A cognitive architecture-based modelling approach to understanding biases in visualisation behaviour

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Outline of the talk

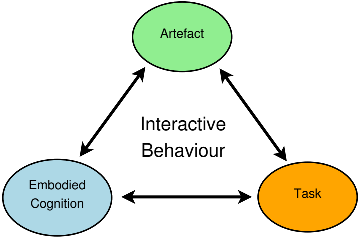
Two aims of the research:

- To understand at a very detailed level of analysis the processes by which people interact with external representations of information (cognitive science).
- To develop artificial agents that can provide expert interpretations of data presented in external representations (AI).

Structure of the talk:

- Human performance modelling.
- Cognitive architectures.
- ACT-R cognitive architecture.
- A recent example: An ACT-R model of graph comprehension.

The embodied cognition-task-artefact triad



- **Interactive behaviour:**
  - Emerges from dynamic interaction of goal-directed, task-driven cognition/perception/action with designed task environment.
  - A complex combination of bottom-up stimulus driven and top-down goal and knowledge driven processes.
- Makes little sense to consider and investigate cognition in isolation.

Understanding behaviour with visualisations

Requires detailed understanding of the wide range of factors that affect human performance.

- **Internal to the agent:**
  - Domain and graphical representation knowledge (expertise)
  - Working memory capacity
  - Strategies
  - Learning/adaptation to task environment
- **External to the agent:**
  - Computational affordances
  - Emergent/salient features
  - Gestalt principles of perceptual organisation
  - Task and environment complexity

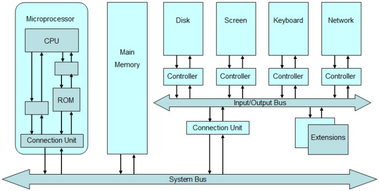
Human performance modelling

Requires the development of two connected models:

- **Functional task environment:**
  - Specifies elements of the physical environment relevant to the agent's goals and particular cognitive, perceptual and motor characteristics (Gray, Schoelles & Myers, 2006).
- **Human performance model:**
  - Incorporate current theories of the cognitive, perceptual and motor processes.
  - Specify the modular architecture of the mind, the functions and limitations of the various modules, and the connections between them.
  - Specify the task-general and task-specific knowledge that the agent must possess.
  - Specify the control mechanisms (i.e., interactive routines, methods and strategies) that determine performance.

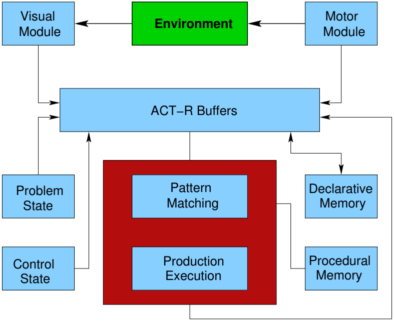
Cognitive architectures

- Theories of how the permanent computational structures and processes that underlie intelligent behaviour are organised.
- "Unified theories of cognition" (Newell, 1990)



- Three main symbolic cognitive architectures: Soar (Newell, 1990; Laird, 2012), Epic (Kieras & Meyer, 1997), ACT-R (Anderson, 2007)
- All three based on *production system* architecture.
- All can interact with simulated task environments to model interaction with external representations.

The ACT-R cognitive architecture

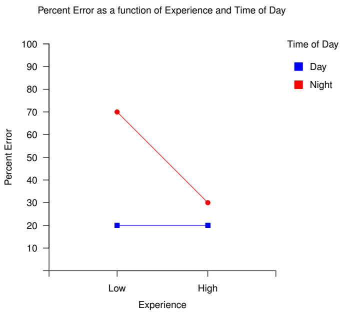


- Hybrid architecture with symbolic and subsymbolic components
- Production system model of procedural memory & cognitive control
- Semantic network model of declarative memory
- Activation-based learning, memory retrieval & forgetting mechanisms
- Simulated eyes & hands for interacting with computer-based tasks

Graph comprehension

- Initial familiarisation stage prior to other tasks involving:
  - Identification & classification of variables into IV(s) and DV
  - Association of variables with axes and representational features (e.g., colours, shapes, line styles)
  - Identification of relationship(s) depicted
- May be an end in itself or a prerequisite for other tasks

