Modelling alternative strategies for mental rotation

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Motivation for this work

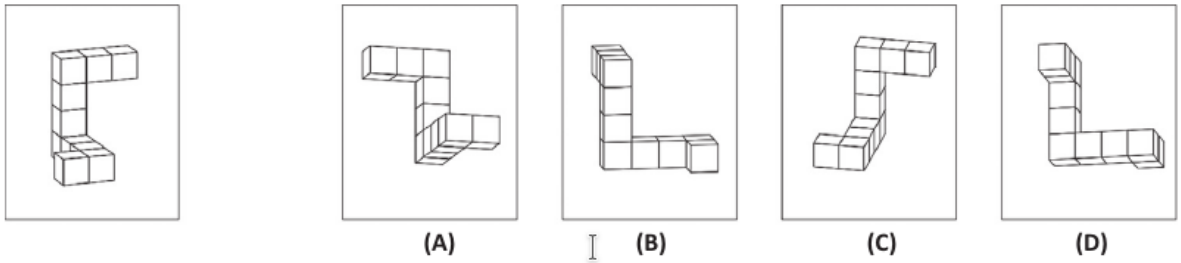
- Several formal computational accounts of mental imagery (e.g., Glasgow & Papadias, 1992; Just & Carpenter, 1985; Kunda, McGreggor, & Goel, 2013; Tabachneck-Schijf, Leonardo, & Simon, 1997)
- Long standing issue of whether imagery requires
  - Some form of array based representation
  - Abstract, amodal representations and processes
- All of the above employ an array representation
- Recent attempts using cognitive architectures
  - Sigma (Rosenbloom, 2012)
  - Soar (Lathrop, Wintermute, & Laird, 2011; Wintermute, 2012)

Motivation for this work

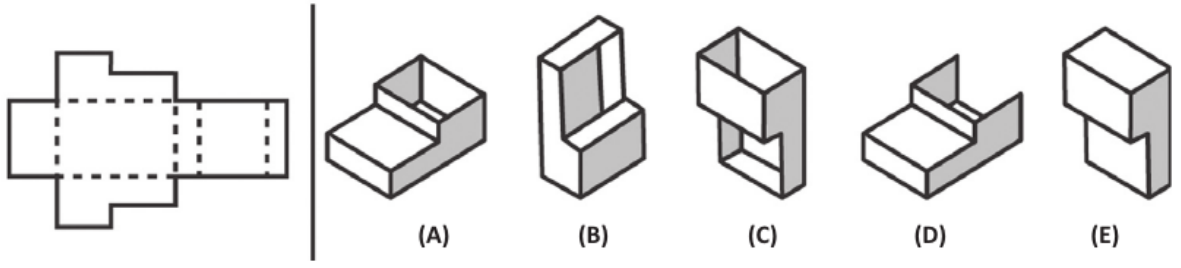
Questions

- How can mental imagery be modelled in ACT-R?
- What representations and processes can support it?
- Does it need an array based representation?
- What are the minimal changes necessary to do this?

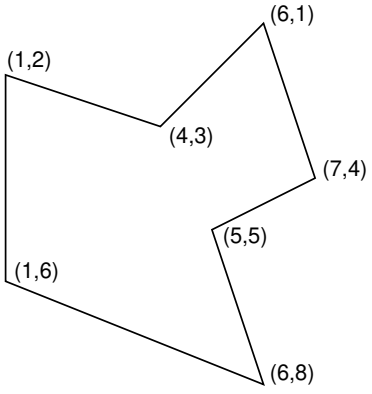
Representations in ACT-R



- Many spatial imagery phenomena involve mental representations of the shape, location, orientation and spatial extent of imagined objects
- ACT-R has discrete symbolic representations in visual module (e.g., shape = ‘square’)
- Only one x-y coordinate location for each object



Modifications made



(1)

```
VISUAL:    POLYGON0-0 [POLYGON0]
   POLYGON0-0
   SCREEN-POS    POLYGON-FEATURE8-0
   VALUE         "poly4"
   COLOR         WHITE
   HEIGHT        8
   WIDTH         8
   POINTS        ((1 2) (4 3) (6 1) (7 4) (5 5) (6 8) (1 6))
   CENTRE-X      4
   CENTRE-Y      4
   REGULAR       FALSE
   SIDES         7
   POLYGON       T
```

(2)

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

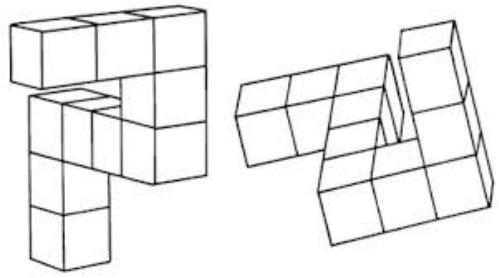
(3)

1. Explicit representation of vertex coordinate locations in stimulus objects
2. Encoding of vertex coordinates in the visual buffer
3. Affine and Boolean operations on spatial objects using computational geometry and matrix multiplication
4. Use of **imaginal action** function of the imaginal buffer

Testing the approach

Initial application (Peebles, 2019) CogSci Saturday

- Mental scanning (Kosslyn, Ball, & Reiser, 1978)
- Mental rotation (Shepard & Metzler, 1971).



This application

- Different rotation strategies (Khooshabeh, Hegarty, & Shipley, 2013).

