A cognitive-architecture-based model of graph comprehension

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Previous process models of graph use

GOMS-based task-analytic models:

- UCIE (Lohse, 1993)
- MA-P (Gillan, 1994)

Computational models:

- BOZ (Casner, 1991)
- CaMerA (Tabachneck-Shijf, Leonardo & Simon, 1997)
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None of the above address graph *comprehension*

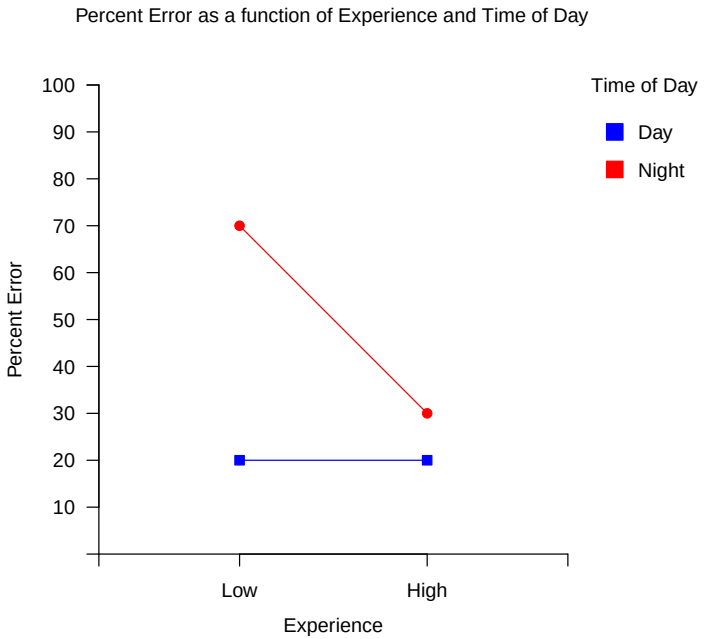
Graph comprehension

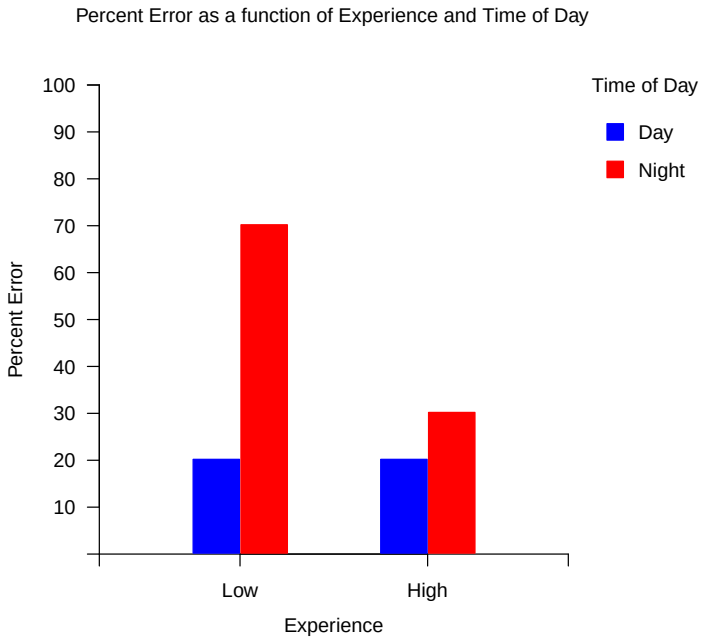
Initial familiarisation stage prior to other tasks involving:

- Identification and 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, in press)

