# Analogy, Comparative Intelligence, and Brain

Keith Holyoak

Department of Psychology

University of California, Los Angeles

*Special thanks to*:

Lindsey Richland
Barbara Knowlton
Teena Moody
Russ Poldrack
Bob Morrison
Jim Waltz
Derek Penn
John Hummel
Soohyun Cho
Ty Cannon
Indre Viskontas
Dan Krawczyk
Jim Kroger
Daniel Povinelli

*Research supported by ONR, IES, NIH*

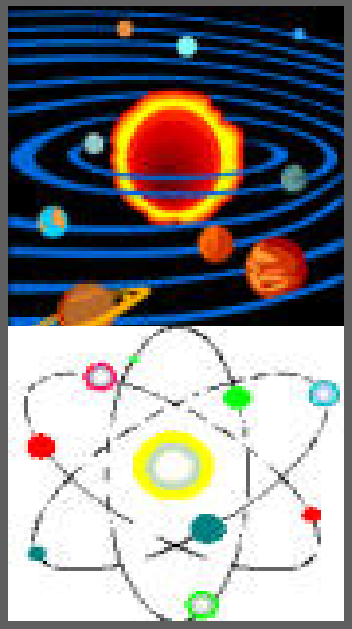
# Analogy and Intelligence

- What is special about human intelligence?
- How does analogy ability change over the course of development and aging?
- How are the component processes of analogical reasoning realized in the brain?

# Analogy in Science

## (Holyoak & Thagard, *Mental Leaps*, 1995)

**"If genius has any common denominator, I would propose breadth of interest and the ability to construct fruitful analogies between fields." —Steven Jay Gould**

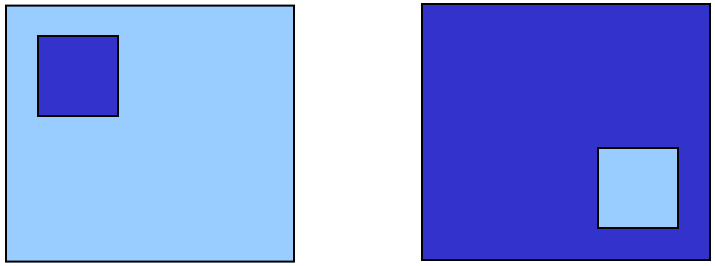


***Bohr/Rutherford model of atom***

- Sound / water waves (Vitruvius, 60 BC)
- Earth / small magnet (Gilbert, 1600)
- Earth / ship (Galileo, 1630)
- Light / sound (Huygens, 1678)
- Planet / projectile (Newton, 1687)
- Heat / water (Carnot, 1824)
- Natural / artificial selection (Darwin, 1859)
- Chromosome / beaded string (Morgan, 1915)
- Mind / computer (Turing, 1950)

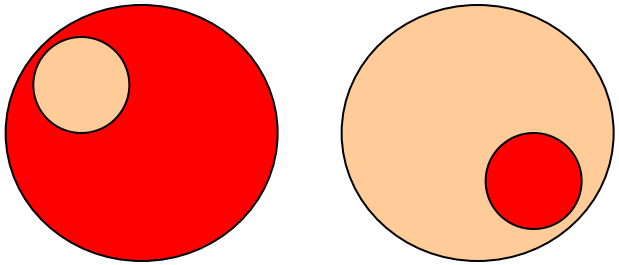
# Psychometric Analogy Problems

A : B



PLAY GAME

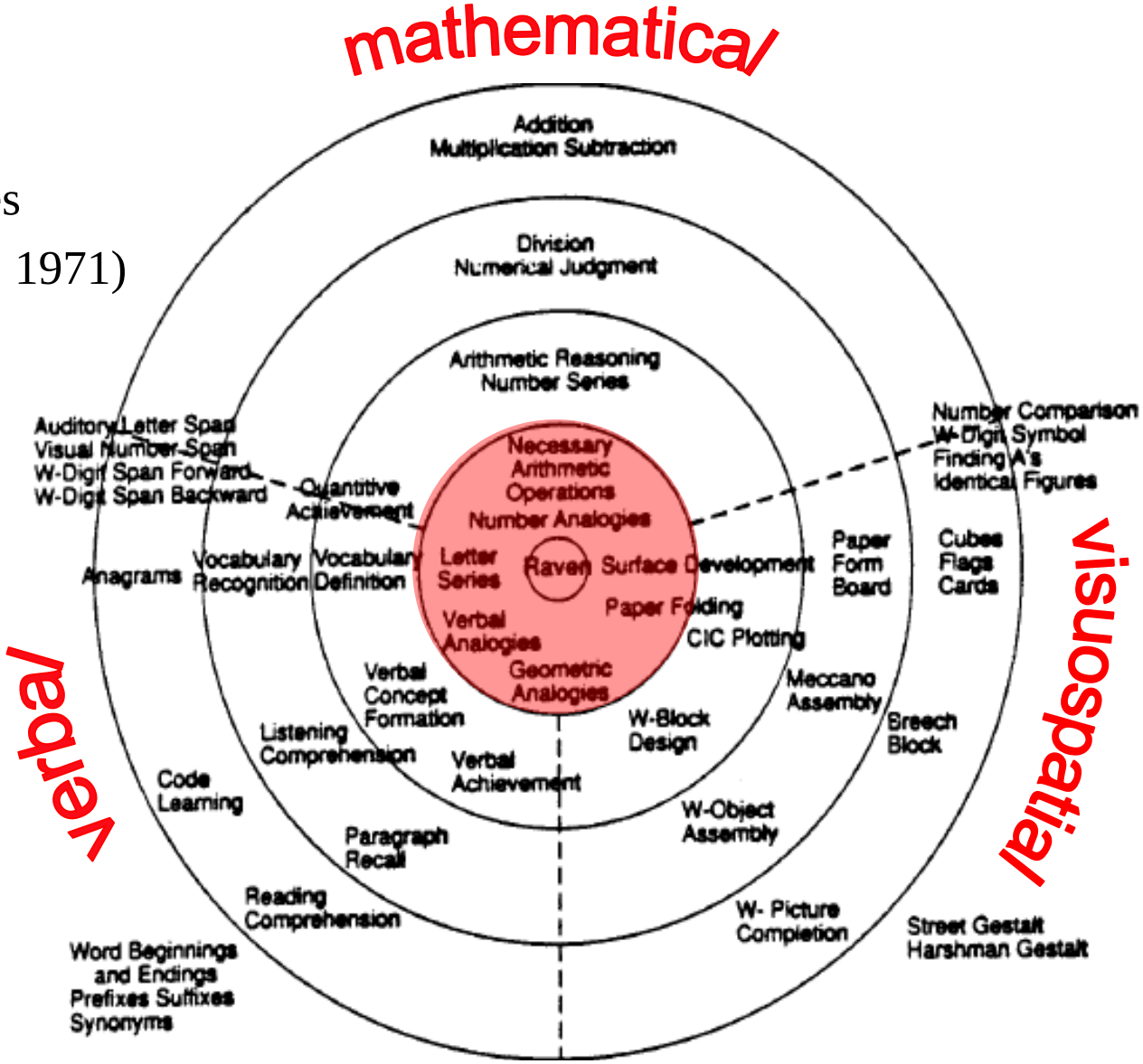
C:D



GIVE PARTY

# Analogical Reasoning as the Core of Fluid Intelligence (*gF*)

Analogy tests provide
the best measure of
fluid intellectual processes
(Spearman, 1923; Cattell, 1971)




Multidimensional scaling analysis of intelligence tests (Snow et al., 1984)

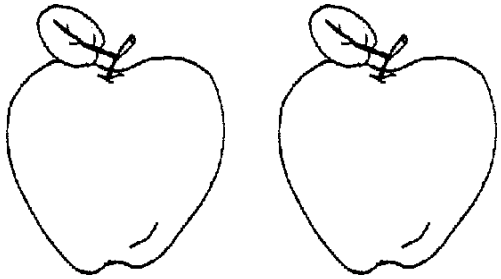
# Comparative Analogy

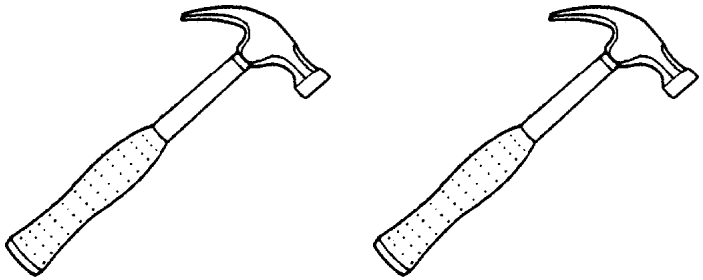
## Darwin's mistake? (1871)

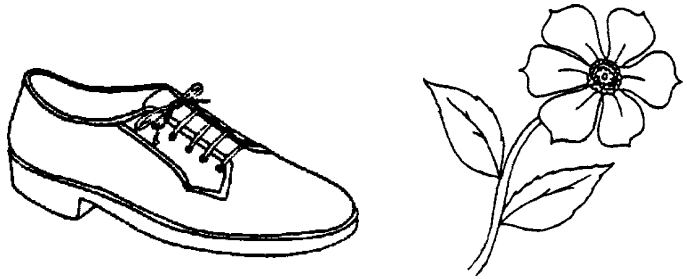
"…The difference between the mind of the lowest man and that of the highest animal is immense… (but the difference) certainly is one of degree and not of kind."