Mental rotation

Standard task

- Pairs of similar images, one rotated around its centre. Decide whether the images are identical or not.
- RT increases monotonically with the degree of angular rotation between the images.

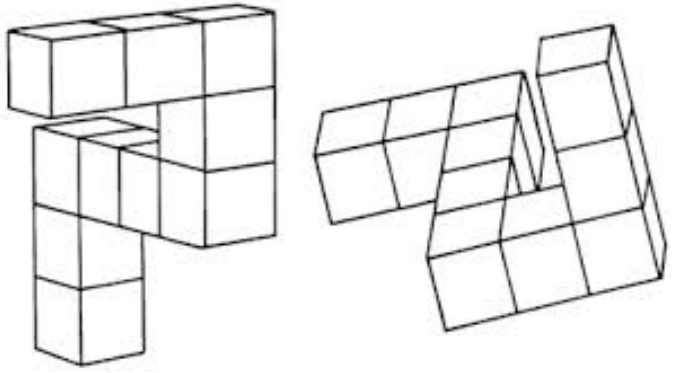
Strategies

- **Holistic.** Rotated figure manipulated as a single, whole unit (Cooper, 1975; Shepard & Metzler, 1971).
- **Piecemeal.** Rotated figure subdivided, component pieces manipulated separately (Just & Carpenter, 1976, 1985).

Holistic rotation strategy

Requires greater capacity to build and maintain complete images in working memory (Bethell-Fox & Shepard, 1988; Mumaw, Pellegrino, Kail, & Carter, 1984).

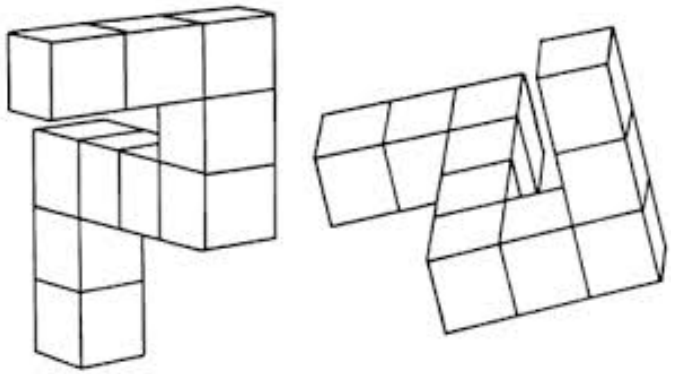
1. **Search.** Look for corresponding regions in the figures.
2. **Confirm.** Determine that the figures have related features.
3. **Transform and compare.** Re-rotate whole figure towards target.



Piecemeal rotation strategy

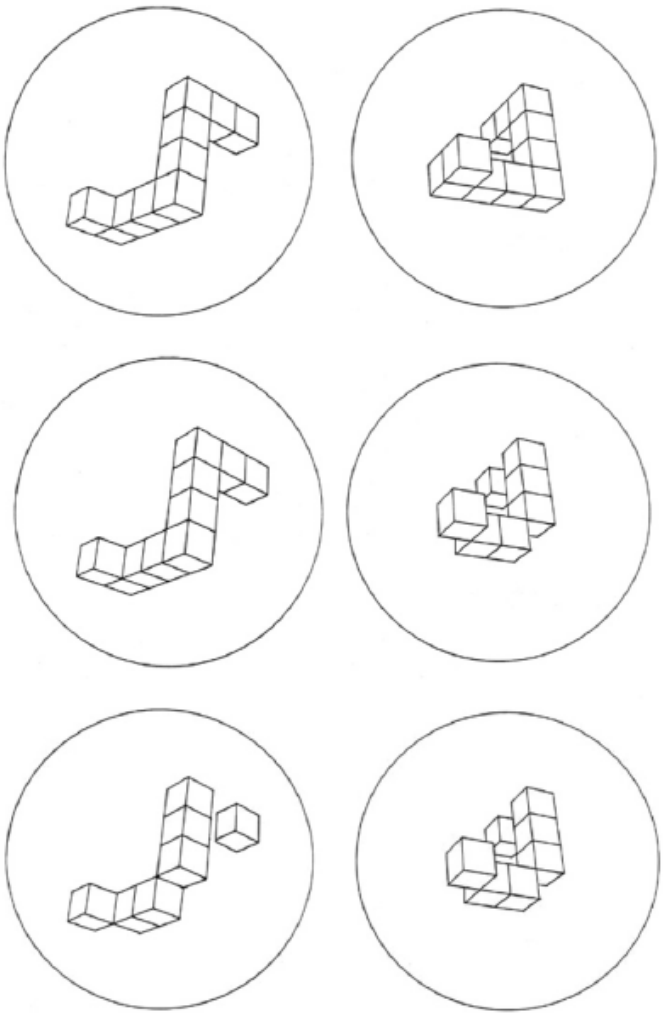
Favoured by lower spatial ability individuals

1. **Search.** Look for corresponding regions in the figures.
2. **Transform and compare.** Re-rotate selected piece towards its corresponding target piece.
3. **Confirm.** Repeat to see if same rotation applies to other corresponding pieces (Just & Carpenter, 1976, 1985)