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

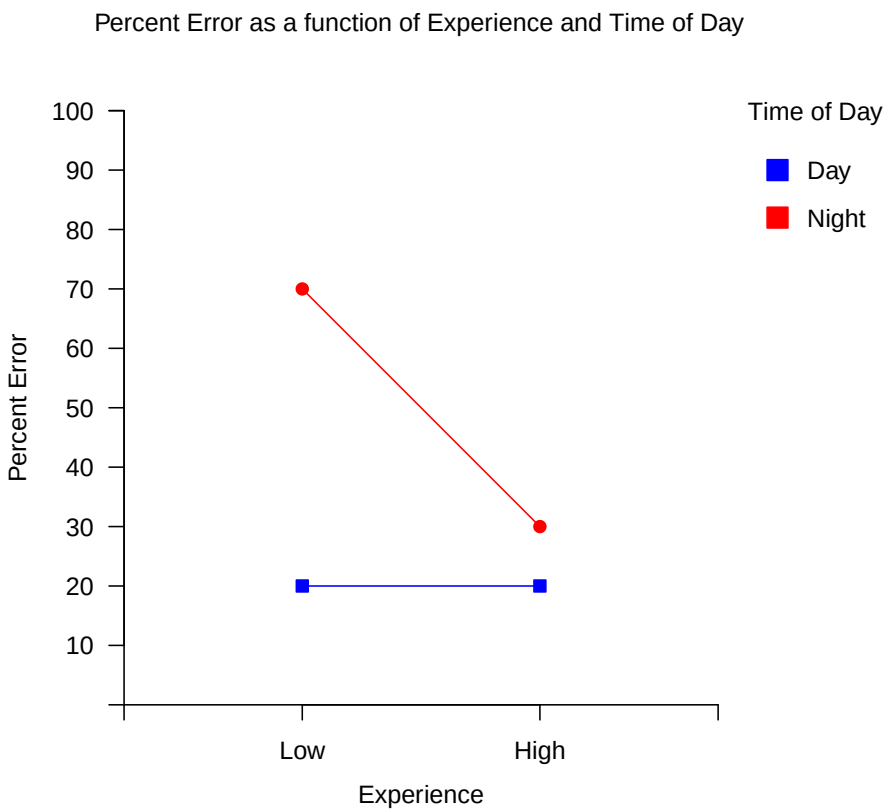
Expert graph comprehension

Experts produce qualitative descriptions of differences between conditions, not individual values (Peebles & Ali, in preparation)

Interpretation carried out in three phases:

- **Variable identification.** Labels categorised as DV or IV according to location, and associated with levels and identifiers: left or right (x axis), or colour (legend)
- **Pattern recognition.** Familiar patterns identified and interpreted
- **Distance comparison.** Distances between plot points compared and interpreted

An example



- Time of Day on legend with levels: Day & Night
- Experience on x axis with levels: High & Low
- Percent error on y axis
- Sloped & flat lines = interaction
- Large gap between lines = main effect: Time of Day
- Flat line = no simple effect: Day
- Errors same for High & Low Experience during Day but more errors at Night for both. But larger effect of Night for people with Low Experience

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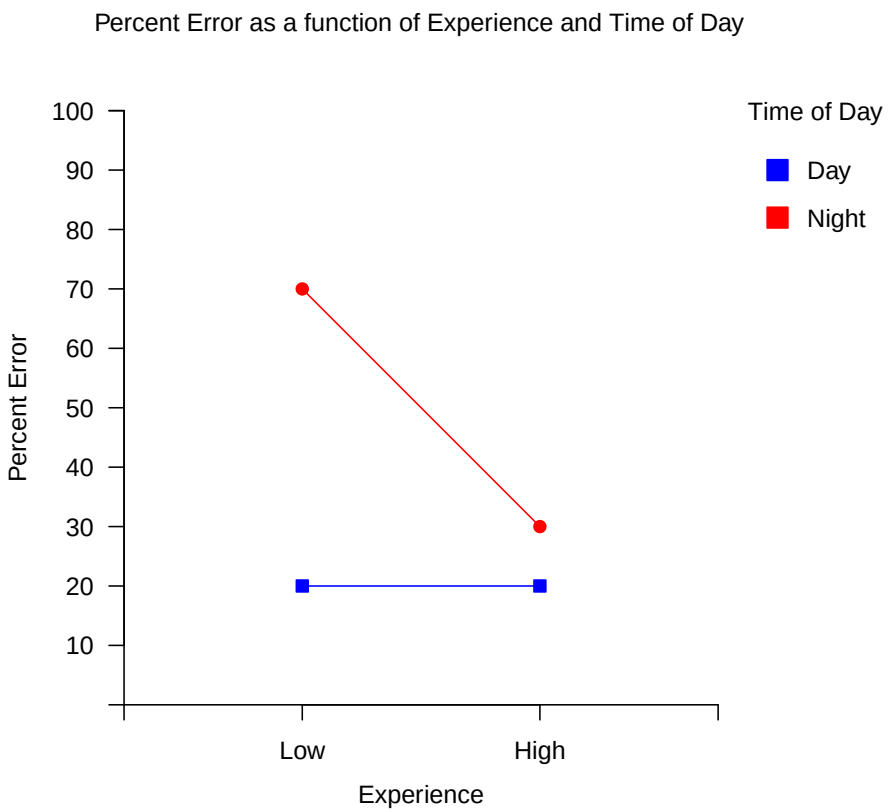