Penn, Holyoak & Povinelli (2008), "Darwin's mistake: Explaining the discontinuity between human and nonhuman minds," *Behavioral and Brain Sciences*

# The Analogical Ape?







Relational Match to Sample (RMTS) passed by symbol-trained chimpanzees (Premack, 1983)

# The Story Continues...

RMTS passed by…

- Language-naïve chimps exposed to tokens for "same" & "different" (Thompson et al., 1997)
- Orangutans and a gorrilla w/o any language training (Vonk, 2003)
- Baboons (Bovet & Vauclair, 2001)
- Dolphins (Herman et al., 1993)
- Parrot (Pepperberg, 1987)
- Pigeons (Blaisdell & Cook, 2005)

# Multi-element RMTS

Sample (displayed first)

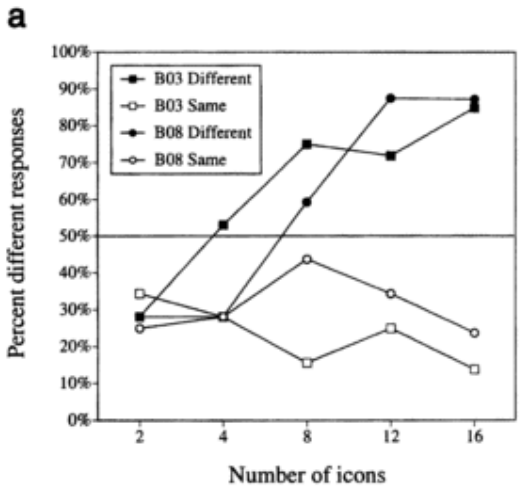
---

Choice (displayed second)

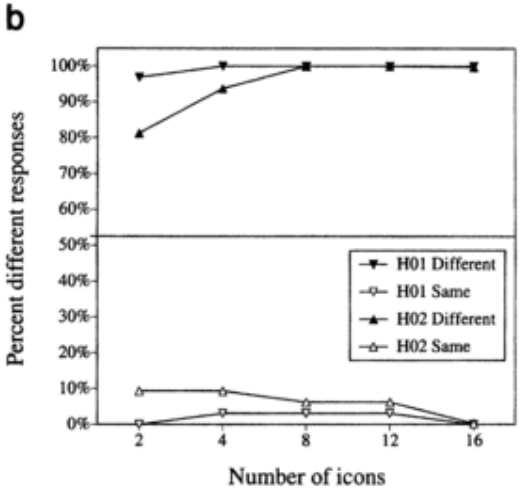
Fagot, Wasserman & Young (2001)

# Relational Match to Sample: *Papio papio* vs *homo sapiens*

Baboons: graded response to entropy



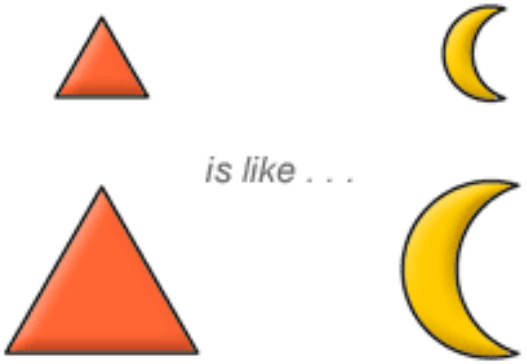

Humans: all-or-none




Fagot, Wasserman & Young, *JEP:ABP* (2001)

# Sarah's Analogies
(Gillan et al., 1981)

## Geometric



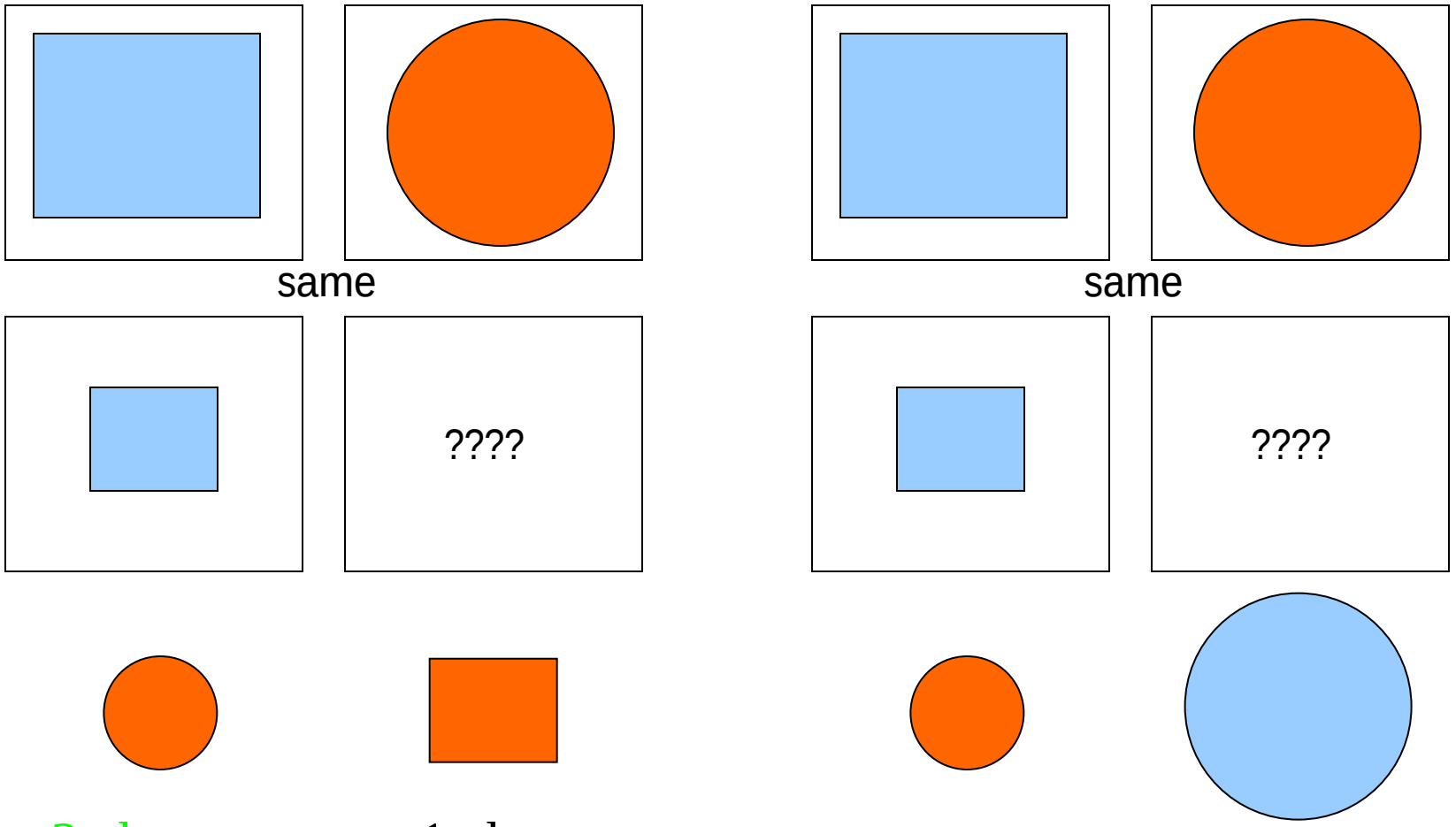

## Functional

PADLOCK *is like* TIN CAN

KEY *is like* CAN OPENER ??

*TASK*: select analogical completion from 2 alternatives

# Oden et al. (2001): Sarah solved analogies by counting feature changes, not by mapping relational roles



# The Analogy Gap

- What non-human animals can do:
  - respond to perceptual similarities
  - and statistical properties of perceptual cues
  - constituents of relations undifferentiated or symmetrical ("high entropy same as high entropy")
- What "true" analogy requires:
  - relations in which constituents play asymmetrical roles ("John loves Mary")
  - mapped objects may be perceptually dissimilar
  - relations may be abstract ("cause")
  - structure-based mapping

# Prefrontal Cortex: The Phylogeny of Relational Reasoning?

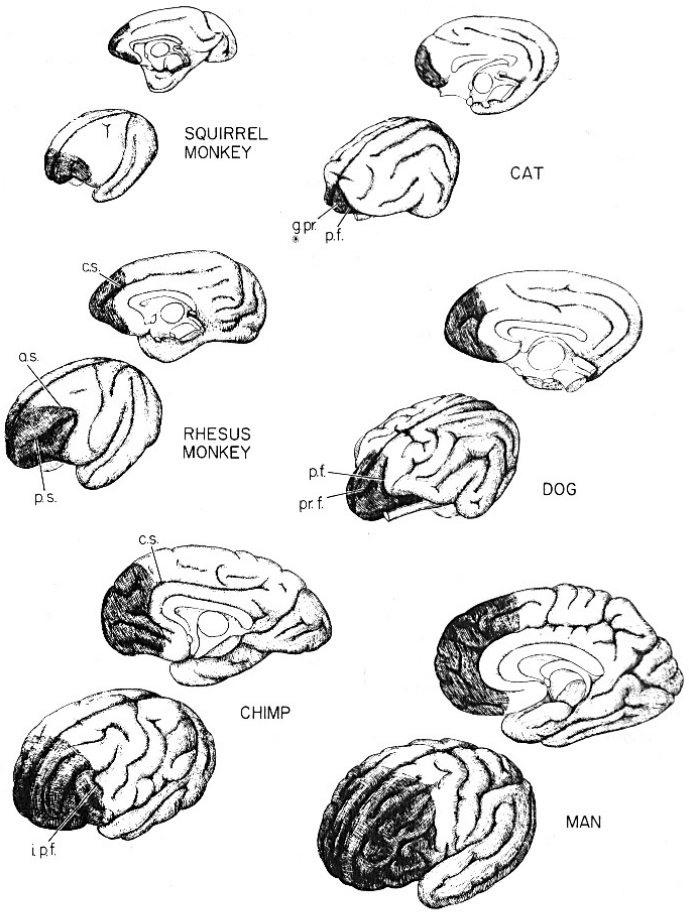
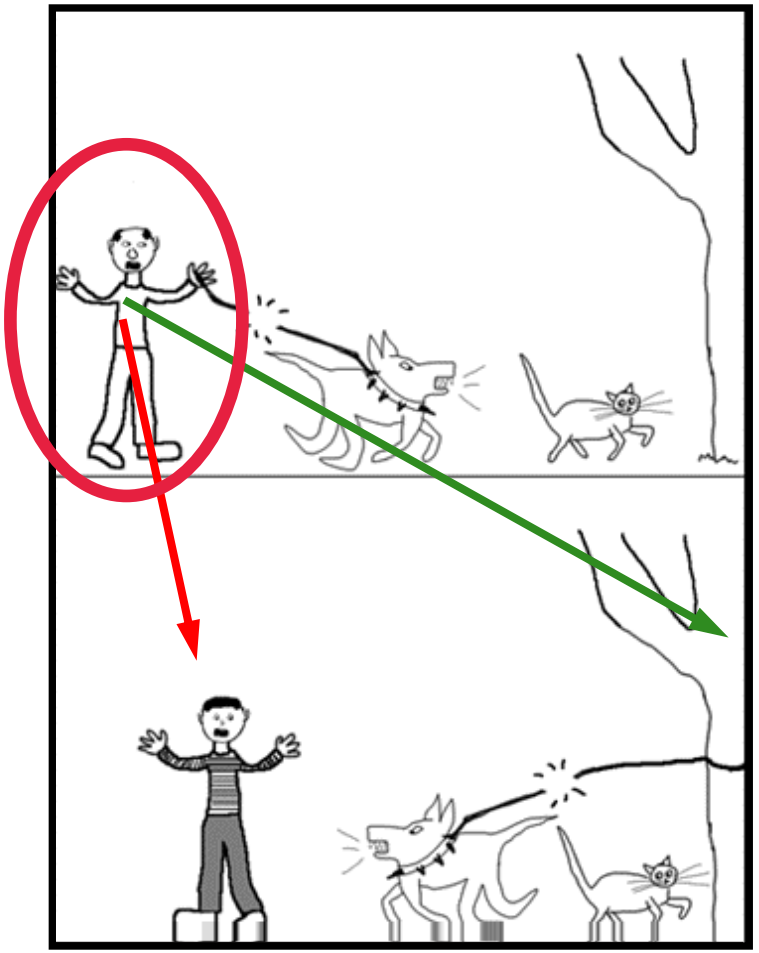