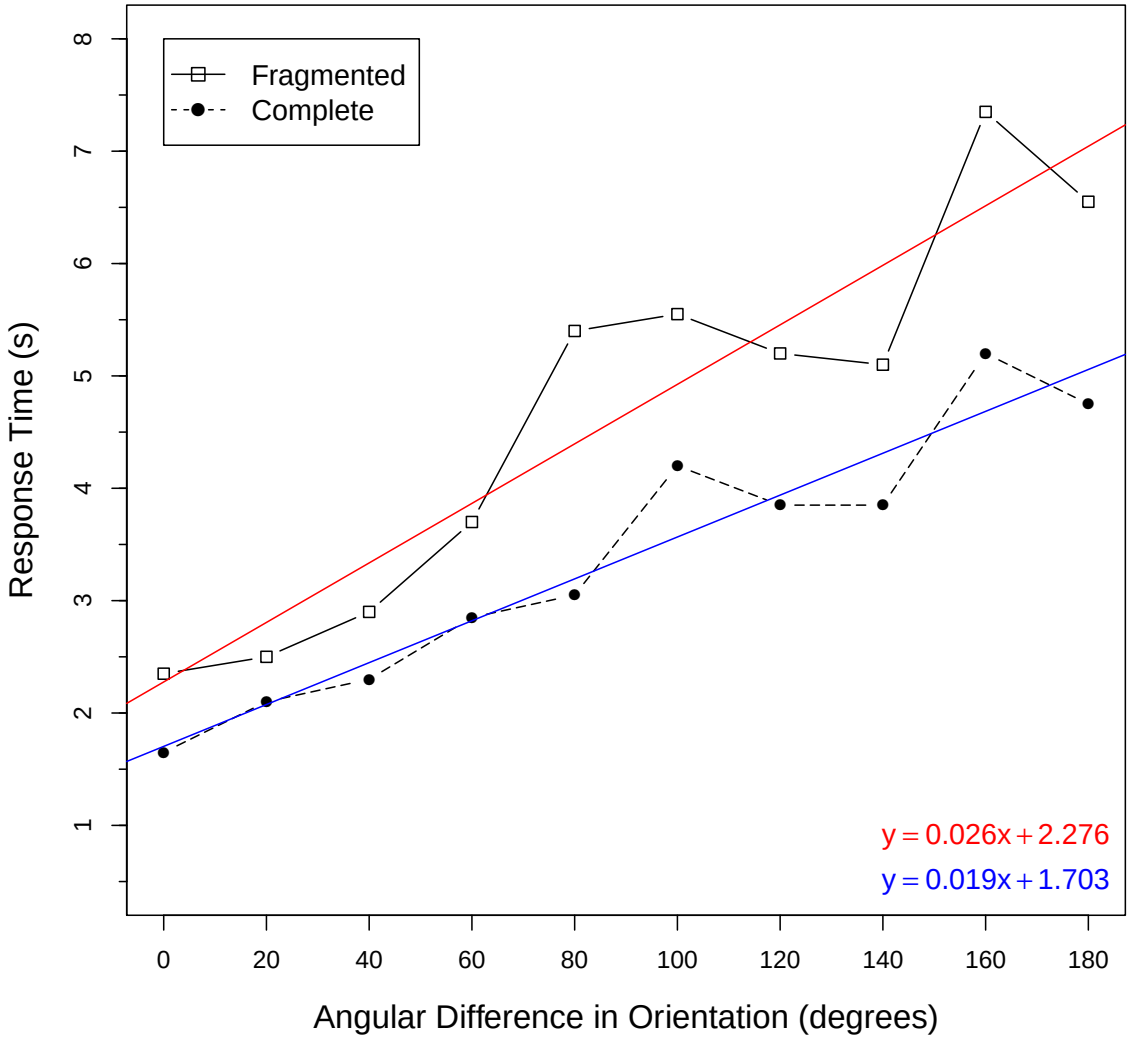


Khooshabeh et al. (2013)

- Forced people to use holistic or piecemeal strategy by using fragmented versions of Shepard and Metzler (1971) stimuli.
- Categorised people into **high** and **low** spatial ability based on performance.
  - Assume that **low** ability people use piecemeal strategy most of the time.
  - Compared **high** ability people's performance on whole (holistic) and fragmented (piecemeal) stimuli.



Results – high spatial ability participants



Creating the models

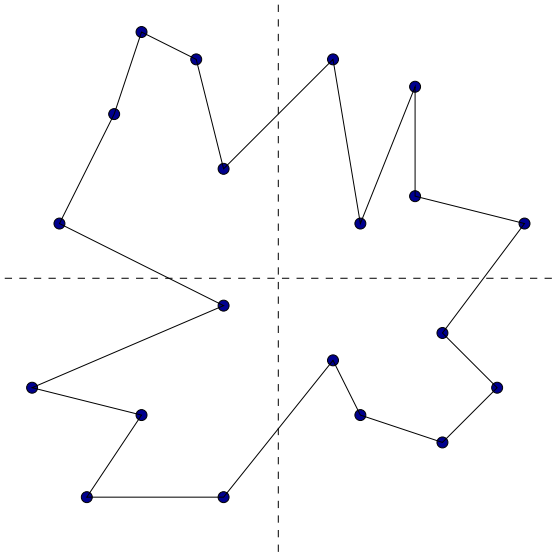
Structure

- Two models instantiating the two strategies
  - Holistic (7 productions)
  - Piecemeal (8 productions)
- Rotation process (Just & Carpenter, 1976, 1985)
  - Not a single ballistic rotation
  - Series of discrete "rotate and compare" steps until images are sufficiently congruent to stop.