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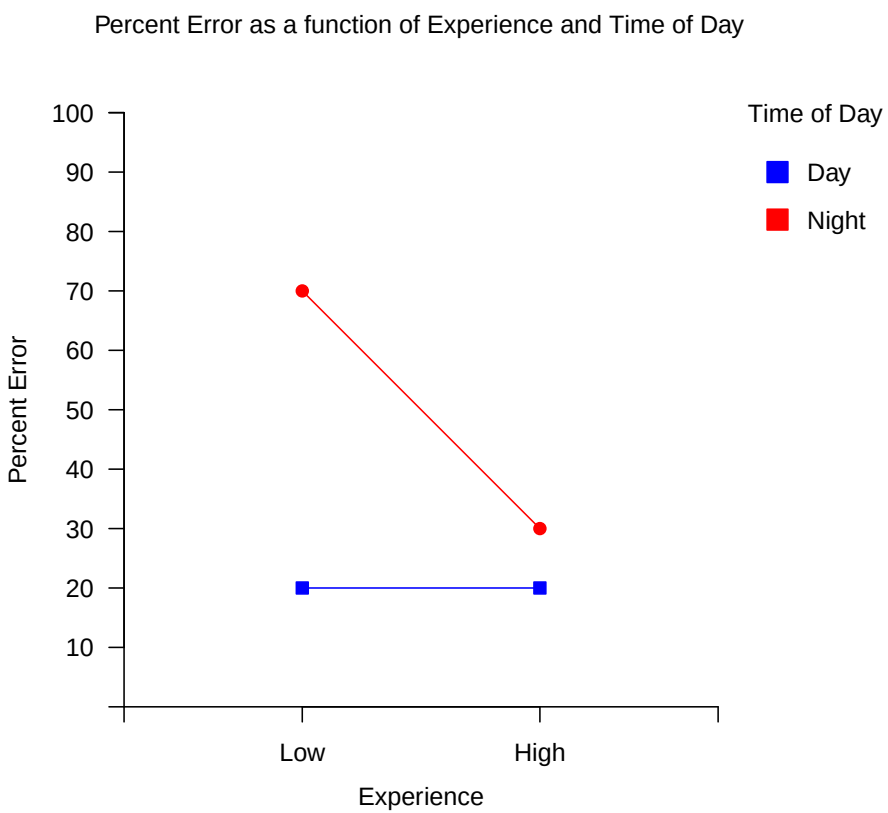

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Aims of the model

Provide an account of:

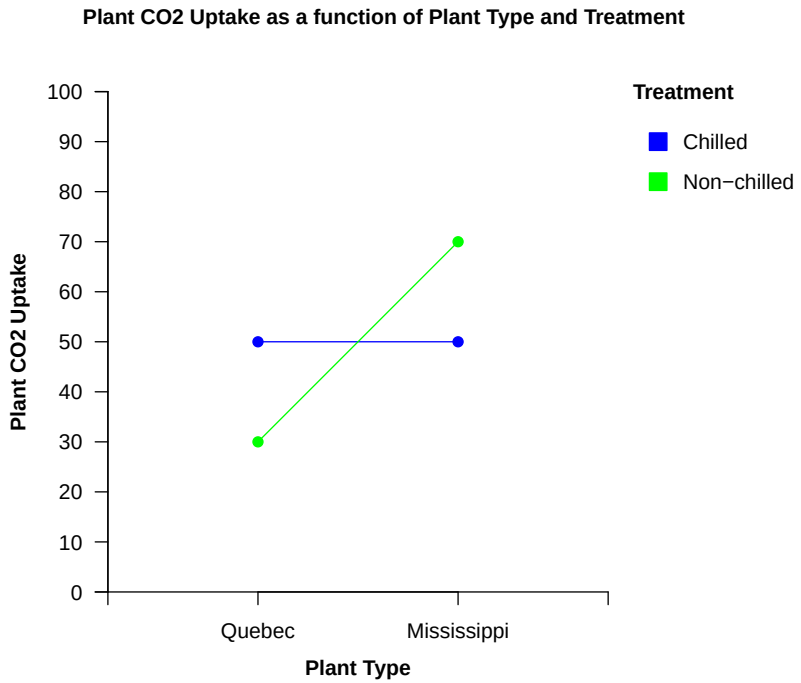
- Prior graph knowledge (general and specific) required
- Essential information extracted from the graph
- Knowledge structures generated during comprehension
- Sequence of cognitive & perceptual operations involved
- Strategic processes that control comprehension
- Differences between expert and novice performance