**Fig. 2.1 The prefrontal cortex in six different species. (from Fuster, 1997)**

Preuss (2006): Microscopic differences in brain organization between apes and humans

# Mechanisms of Analogical Mapping

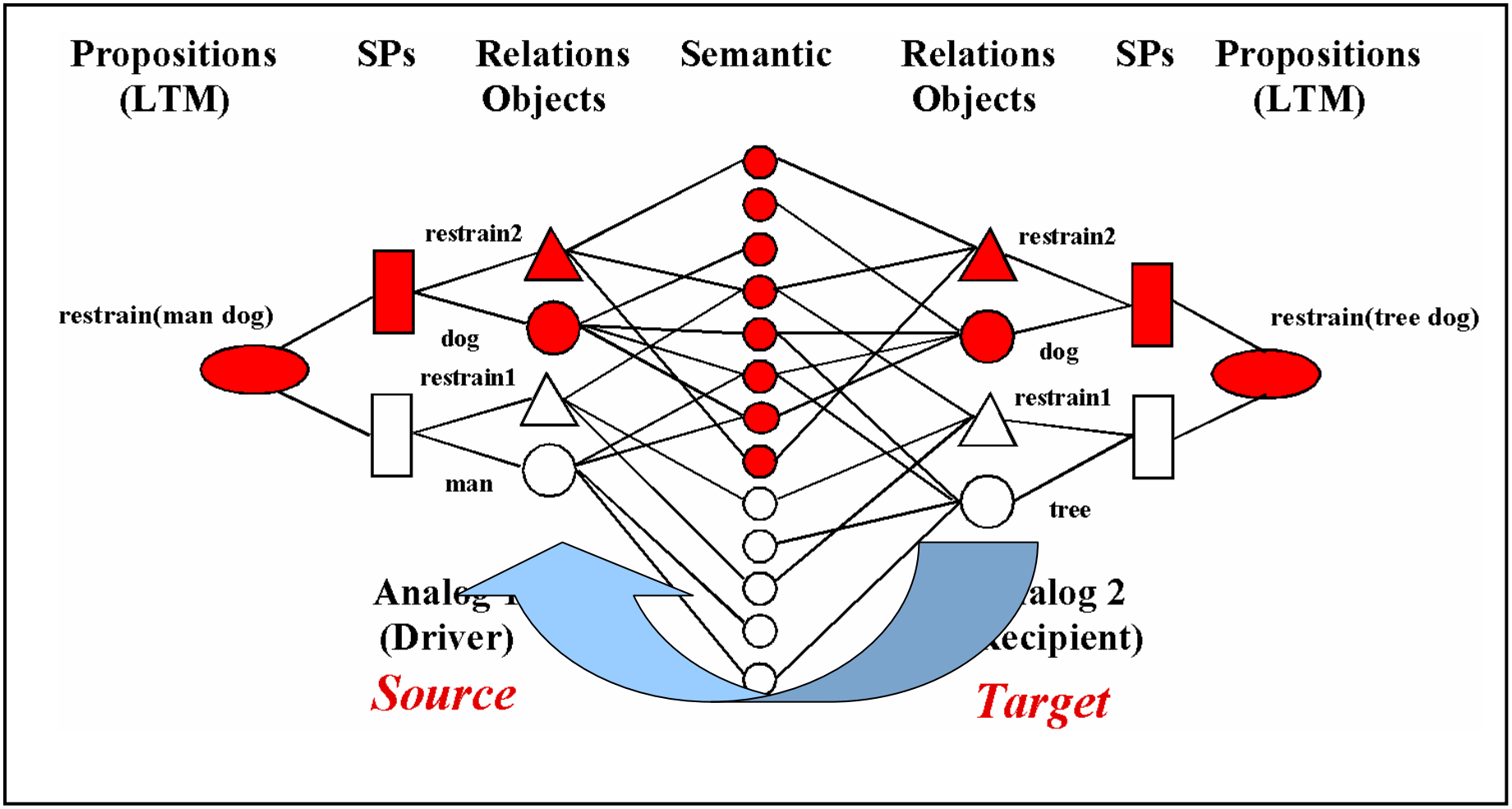


- **Featural**
  ***man looks like the boy***
- **Relational**
  - ***man tries to restrain dog***
  - ***tree "tries" to restrain dog***
  - ***map the man to the tree***

**(Markman & Gentner, 1993; Tohill & Holyoak, 2000)**

# Analogy in a Neural System: LISA

**Hummel & Holyoak (1997, 2003)**



# Working Memory, Inhibition, and Mapping

- Analogy models such as LISA link the number of "active" relational roles to the capacity of WM
- Sequencing of activity depends on inhibitory control
- Selection between alternative mappings also depends on inhibition
- Both WM for relations and inhibitory control depend on prefrontal cortex

# Development of Analogy

(Richland, Morrison & Holyoak, *J. Exp. Child Psych.* 2006)

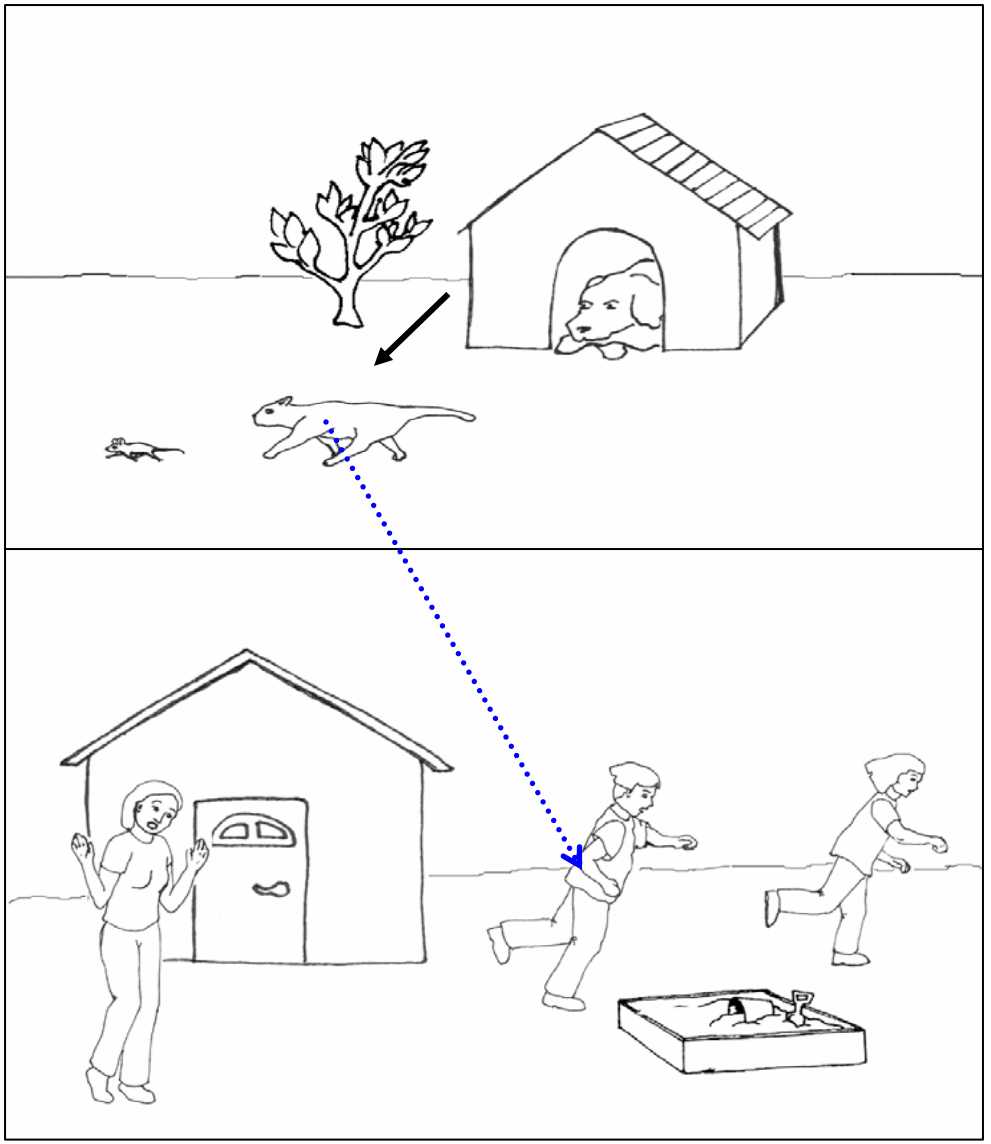
- Fundamental to acquisition of relational concepts
- Improves with age: the “relational shift” (Gentner & Rattermann, 1991)
- Scene Analogy Task: Examine constraints underlying development

# Developmental Hypotheses for “Relational Shift”

- Increase in relational knowledge
- Increase in relational integration
  - development of WM
- Increase in ability to suppress salient alternatives
  - development of inhibitory control