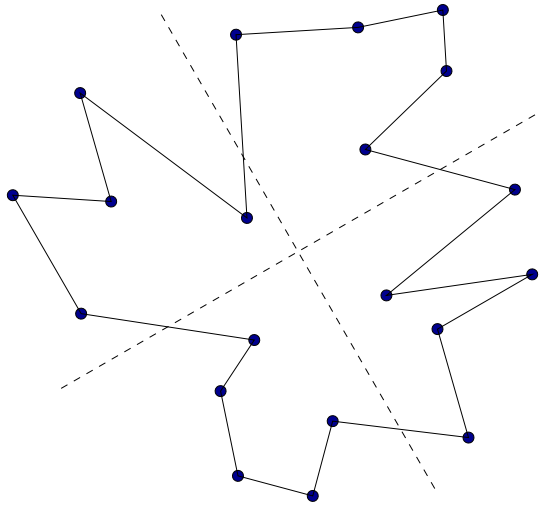
Key parameters

- Rotation distance at each step
- Threshold distance to stop
- **Imaginal delay time** determines completion time for imaginal buffer modification. Set to .1s (default =.2s).

Creating the models



Target image



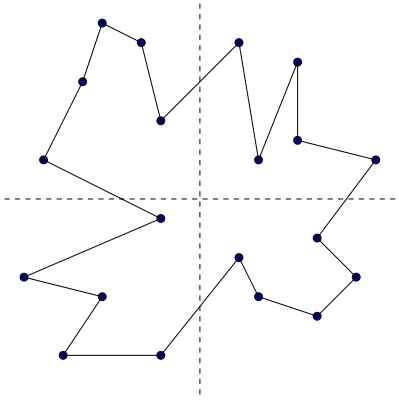
Rotated 60° clockwise

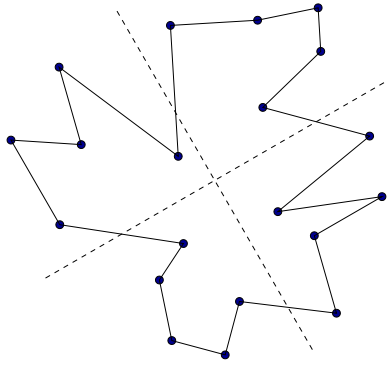
Stimuli

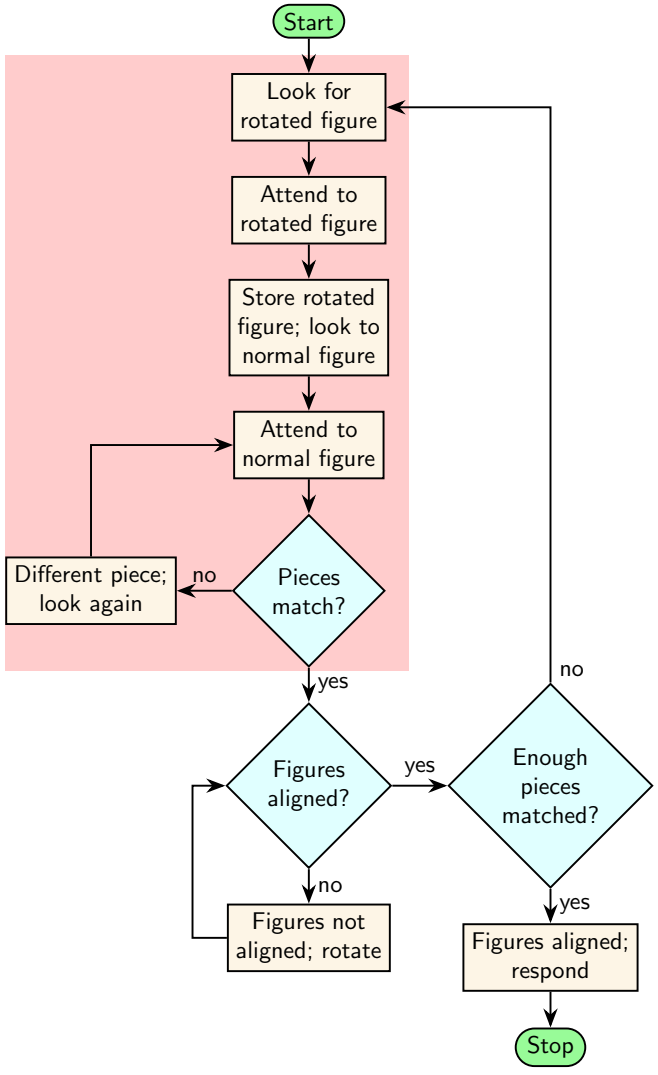
- Four component pieces of five random points – complex irregular polygons (Cooper, 1975; Cooper & Podgorny, 1976)
- Model can attend to compound image or individual components

Piecemeal strategy

1. **Search.** Look for corresponding regions of the two figures.