Behavioural output to be compared with human data:

- Sequence of propositions to compare with expert verbal protocols
- Scan paths to compare with expert eye movements

Declarative knowledge required

- Allocation of DV and IVs to axes and legend
- Distance between plot elements indicates magnitude of relationship between conceptual entities



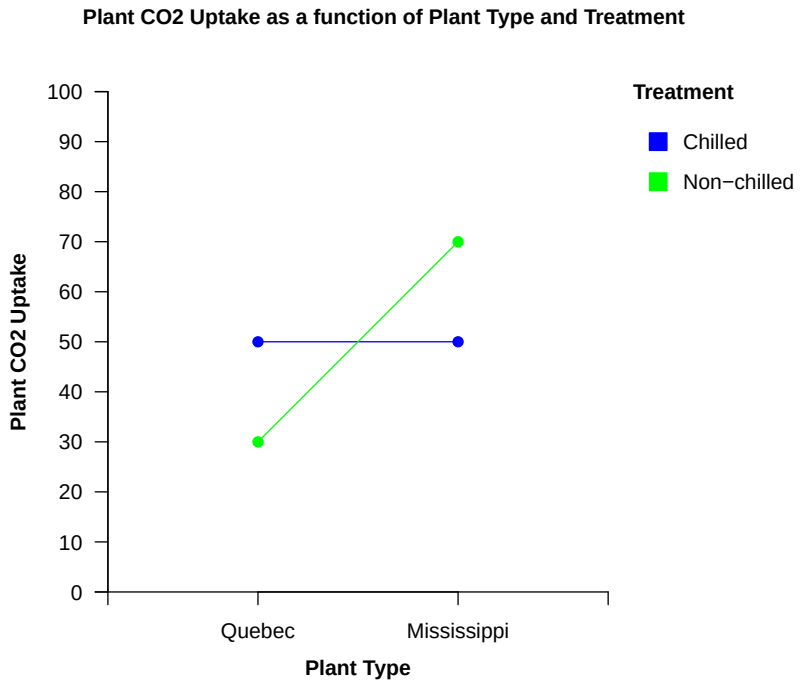
Declarative knowledge required

- Graphical/spatial indicators of three effects:

  Simple Distance between two plot points

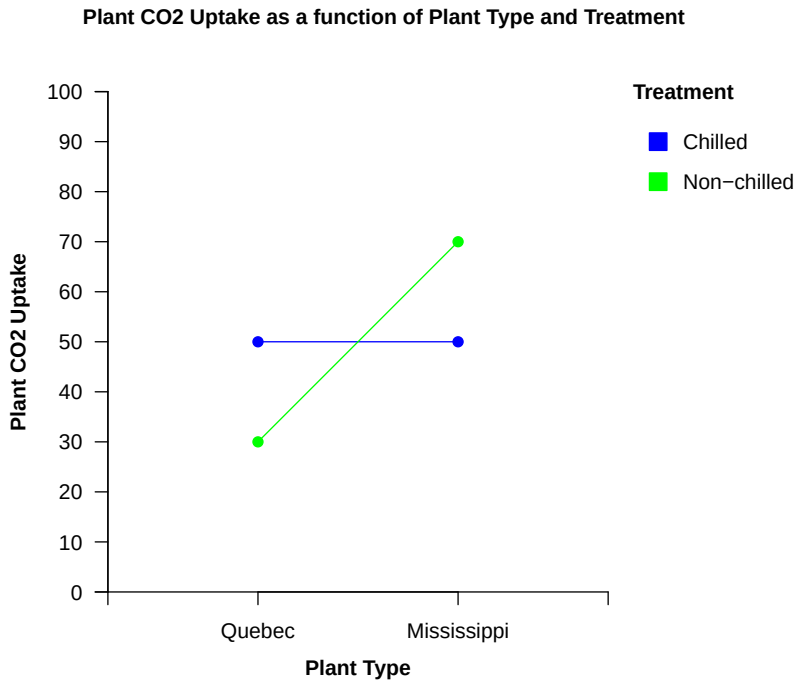
  Main Differences in the y-axis location of the midpoints between two pairs of plot points.