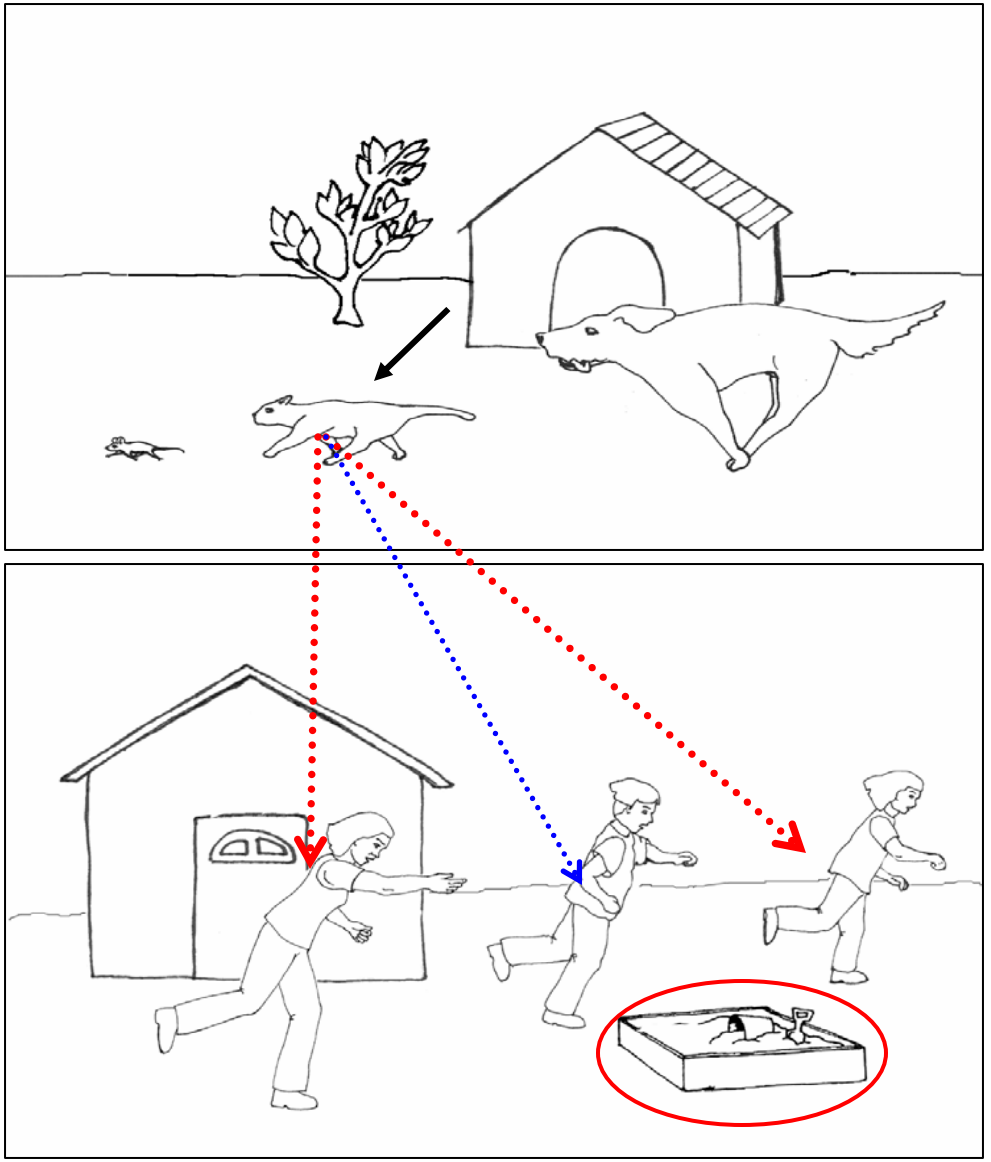
# Scene Analogy Task

1 relation, no distractor



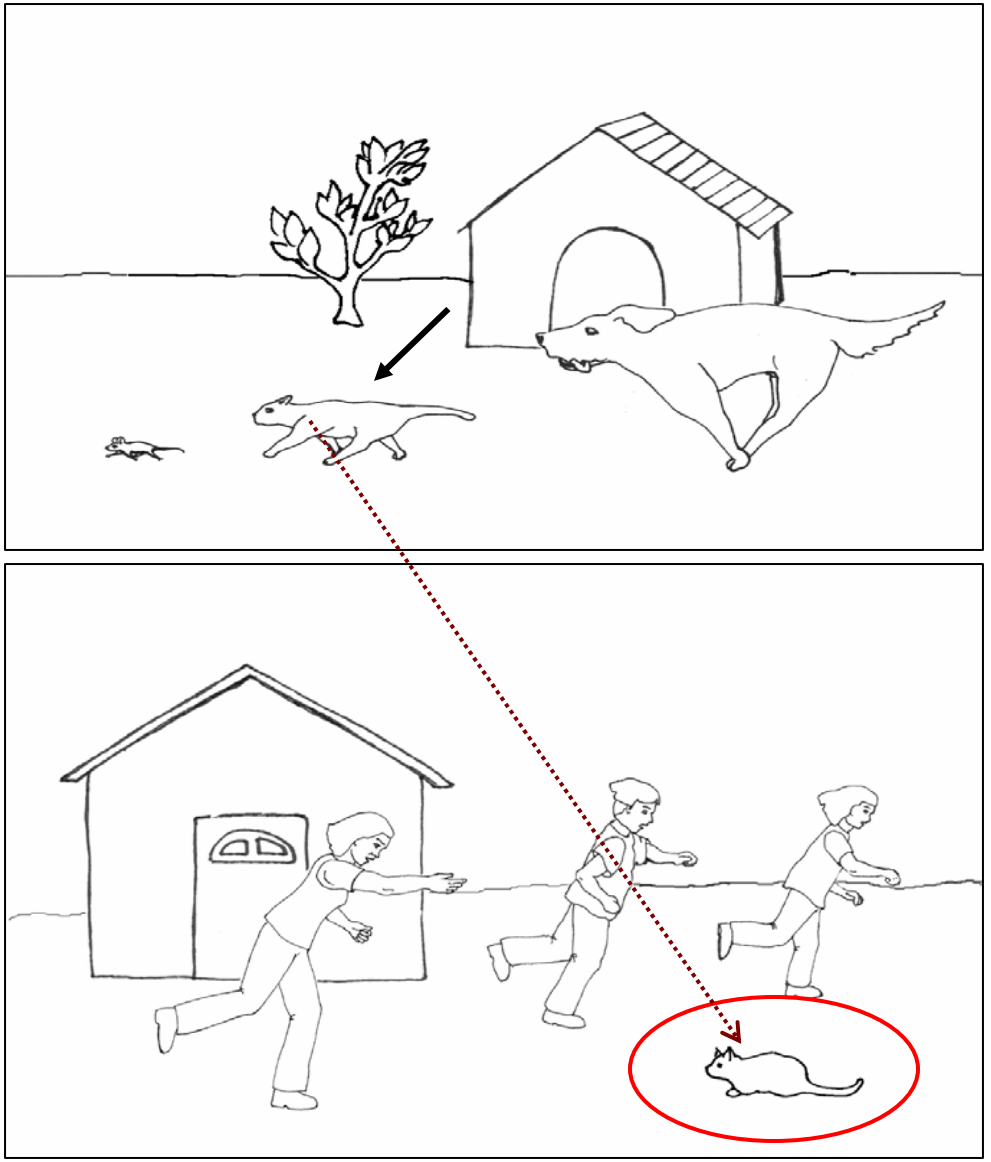
# Scene Analogy Task

2 relations, no distractor

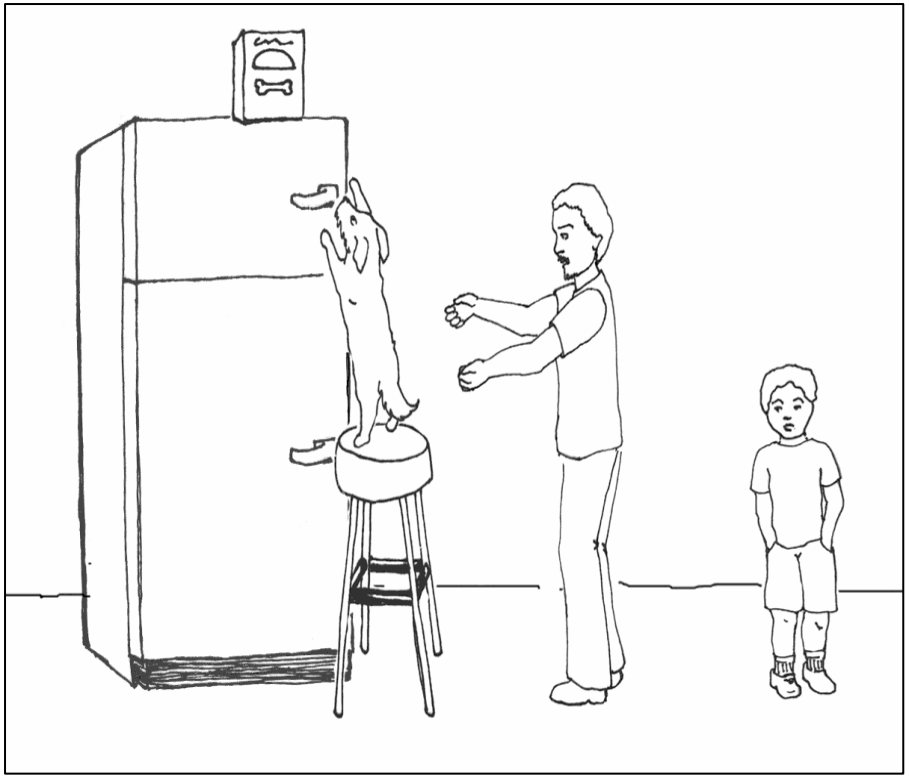


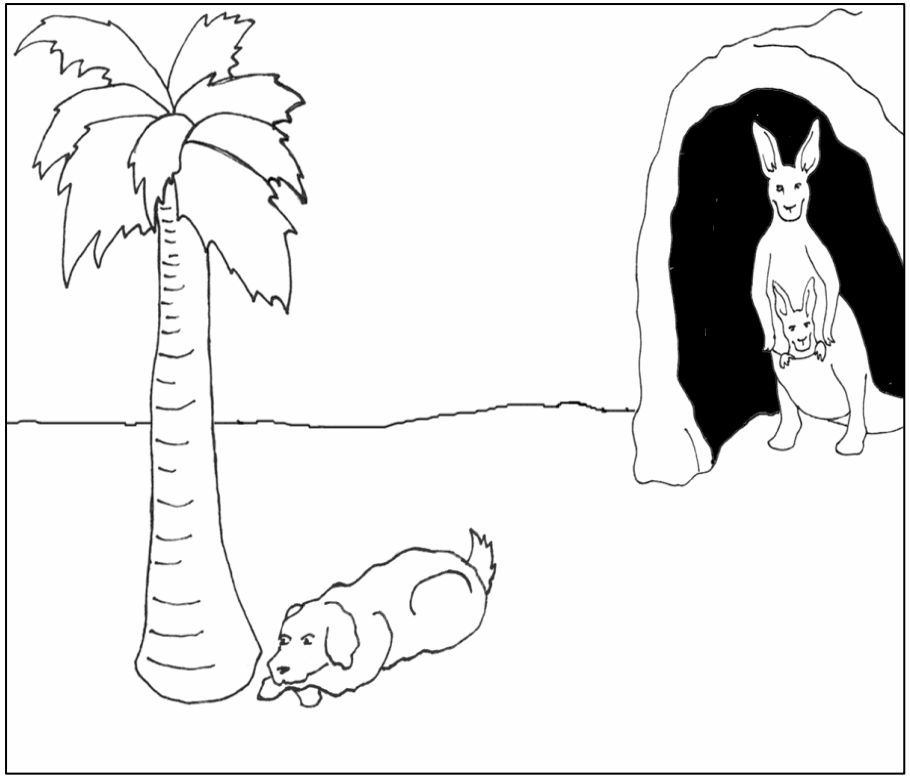