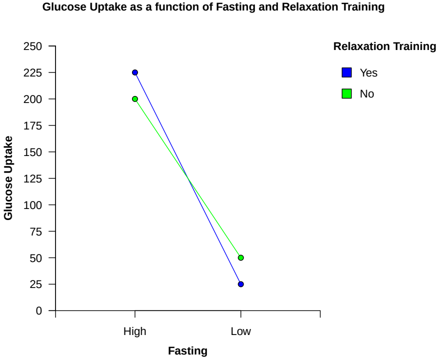
Interaction graphs



- Students more likely to misinterpret (Zacks & Tversky, 1999) or inadequately interpret line graphs (Peebles & Ali, 2009, Ali & Peebles, 2013)

- Line graphs better at depicting common relationships for experts (Kosslyn, 2006)
- Interpretation facilitated by recognition of familiar patterns

An example expert verbal protocol



1. (Reads) "Glucose uptake as a function of fasting and relaxation training"
2. Alright, so we have. . . you're either fasting or you're not. . .
3. You have relaxation training or you don't. . .
4. And so. . . not fasting. . . er. . .
5. So there's a big effect of fasting. . .
6. Very little glucose uptake when you're not fasting. . .
7. And lots of glucose uptake when you are fasting. . .
8. And a comparatively small effect of relaxation training. . .
9. That actually interacts with fasting.

Stages of comprehension

Comprehension proceeds in the following order:

1. Read title. Identify variable names and create declarative chunks.
2. Seek variable labels, identify what they are by their location and if required, associate with label levels
3. Associate variable levels with indicators (position or colour)
4. Look at plot region and attempt to interpret distances. If a highly salient pattern exists (e.g., cross, large gap) process that first
5. Continue until no more patterns are recognised

Videos of the model

An example model protocol

text at top of display...
[chickweight] [= variable]
[as] [a] [function] [of] [diet] [= variable]
[and] [hormonesupplement] [= variable]

text at bottom of display...
[diet] at [bottom] [= IV]
look to nearest text...
[natural] is a level of [diet]
[natural] is [right]
[artificial] is a level of [diet]
[artificial] is [left]

text at far right of display...
[hormonesupplement] at [far-right] [= IV]
look to nearest text...
[mpe] is a level of [hormonesupplement]
[gce] is a level of [hormonesupplement]

An example model protocol

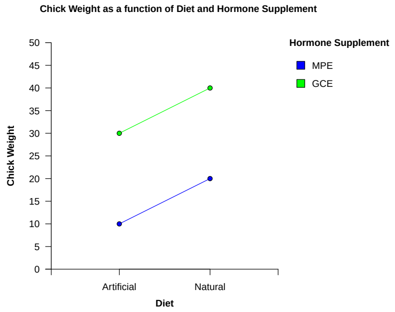
objects in plot region. . .
a [green] [line]
no memory for [green] look to legend. . .
[green] [rectangle]. look for nearest text. . .
[green] represents [gce]
[blue] [rectangle]. look for nearest text. . .
[blue] represents [mpe]

text at far left of display. . .
[chickweight] at [far-left] [= DV]

look to pattern. . .
substantial difference between legend levels. . .
[0.2] diff [blue] = [small] effect [mpe]
[0.2] diff [green] = [small] effect [gce]

compare [blue] and [green] levels. . .
[moderate] diff: [gce] greater than [mpe]
[moderate] [main] effect [hormonesupplement]

An example model protocol



identify x-axis levels. . .
[0.4] diff [left] = [moderate] effect [artificial]
[0.4] diff [right] = [moderate] effect [natural]

compare [left] and [right] levels. . .
[small] diff [natural] > [artificial]
[small] [main] effect [diet]

compare left and right patterns. . .
[0.0] diff between points. [neither] bigger
[no] diff & [same] order = [no-interaction]
for [artificial], [gce] > [mpe]
for [natural], [gce] > [mpe]

Summary

- ACT-R is a powerful, empirically verified, tool for creating models of interactive behaviour with complex task environments.
- Model output (errors, task completion times, eye movements, verbal protocols) can be compared with human data.
- Contains learning mechanisms to model adaptation to task environment and development of expertise.
- Can be used as a platform for creating human-level artificial agents to interpret graphical representations and visualisations.