  Interaction Differences in the inter-point distances between levels, combined with information about their point ordering.

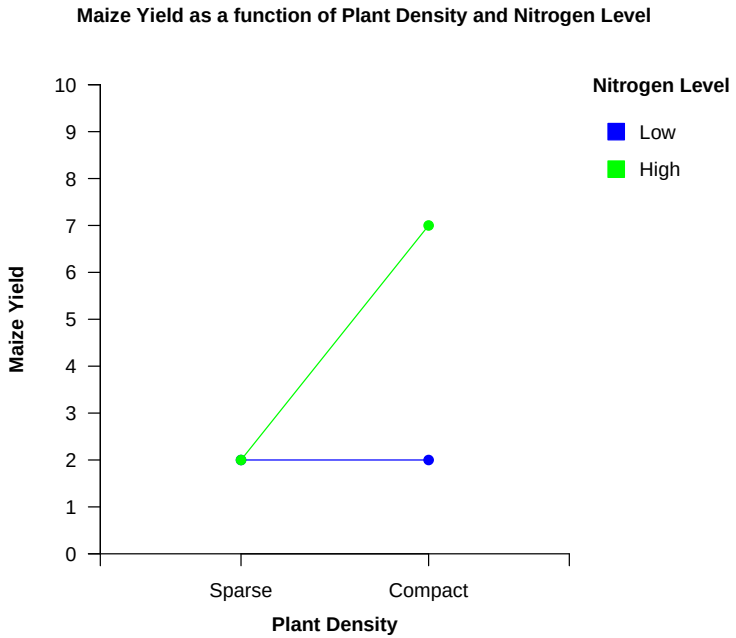


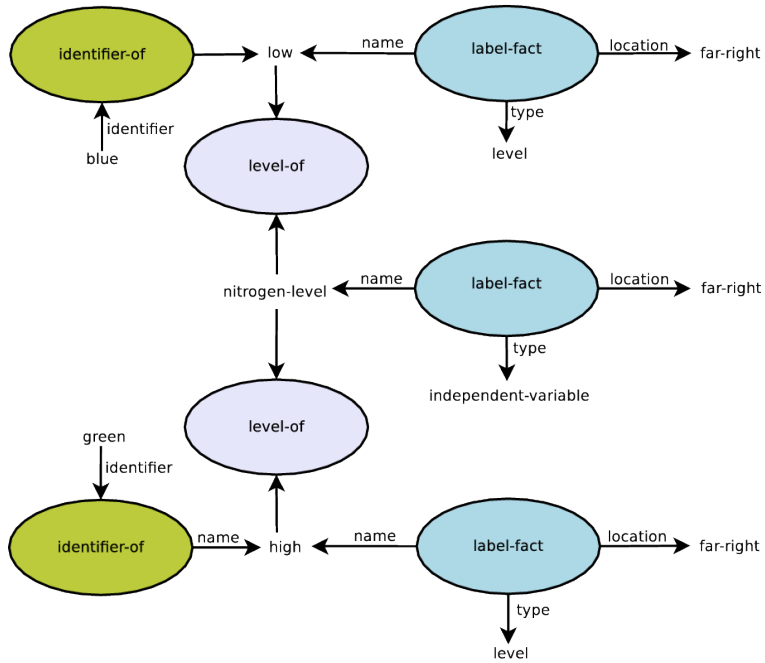
Declarative knowledge required

- Common patterns and salient features:
  - Crossed lines
  - Parallel lines (sloping and horizontal)
  - Diverging lines
  - Very large/small gaps or differences