# Scene Analogy Task

2 relations, salient distractor



*“Which picture shows ‘reaching’?”*

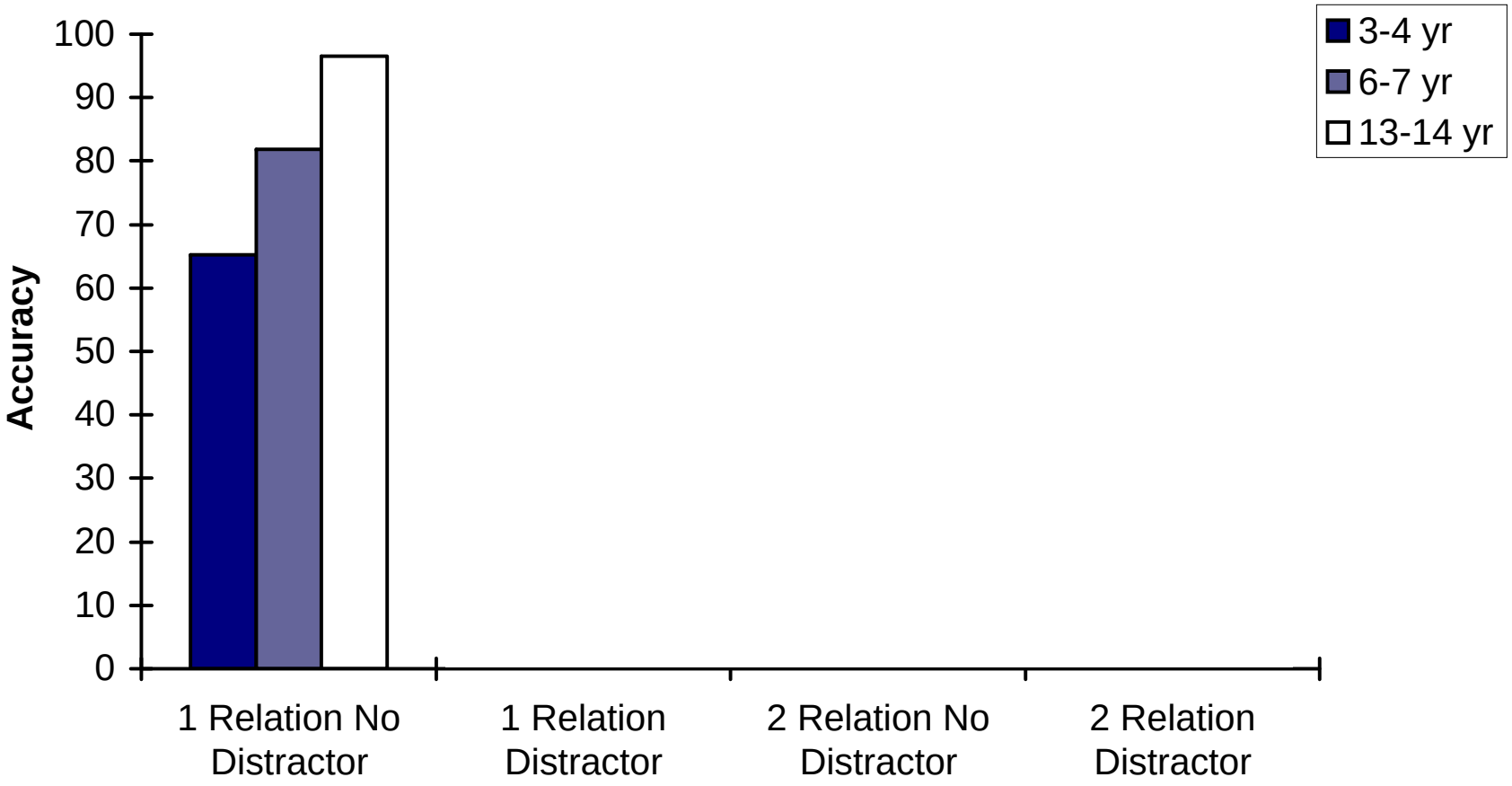




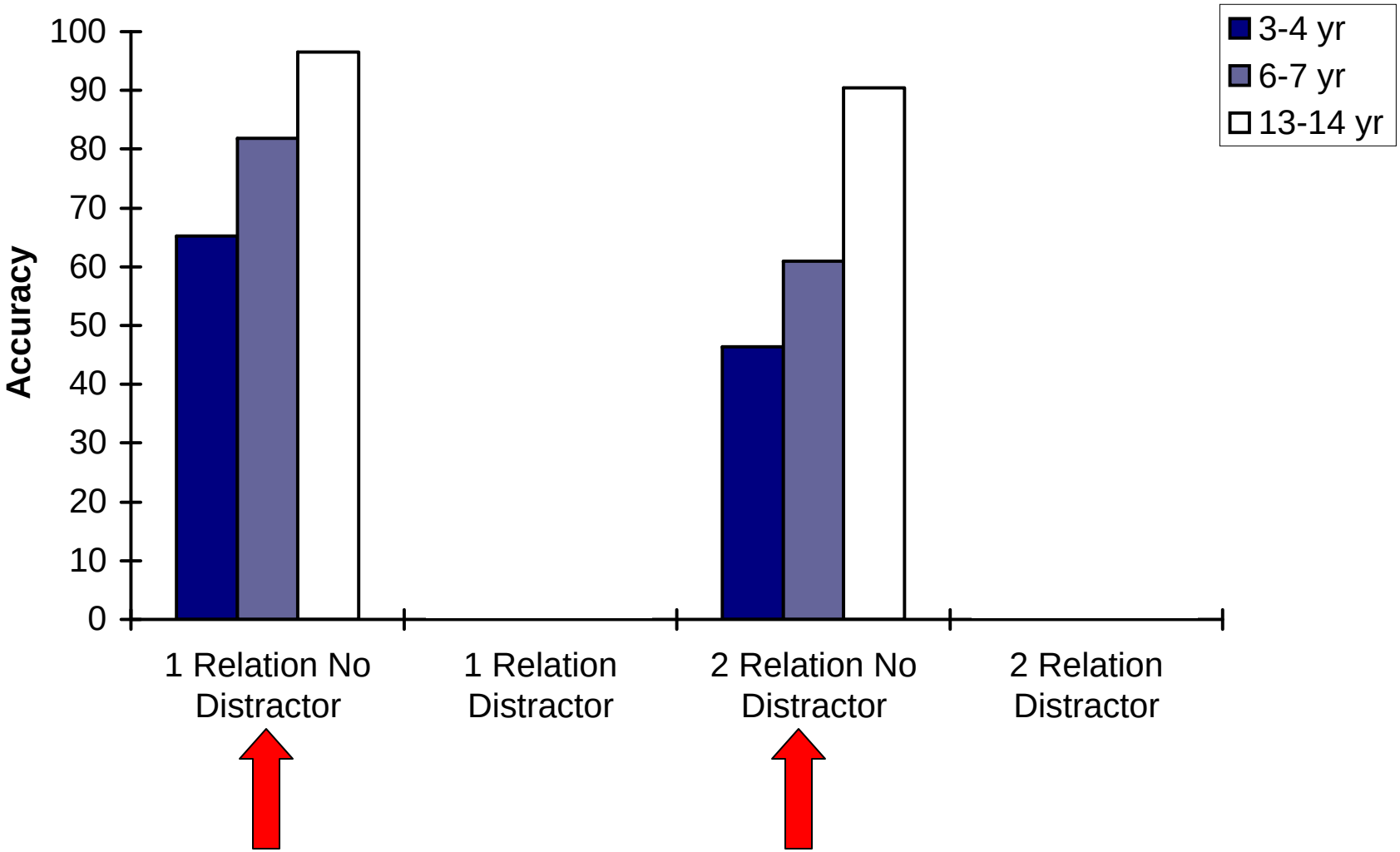
# Experiment 1: Participants

- 68 Children
  - 22, 3-4 years old
  - 21, 6-7 years old
  - 25, 13-14 years old