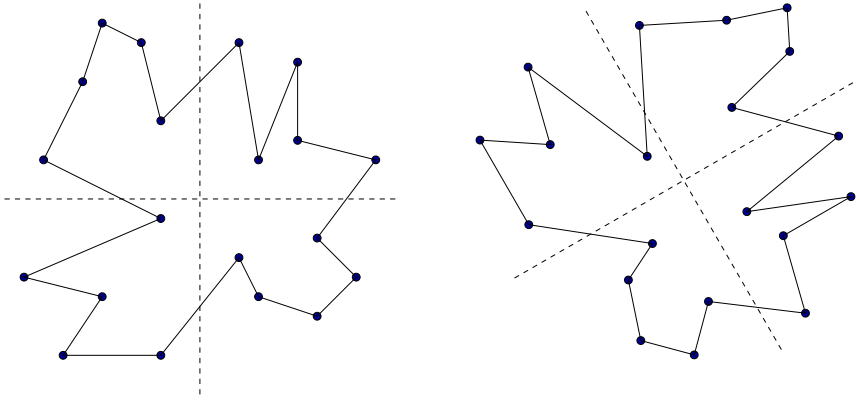


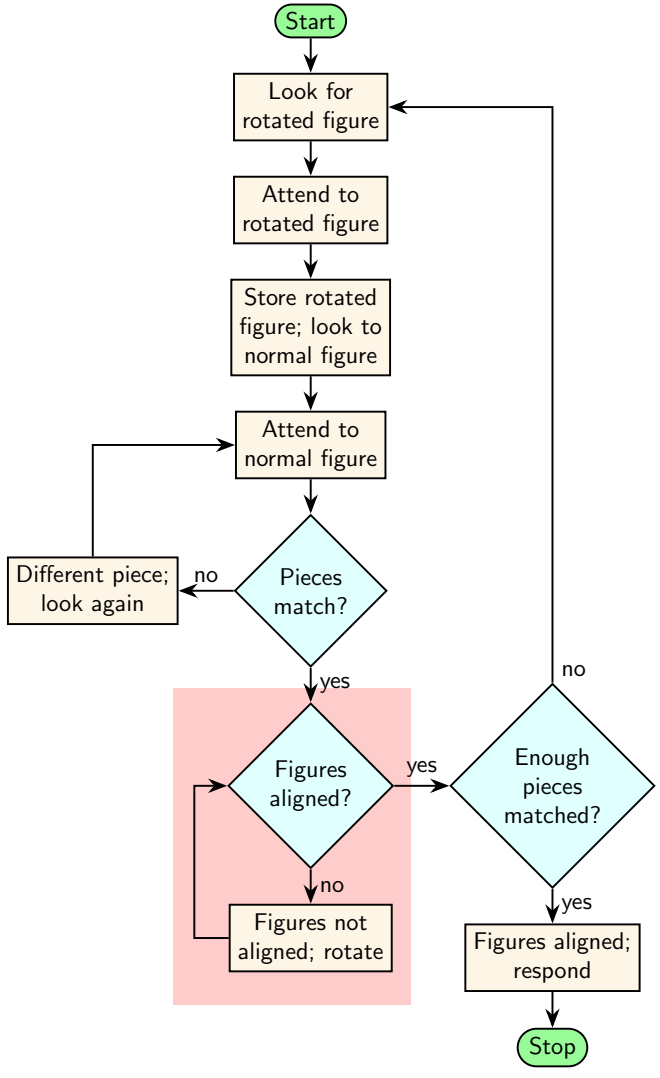




Piecemeal strategy

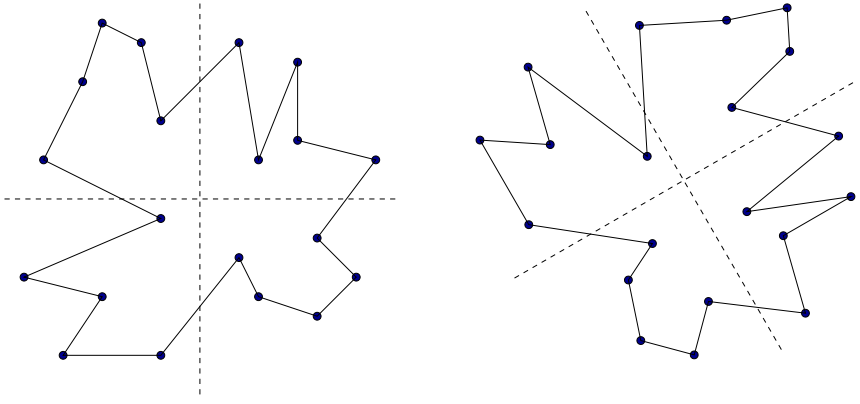
1. **Search.** Look for corresponding regions of the two figures.
2. **Transform and compare.** Re-rotate selected piece towards its corresponding target piece.