Variable identification and classification

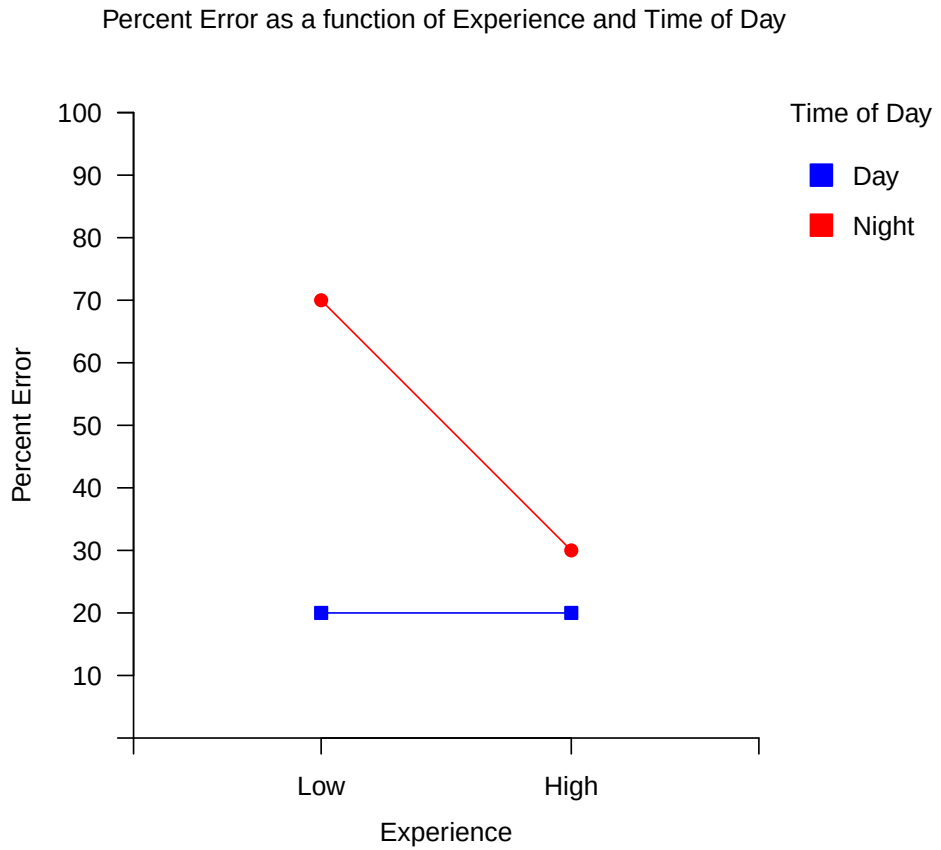




- In the initial phase, variables are classified as IV or DV by location
- and associated with levels and identifiers by proximity or location
- Declarative chunks are constructed associating the different items of information

Essential information extracted from the graph

- Model encodes four x-y coordinate points and spatial distances between them
- Encoded numerically then translated to symbolic descriptions (e.g., “small”, “very large”).
- “Elementary perceptual tasks” (Cleveland & McGill, 1984)
  - Encode spatial distance between plot points
  - Compare magnitude of two distances and produce a symbolic description of difference



Stages of comprehension

Comprehension proceeds in the following order:

- Read title. Identify variable names and create declarative chunks
- Seek variable labels, identify what they are by their location and if required, associate with label levels
- Associate variable levels with indicators (position or colour)
- Look at plot region and attempt to interpret distances. If a highly salient pattern exists (e.g., cross, large gap) process that first
  - Individual production rule for each pattern
  - No production rule then pattern not processed
- Continue until no more patterns are recognised