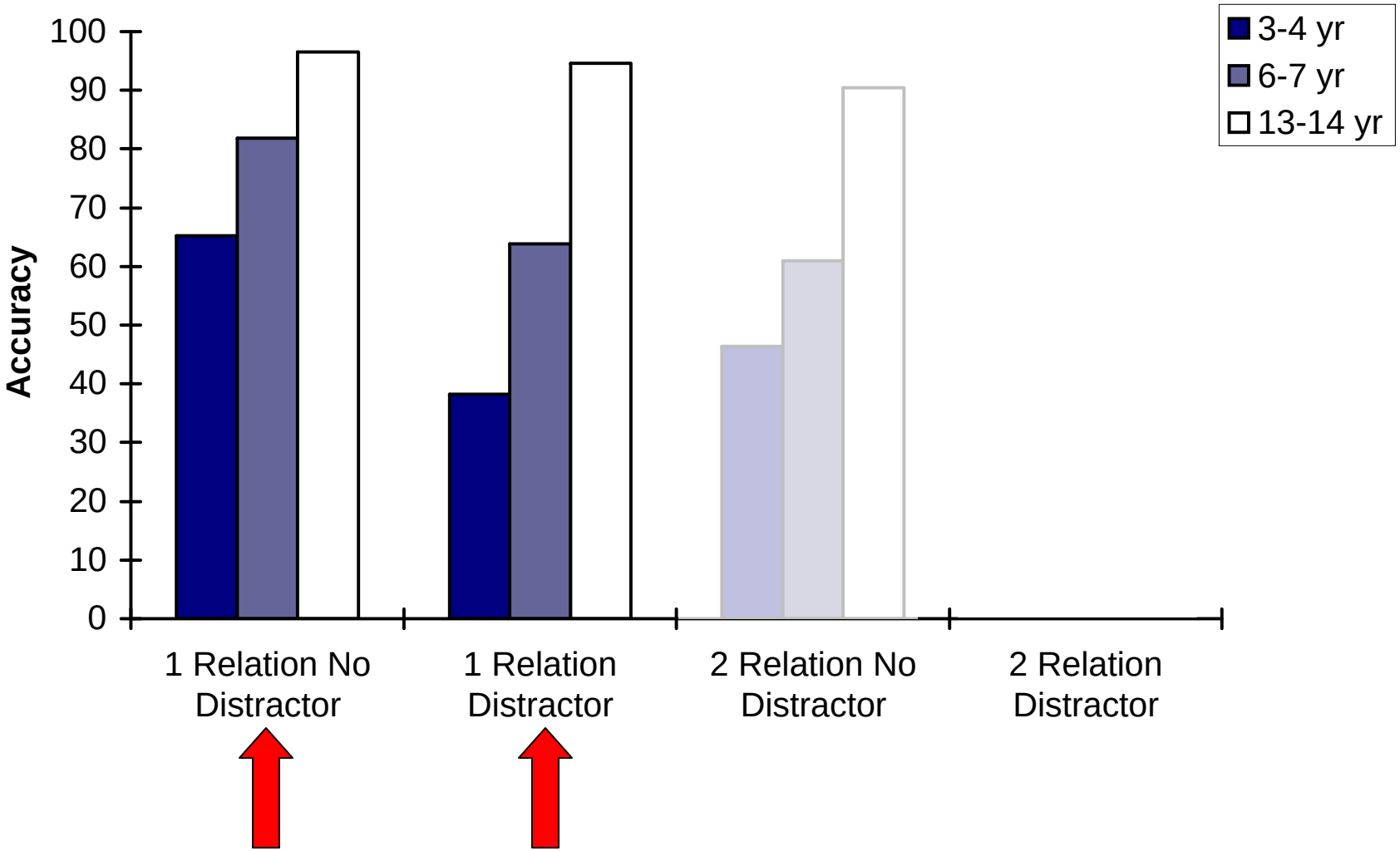
# Accuracy: Correct Relational Responses



