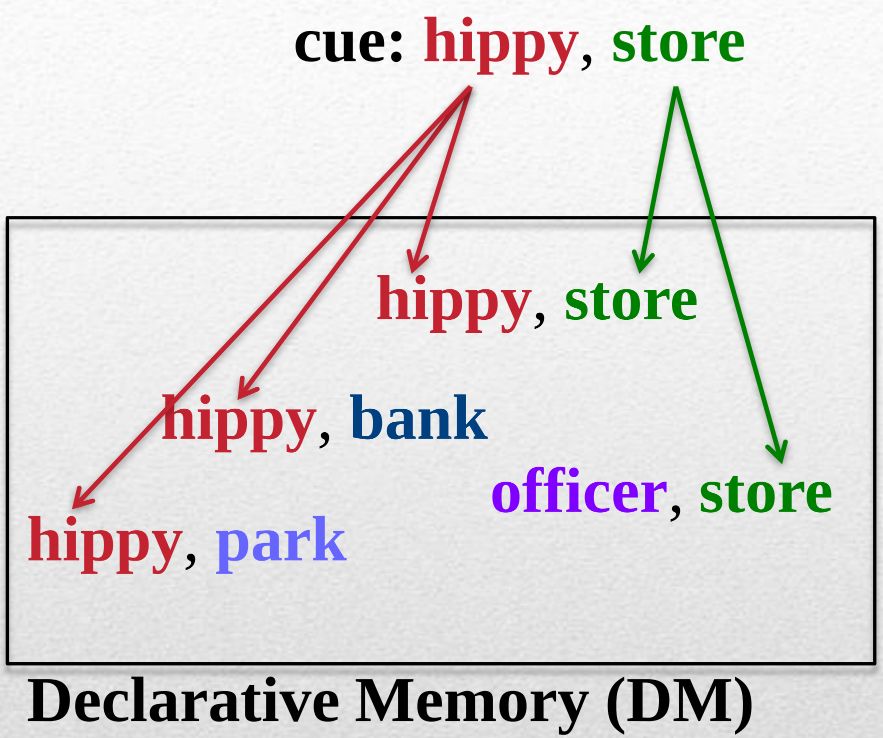
fan(**hippy**) = 3

fan(**store**) = 2

fan(**officer**) = 1

ACT-R DM model

- sentences are represented as *person*, *location* **chunks** in **DM**
- when the model is cued, **activation** spreads to chunks that share concepts with the **cue**
- DM retrieves most active chunk



- Reaction time T is calculated as:

$$T = I + Fe^{-A_i}$$

- Activation A_i of chunk i is calculated as:

$$A_i = B_i + \sum_{j=1}^{n} W_j \, S_{ji}$$

- Association strength S_{ji} with concept j is:

$$S_{ji} = \mathrm{S} + \ln(\ \mathrm{P}(i|j)\ )$$

- Where $\mathrm{P}(i|j) = 1 / \text{fan of } j$

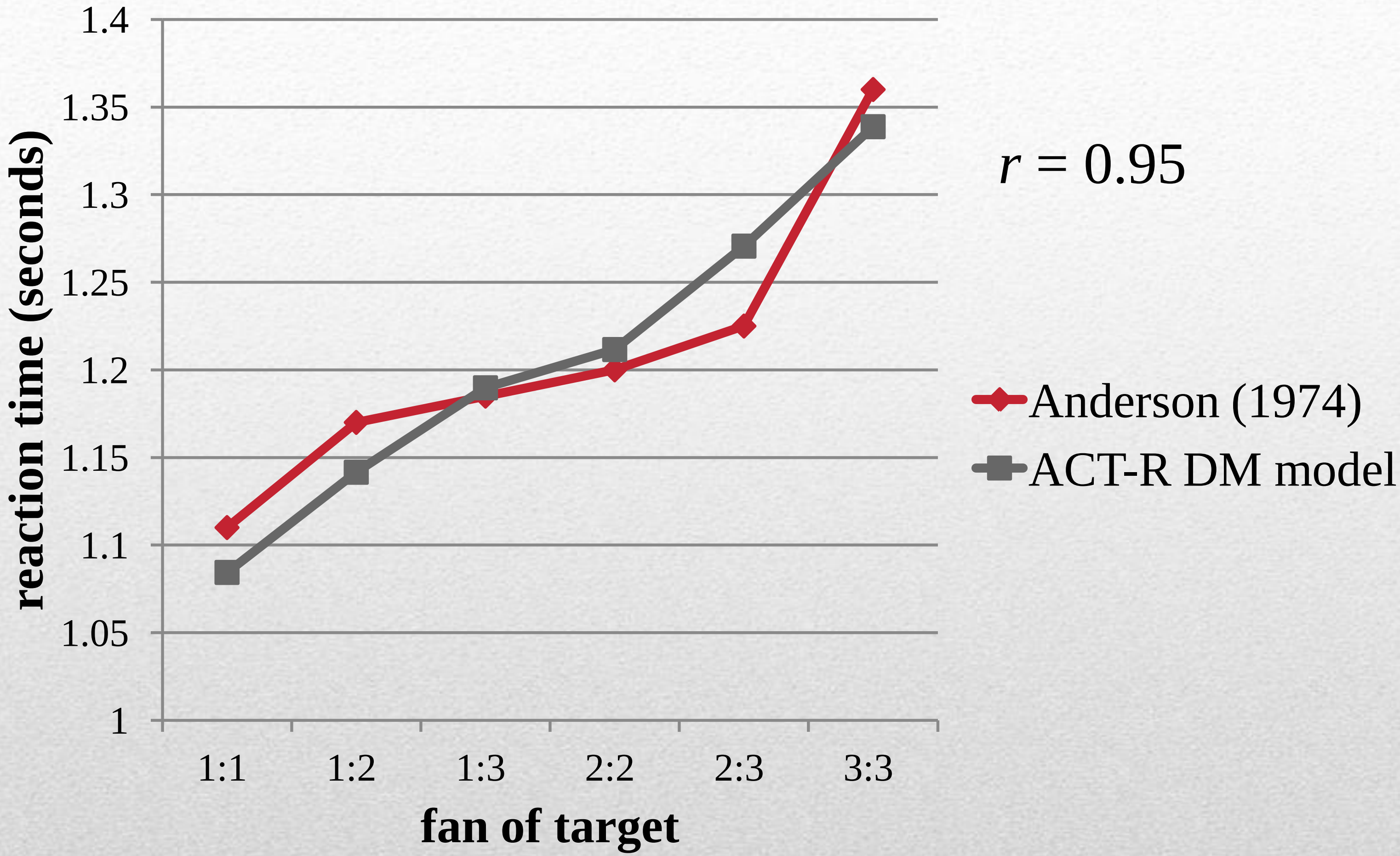
ACT-R DM model

- Anderson and Reder's (1999) model is, in milliseconds:

$$T = 233(f_{\text{person}}\, f_{\text{place}})^{1/3} + 845$$

- where f_{person} is the person's fan and f_{place} is the place's fan

ACT-R DM model
(Anderson & Reder, 1999)



ACT-R DM vs. Human

For each task symbol (or concept) there are two vectors:

environmental vector

- a random vector that stands for what the symbol looks like

memory vector

- a continuously updated vector of the symbol's associations

Additionally, there is one special vector used in all associations:

placeholder vector Φ

- can be read as **?**, i.e., the value that we want to retrieve.
- acts as a stand-in for the purposes of storage and retrieval.

HDM model

* circular convolution is used to create associations between symbols in a sequence.

+ addition is used to add new associations to a memory vector

$\mathbf{P}_{before}$ is a permutation indicating that the permuted vector comes earlier in a sequence.