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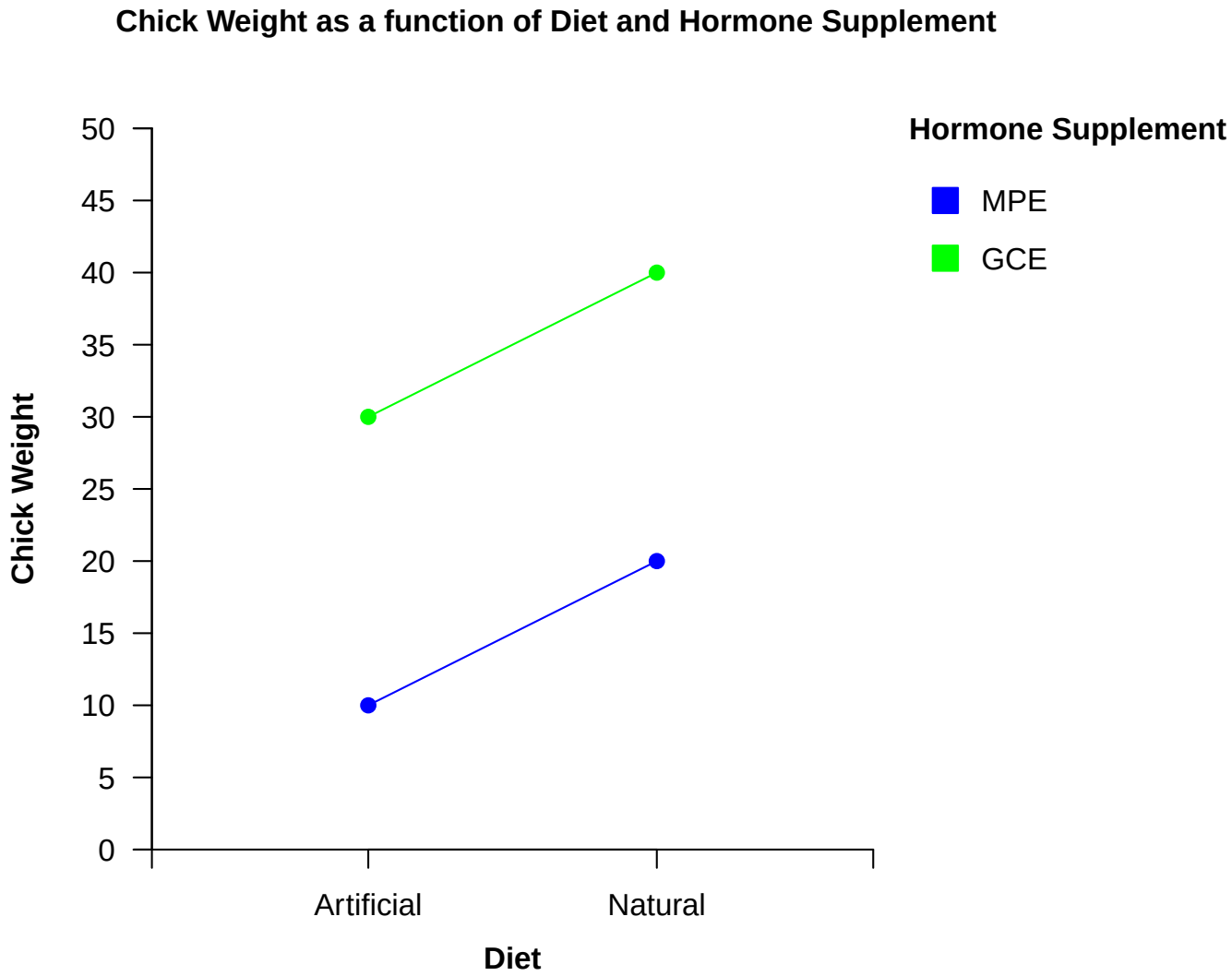
An example graph



Example model output

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

text at bottom of display...
[diet] at [bottom] is the [independent] variable
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] is the [independent] variable
look to nearest text...
[mpe] is a level of [hormonesupplement]
[gce] is a level of [hormonesupplement]

Example model output

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

text at far left of display. . .
[chickweight] at [far-left] is the [dependent] variable

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

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

Example model output

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

compare [left] and [right] levels. . .
[small] diff [natural] [diet] greater than [artificial] [diet]
[small] [main] effect of [diet]

compare left and right patterns. . .
[0.0] diff in distance between points. [neither] bigger
[no] diff and [same] point order indicates [no-interaction]
for [artificial] [diet] [gce] [hormonesupplement] greater than [mpe] [hormonesupplement]
for [natural] [diet] [gce] [hormonesupplement] greater than [mpe] [hormonesupplement]

Limitations of the model

- Model currently focuses on graph knowledge and not the effects of domain knowledge. Experts do display such general graph knowledge however.
- Low-level visual processes are not specified. Mechanisms for visual and spatial processing are being developed for ACT-R (but not by me).
- Although based on human data, the model has not been rigorously compared to eye movement and verbal protocol data yet.
- Model of novice users has not been developed yet
  - Selectively remove production rules and interpretive declarative knowledge.

Conclusions

- Initial step towards a computational model of graph comprehension
- Given any data set from a 2×2 factorial research design it will produce an expert level description of the effects
- Also describes the patterns used to produce the interpretation
- The model associates variables, levels, and colour identifiers using mechanisms functionally equivalent to Gestalt laws of *proximity* and *similarity* respectively.
- A first approximation to a more detailed model that incorporates additional factors to broaden the scope of behaviour accounted for.
- The model will form the basis of a more general graph comprehension model that can interpret bar interaction graphs and more general bar and line graphs.