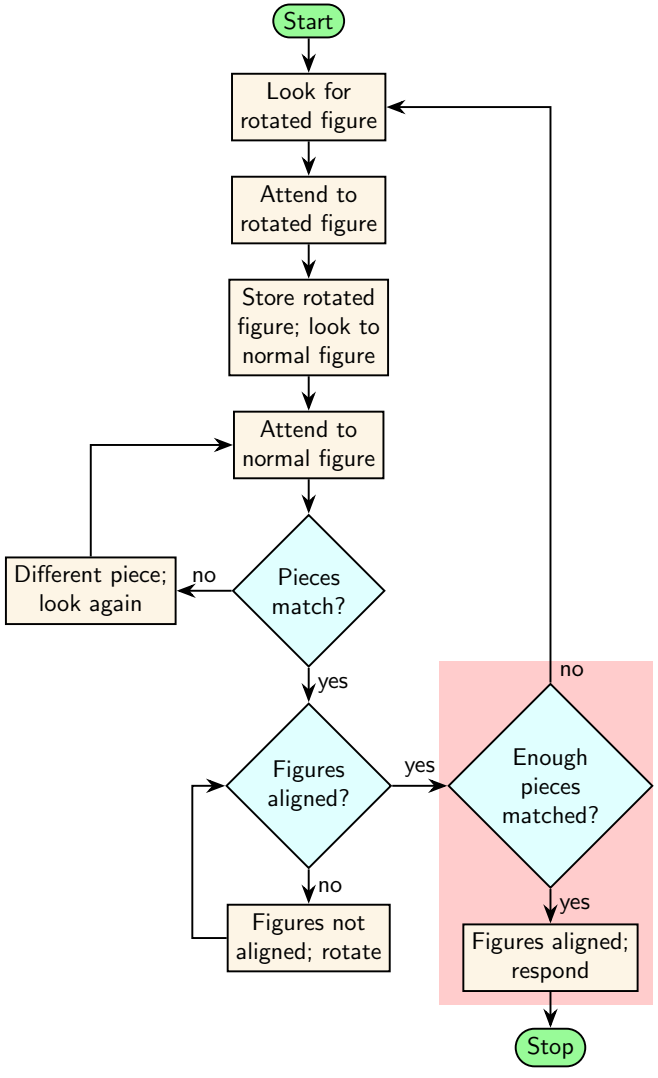




Piecemeal strategy

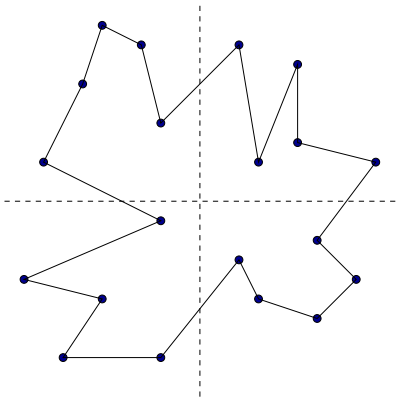
1. **Search.** Look for corresponding regions of the two figures.
2. **Transform and compare.** Re-rotate selected piece towards its corresponding target piece.
3. **Confirm.** Repeat to see if the same rotation will work for other corresponding pieces.

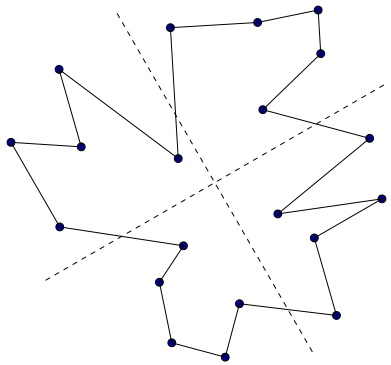


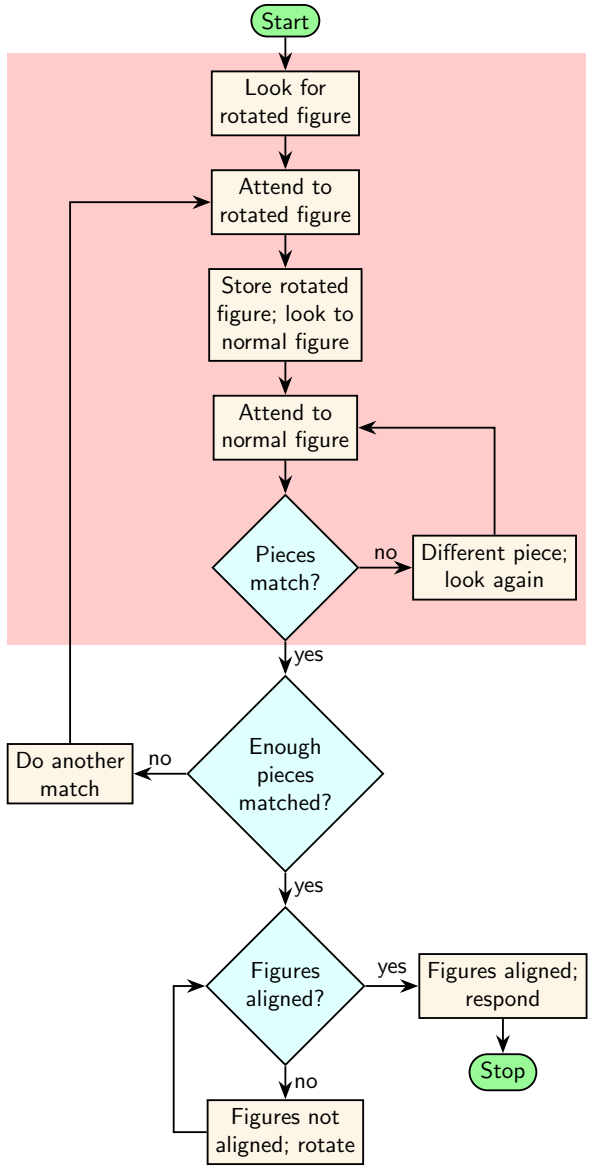


Holistic strategy

1. **Search.** Look for corresponding regions of the two figures.