$\mathbf{P}_{slot}$ is a permutation indicating that the permuted vector is the value associated with the slot *slot*.

Holographic vectors

“the **hippy** is in the **park**”

$\mathbf{m}_{\text{hippy (updated)}} = \mathbf{m}_{\text{hippy}} + (\mathbf{P}_{\text{before}}\ \mathbf{\Phi})*\mathbf{e}_{\text{park}}$ “what came before park?”

$\mathbf{m}_{\text{park (updated)}} = \mathbf{m}_{\text{park}} + (\mathbf{P}_{\text{before}}\ \mathbf{e}_{\text{hippy}})*\mathbf{\Phi}$ “what came after hippy?”

To **encode** an association in HDM, memory vectors are updated with all **questions** to which the memory vector’s **concept** is an appropriate answer given HDM’s experiences.

Encoding associations

To test if “the **hippy** is in the **park**” is in memory, two cues are constructed:

$\mathbf{q}_{hippy?} = (\mathbf{P}_{before}\ \mathbf{e}_{hippy})*\mathbf{\Phi}$ “what came after hippy?”

$\mathbf{q}_{?park} = (\mathbf{P}_{before}\ \mathbf{\Phi})*\mathbf{e}_{park}$ “what came before park?”

The memory vectors most **similar** to these cues are retrieved.

Similarity is measured as the **cosine** of the angle between vectors.

Retrieving associations

Activation & Reaction Time

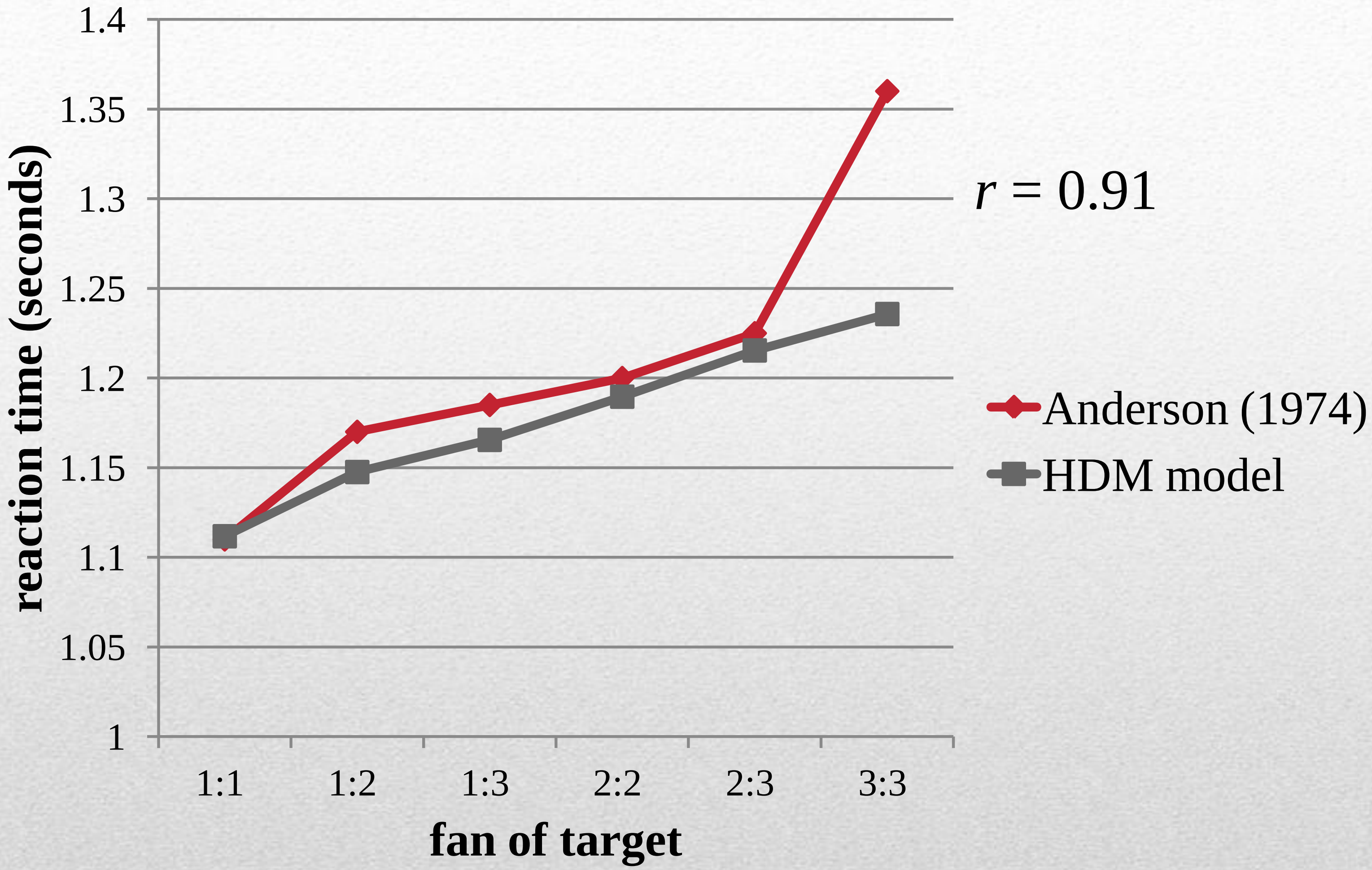
Activation is calculated as the **mean** of the **cosines** between each cue and the memory vector substituted out to create the cue:

$$A = 0.5\ \mathrm{cosine}(\mathbf{q}_{hippy?}\ ,\ \mathbf{m}_{park}) + 0.5\ \mathrm{cosine}(\mathbf{q}_{?park}\ ,\ \mathbf{m}_{hippy})$$

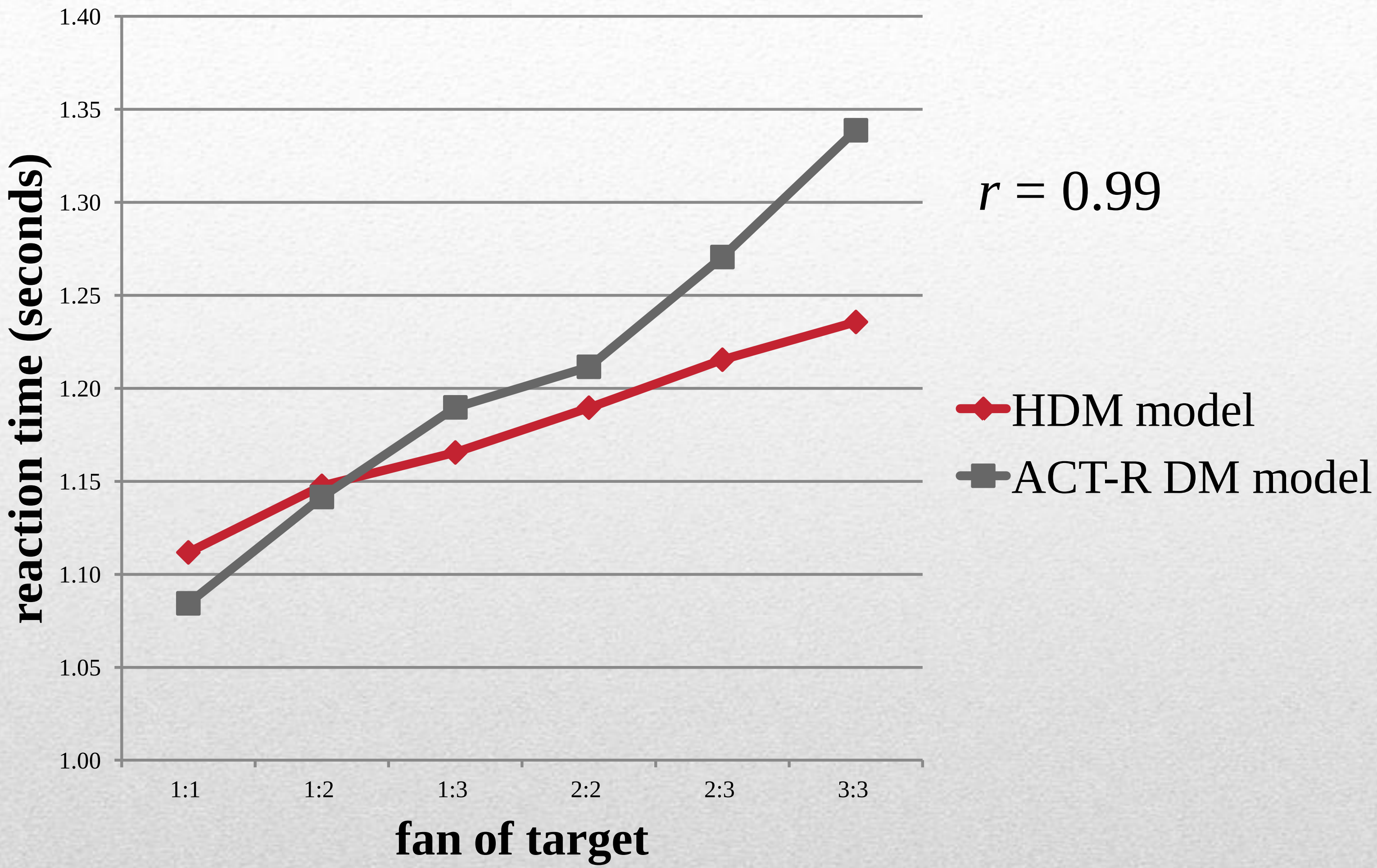
Reaction **time** is computed using **DM**'s reaction time equation:

$$T = I + Fe^{-A_i}$$

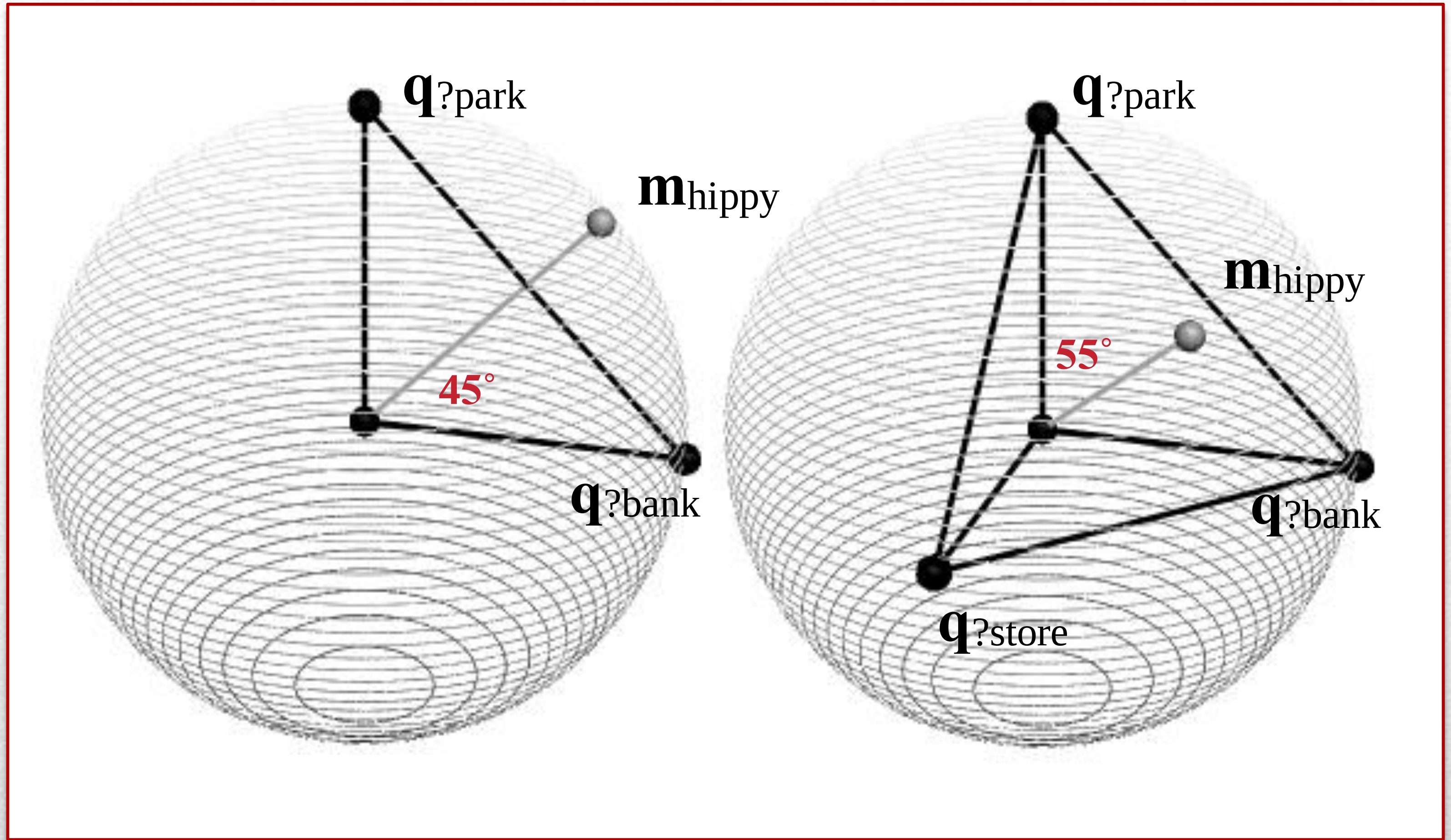
Parameters *I* and *F* set to the values used by Anderson and Reder's (1999) ACT-R DM model.


1.4
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
reaction time (seconds)
1:1
1:2
1:3
2:2
2:3
3:3
fan of target
r = 0.91
Anderson (1974)
HDM model

HDM vs. Human



ACT-R DM vs. HDM



Fan in Vector Space

Probability in Vector Space

- Where f is the fan, the **cosine** between a **cue** and a **memory** vector is $f^{-1/2}$ if the vectors are perfectly orthogonal, or approximates $f^{-1/2}$ for the random vectors used by HDM.

- The cosine in HDM approximates the square-root of the probability only when the events are **equiprobable**.

- For n events with frequencies v_1 to v_n, cosine of event i is:

$$\text{cosine} = \frac{v_i}{\sqrt{v_1^2 + \ldots + v_i^2 + \ldots v_n^2}}$$

Conclusions

We substitute **HDM** for **DM** in the ACT-R model of the fan effect and find that *without changing any parameters* HDM provides a good fit to the **fan effect**.

Both **DM** and **HDM** models of the fan effect claim that reaction time is a function of **conditional probability**. The vector algebra of **HDM** computes an estimate of conditional probability.

We can have HDM mimic DM's fan effect model **exactly** if we substitute **squared cosines** for S_{ji} instead of substituting A for the mean cosine.

HDM, by virtue of being a holographic model, has a number of capabilities for which DM is less suited:

- learning associations between concepts without having association strengths set by the modeler
- analogical or case-based reasoning
- performing tasks that require large amounts of knowledge

Conclusions

A fully vector-symbolic ACT-R would support:

- implementing partial / fuzzy matching in procedural memory
- interference in the buffers
- interfacing with outputs from a perceptual system (e.g., a deep belief network)
- being re-described at the level of neural circuitry

Future work

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