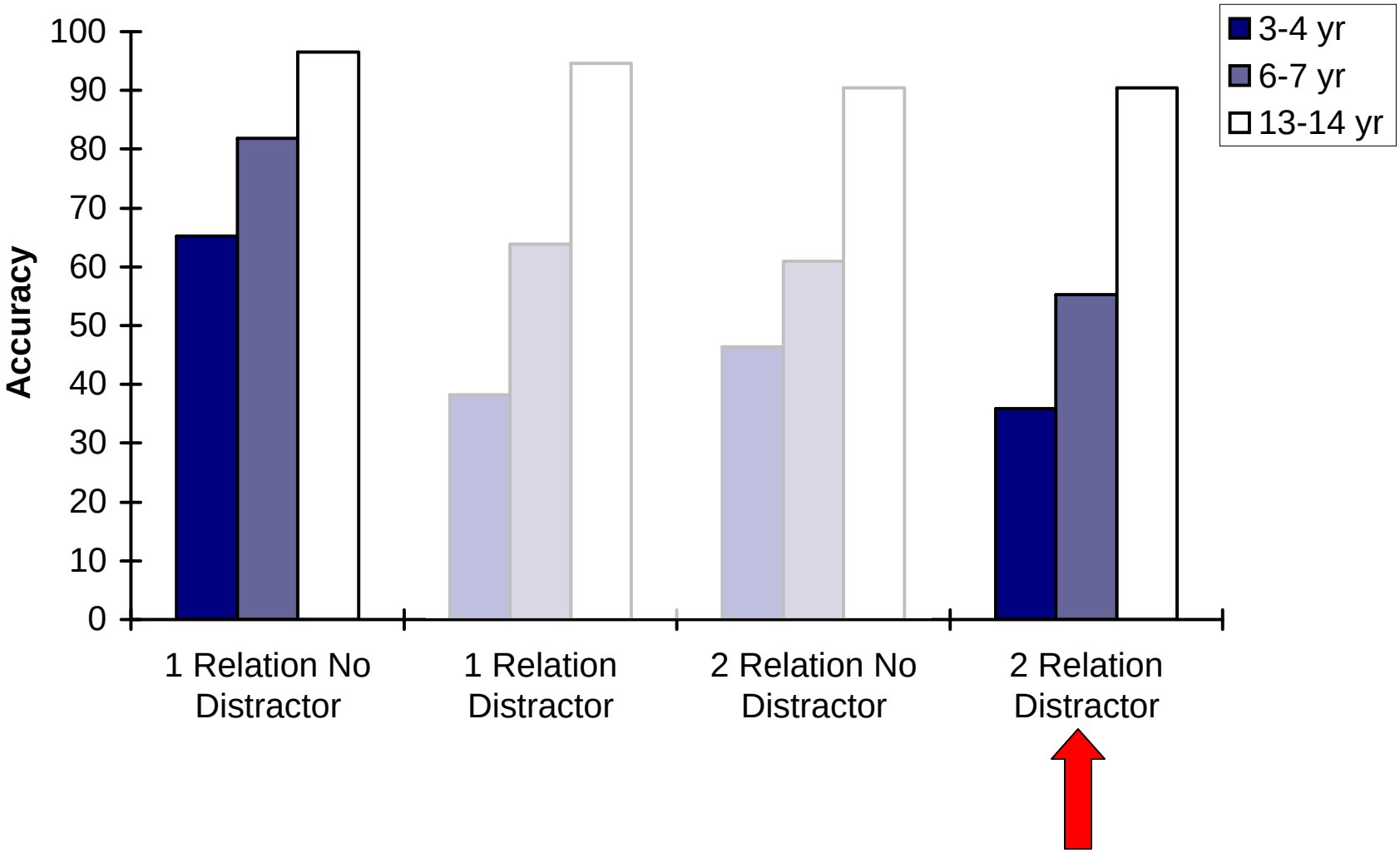
# Relational Complexity



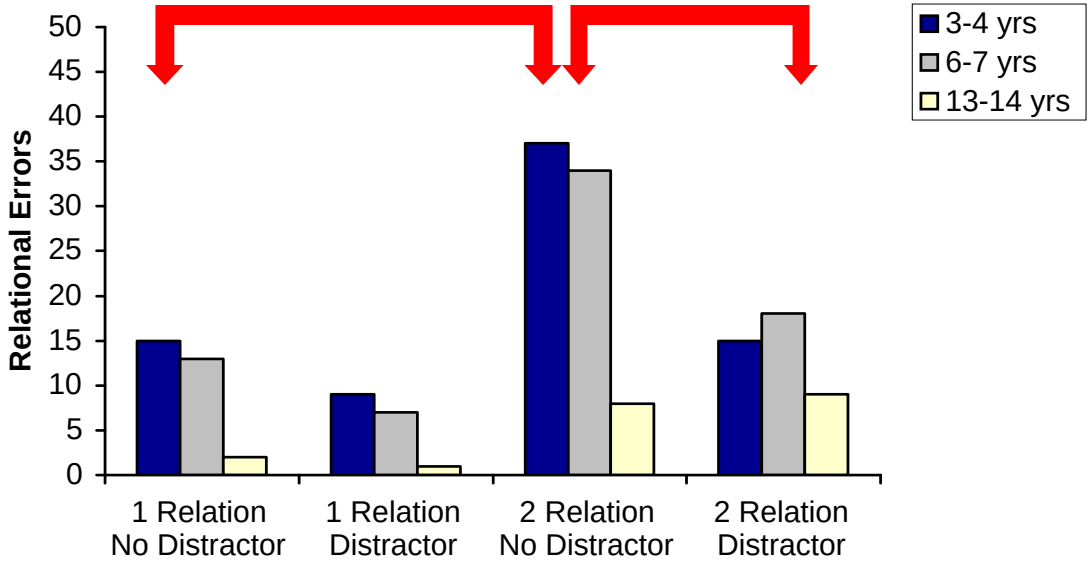
# Object Similarity



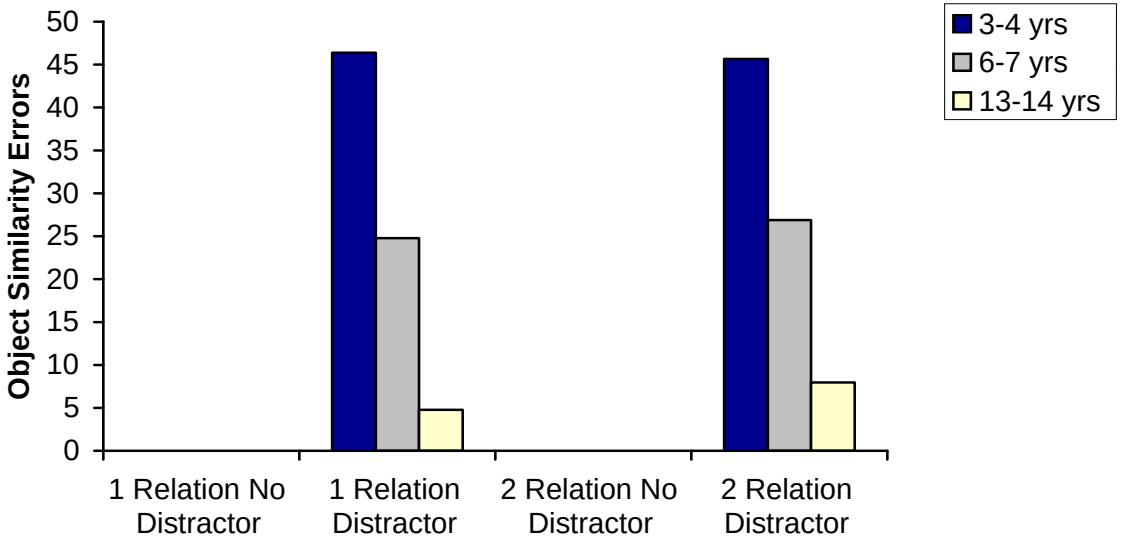
# Relational Complexity + Distractor



# Relational Errors



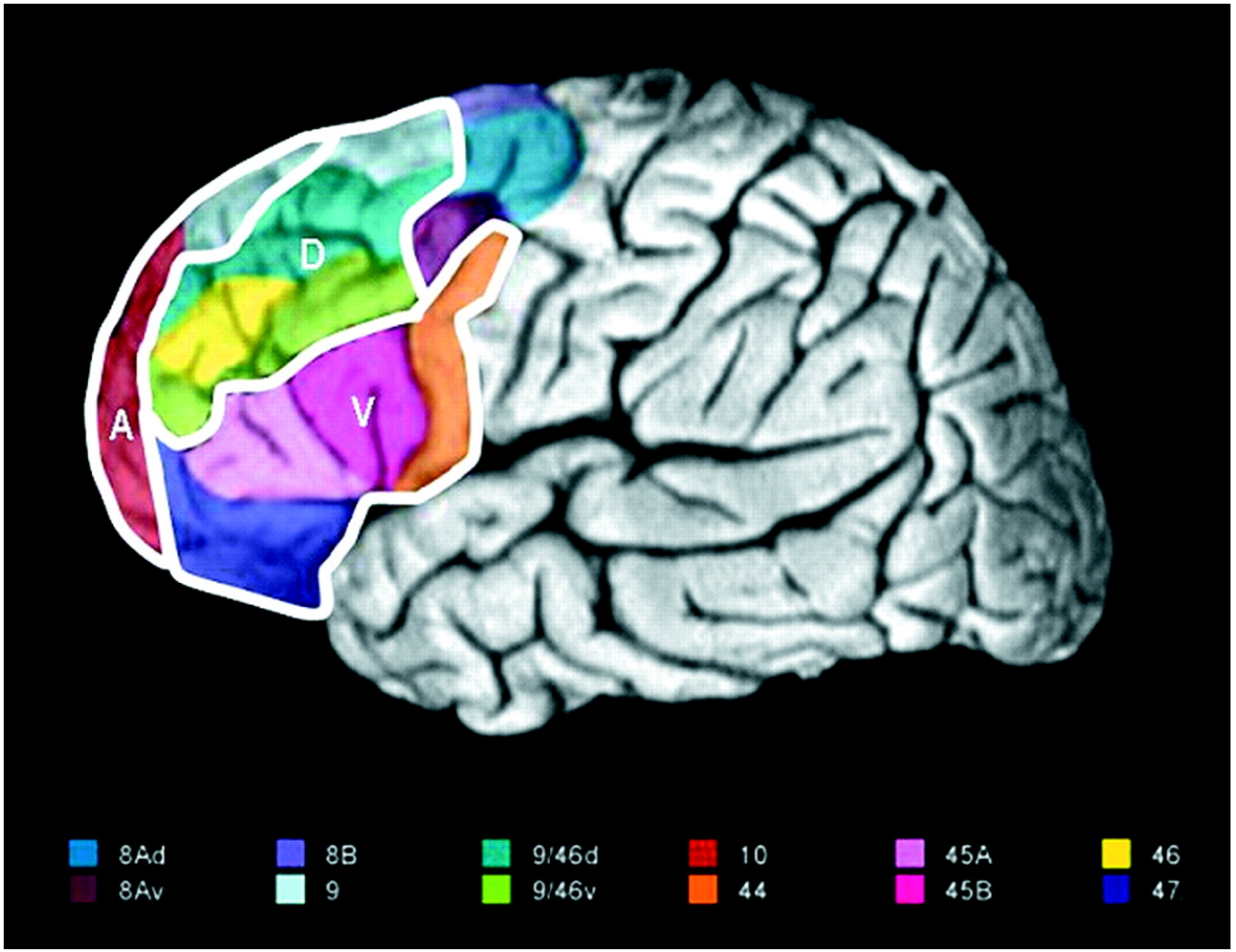

# Distractor Errors



# Conclusions about Analogy Development

- Analogical ability improves with age even for problems based on familiar relations and objects
- Both relational complexity and inhibitory control constrain children's analogical reasoning
- Both processes decline during normal aging (Viskontas et al., 2004, 2005)

# Diagram of the Human Prefrontal Cortex (PFC; left lateral view)




Rajah, M. N. et al. Brain 2005 128:1964-1983; doi:10.1093/brain/awh608



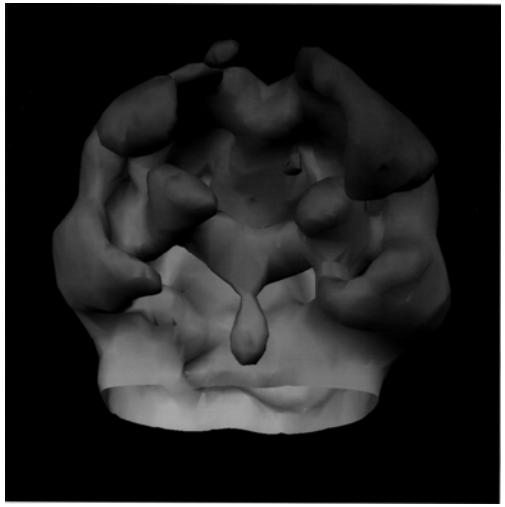
BRAIN
A journal of neurology

# Relational Integration in PFC

(Waltz et al., *Psych. Science*, 1999)

- **Frontotemporal Dementia patients**
- **Broad bilateral damage**
- **Two major variants**

**Normal Brain**



**Frontal-Variant**

- **personality changes**
- **dysexecutive changes**

- **FTD patients**
- **Two major variants**

**Normal Brain**

**Temporal-Variant**

- **semantic memory**
- **emotional changes**
- **preserved episodic & working memory**

# Prefrontal Cortex and Relational Integration

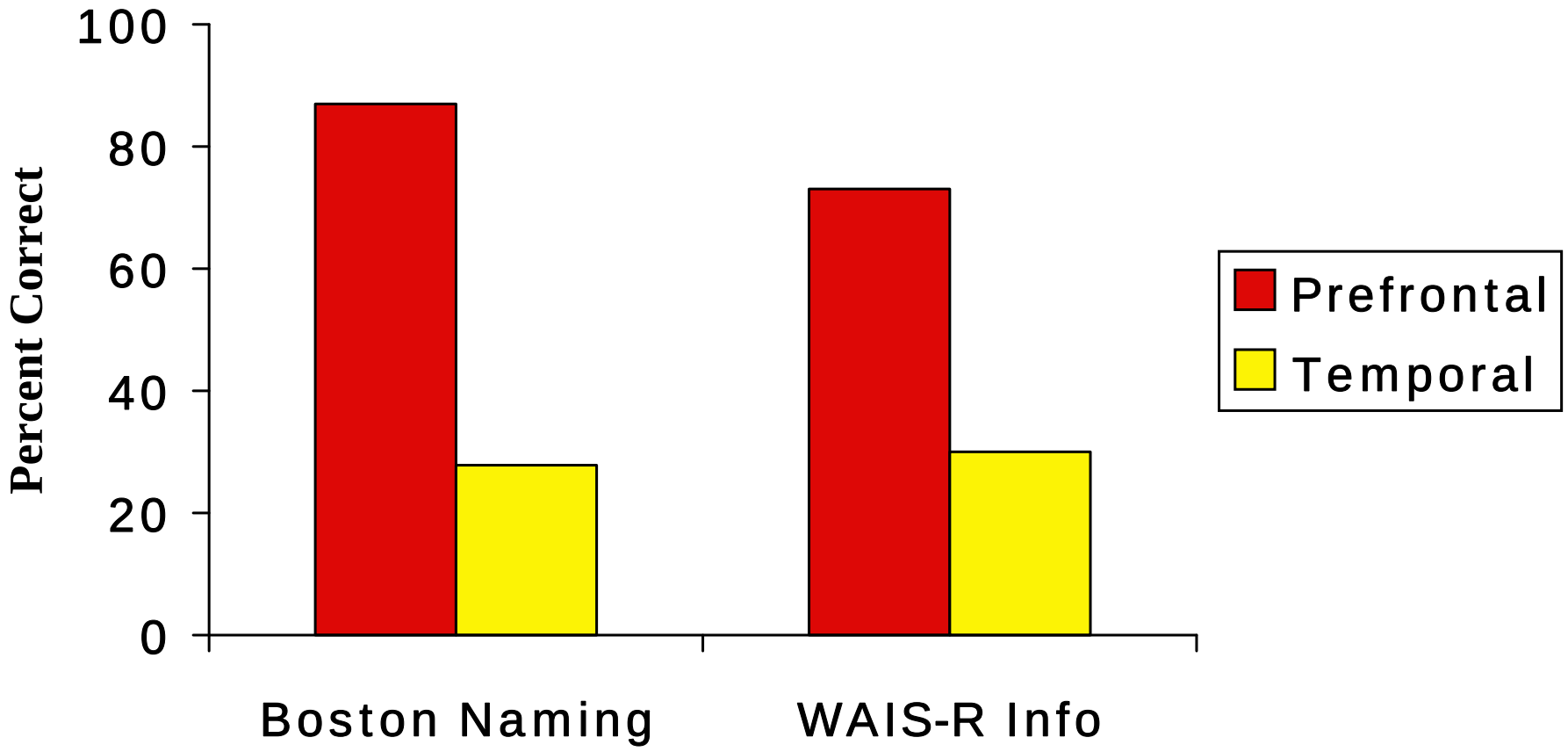
- **Approach**: systematically vary number of relations to be integrated
- **Prediction**: patients with prefrontal damage will exhibit a deficit with relational complexity >1

- **Subjects**: Patients with early stage fronto-temporal dementia (FTD)
- Patients divided into frontal variant and temporal variant groups