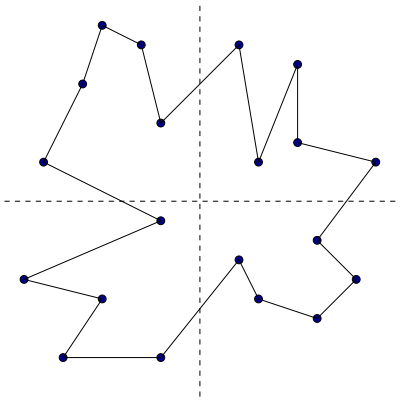


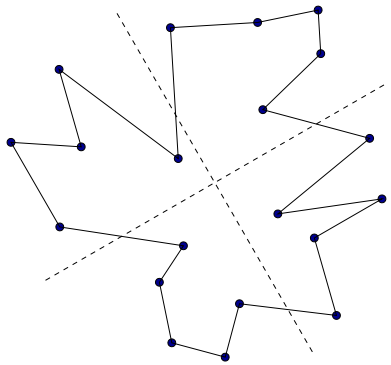


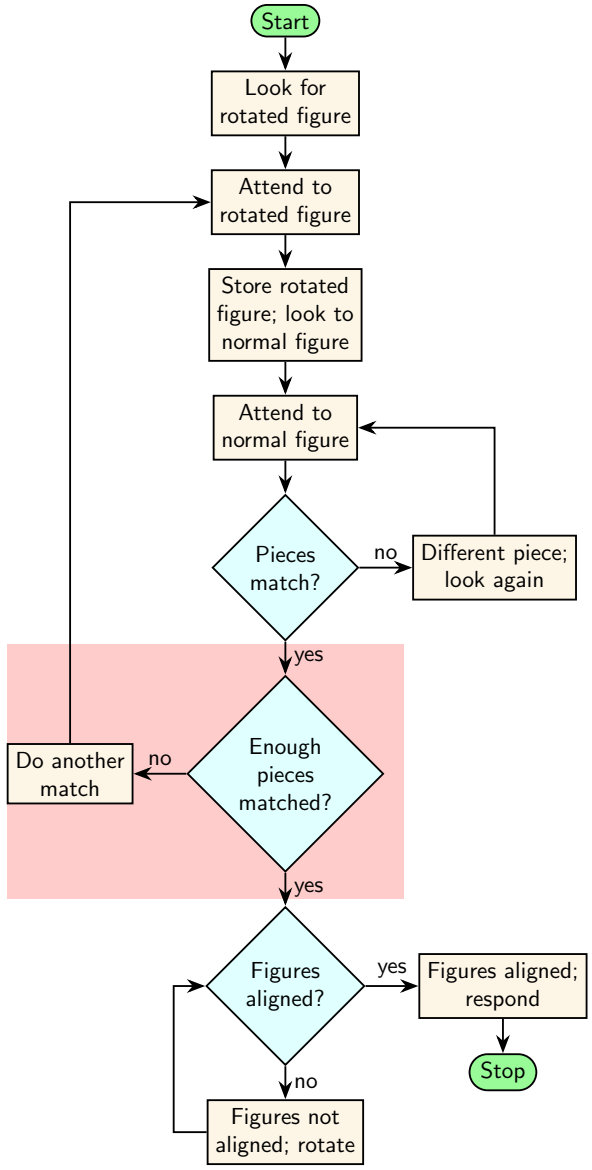


Holistic strategy

1. **Search.** Look for corresponding regions of the two figures.
2. **Confirm.** Determine that the figures have related features.







Holistic strategy

1. **Search.** Look for corresponding regions of the two figures.
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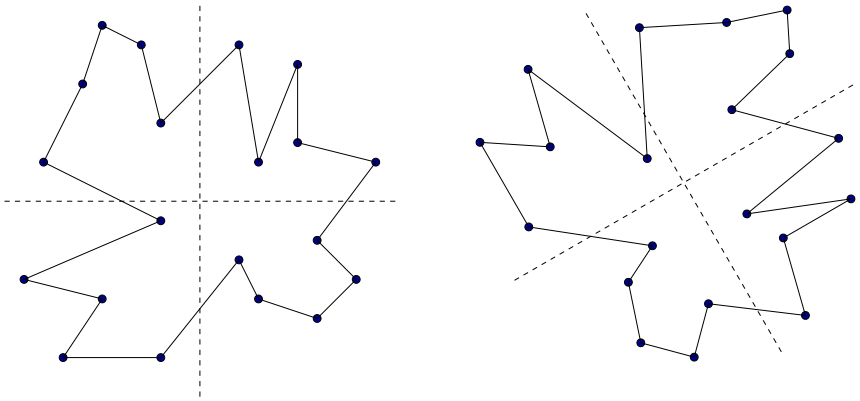
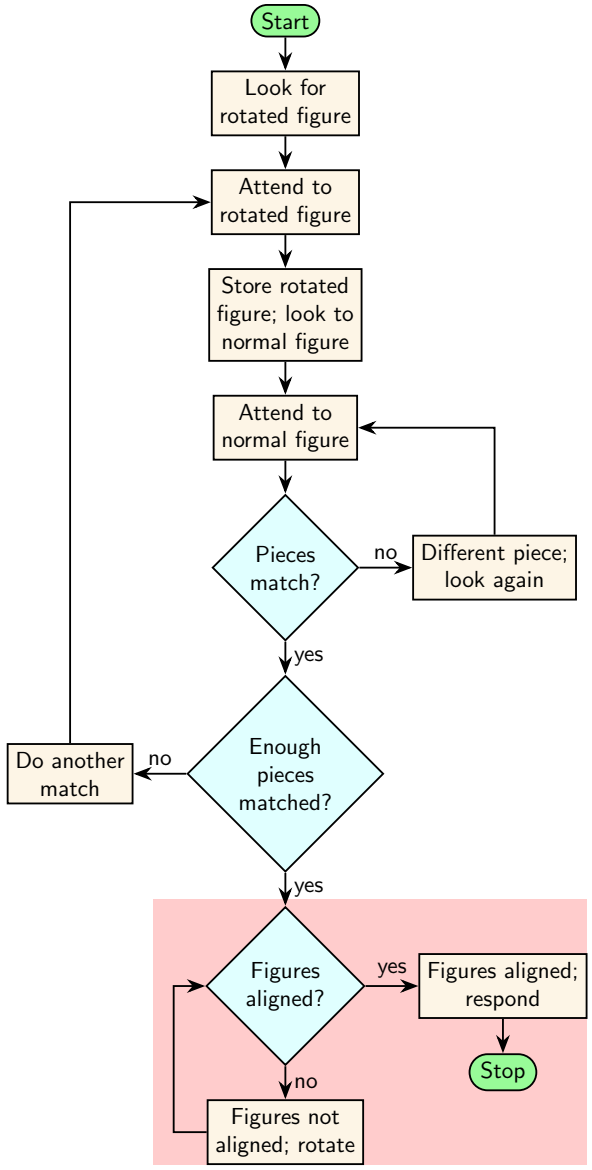
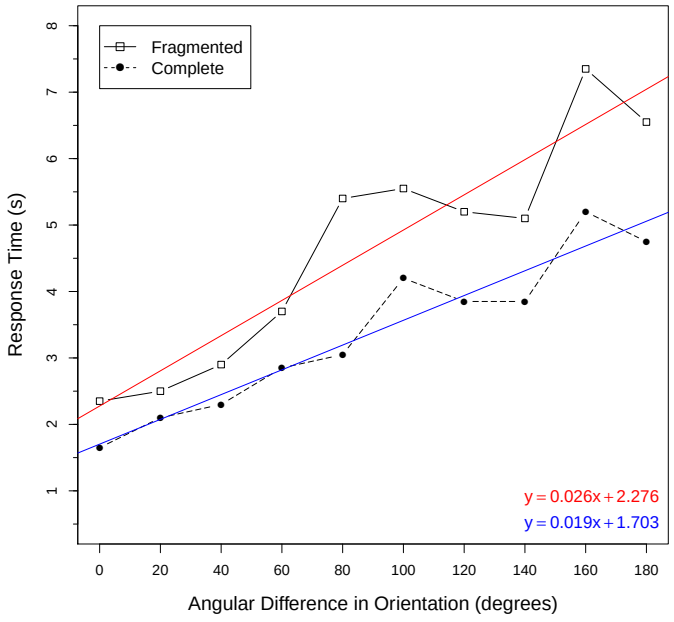
3. **Transform and compare.** Re-rotate whole figure towards target.

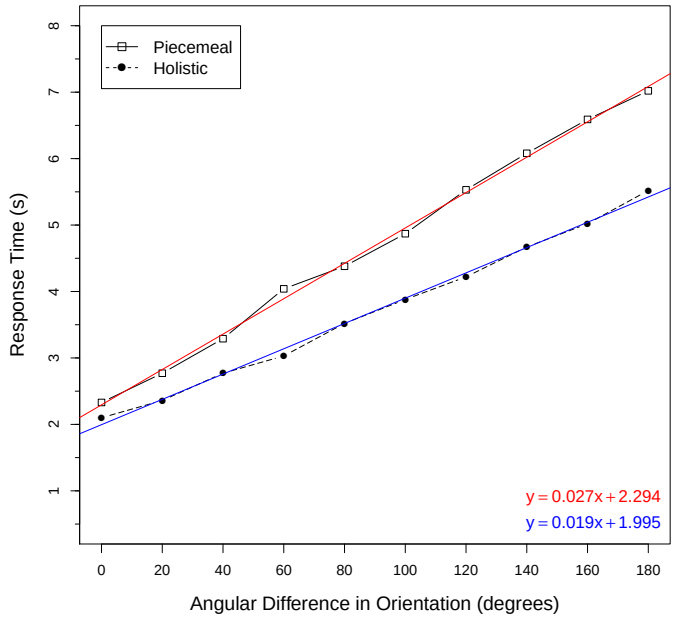




Model performance



Human data



Models

- Piecemeal slower because it requires more piece rotations
- To fit the data, rotation distance for additional piecemeal rotations was larger than the initial rotation.
- Confirmatory action faster because distance known.

Conclusions

Representations and processes

- Not pixel arrays nor discrete symbols – intermediate numerical level that abstracts from pixel level.
- Quantitative, subsymbolic processes assumed to be at a level closer to the visual system but controlled and monitored by higher level actions.
- Approach works well within the constraints of the architecture with minimal adaptations
- May allow ACT-R to interact with other standard vector-based images (e.g., SVG)

Conclusions

Future work

- Mental scanning and rotation are relatively simple — repeated actions producing linear RT functions.
- Just use translation, rotation and Euclidean distance measuring processes.
- More stringent test by modelling more challenging tasks.
  - Raven's Progressive Matrices (c.f. Kunda et al., 2013)
  - "Pedestal blocks world" or "Nonholonomic car motion planning" task (Wintermute, 2012)
- https://github.com/djpeebles/act-r-mental-rotation-models

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