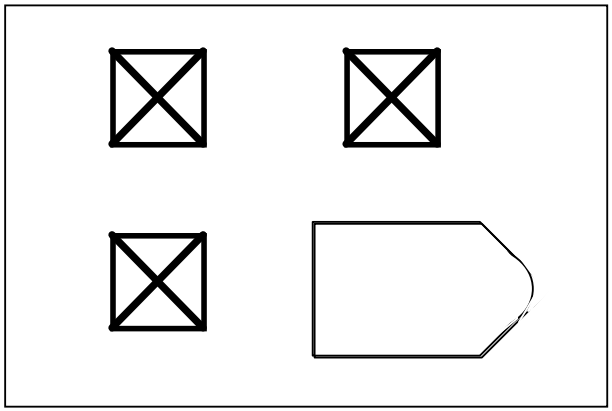
# Patient Characteristics

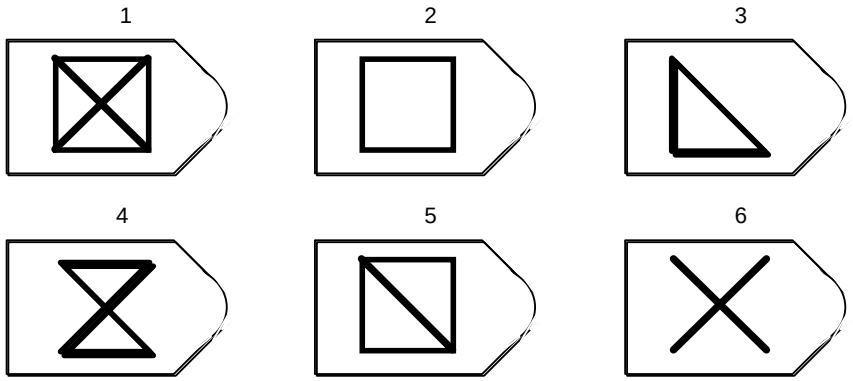
| | N | Age | Edu | IQ | MMSE |
|---|---|---|---|---|---|
| Prefrontal | 6 | 65.4 | 16.0 | 96.0 | 23.8 |
| Temporal | 5 | 63.2 | 17.8 | 94.8 | 23.0 |
| Normal Con | 7 | 64.9 | 16.4 | | |

# Performance on Semantic Knowledge Tests

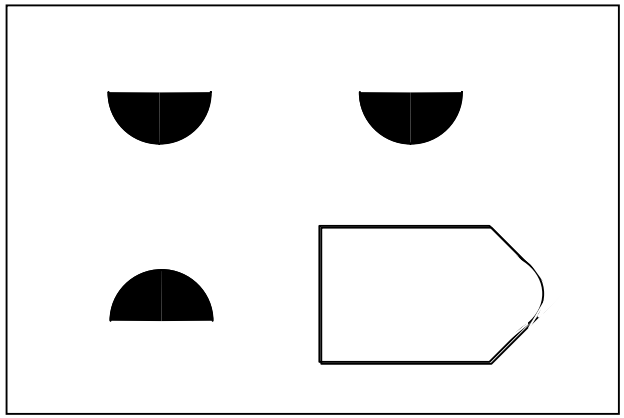


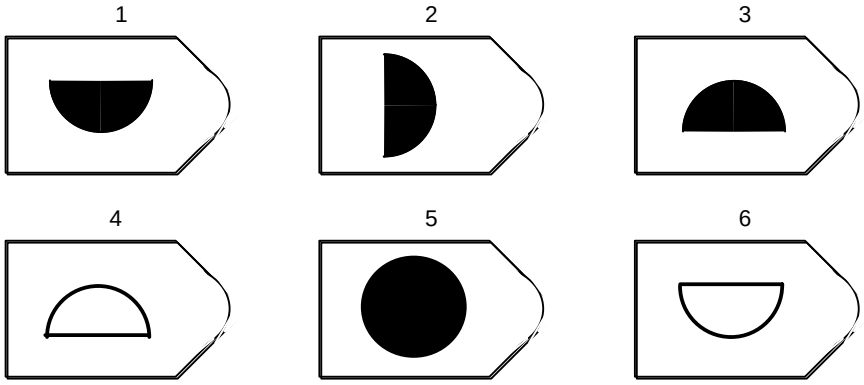
# Level 0 Matrix Problem



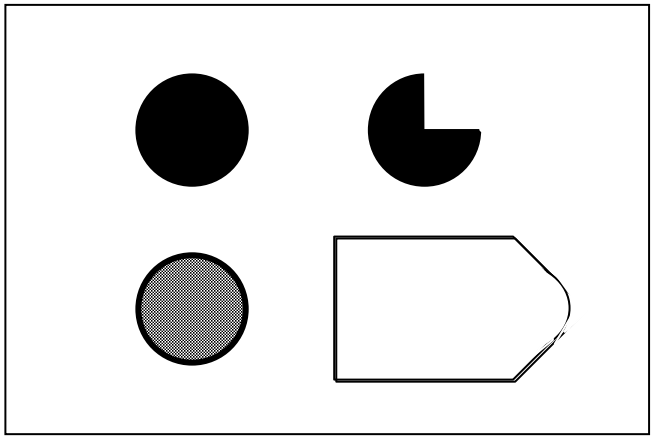


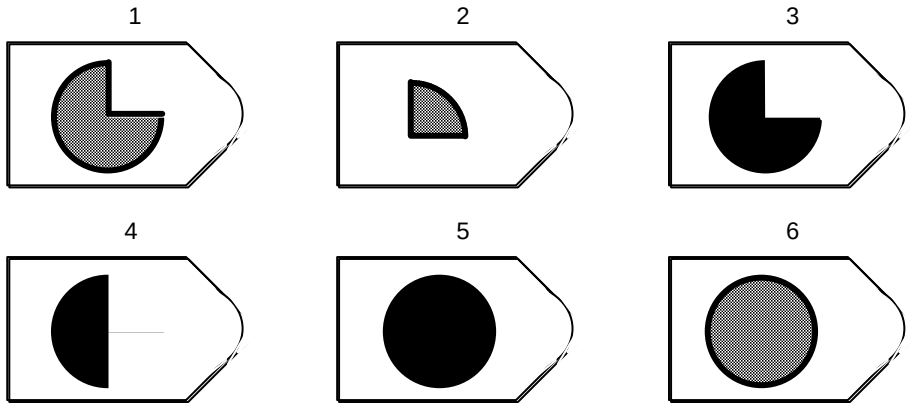
# Level 1 Matrix Problem



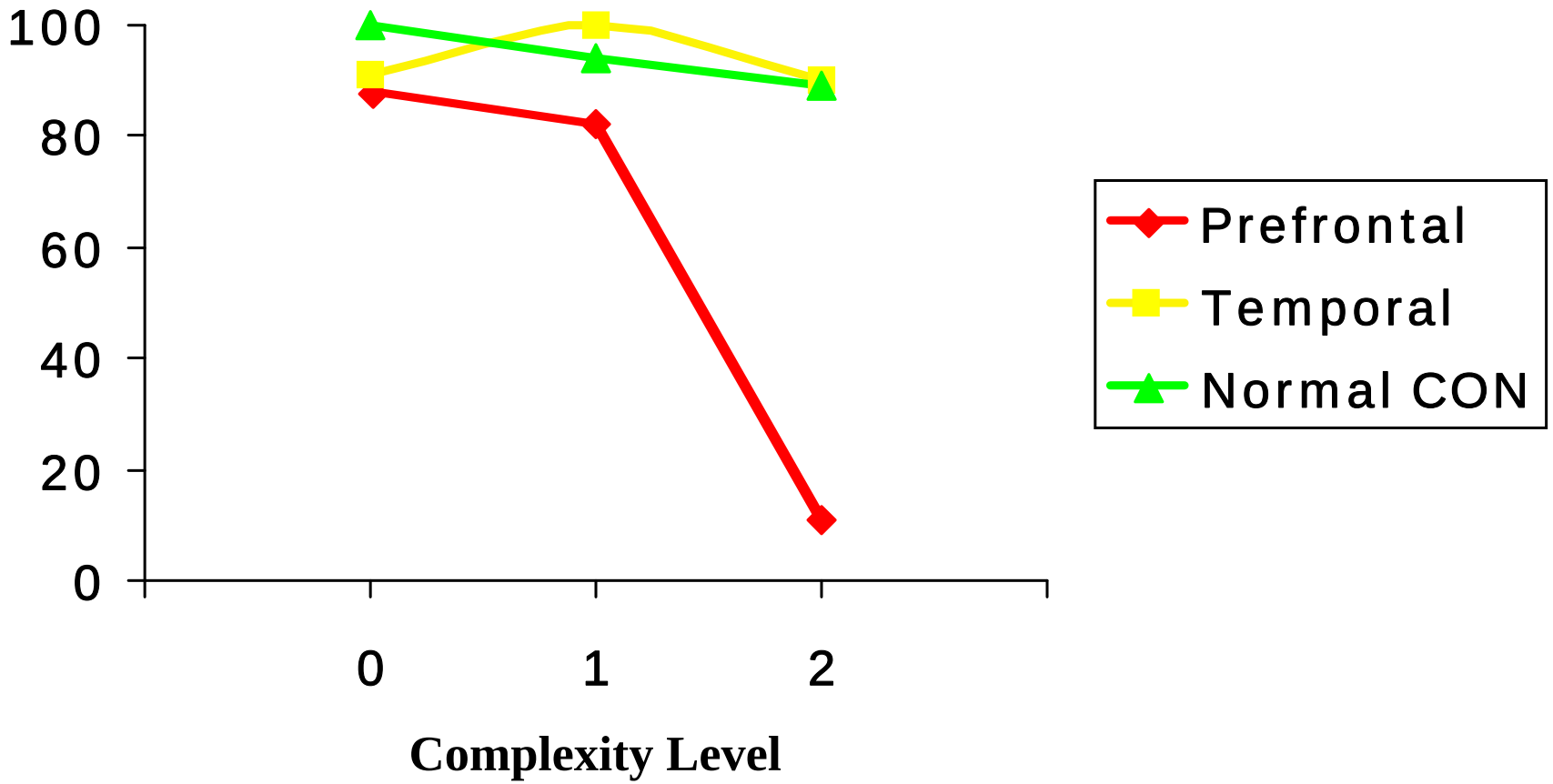


# Level 2 Matrix Problem





# Matrix Problems



# Role of Inhibition with Verbal Analogies

Morrison et al., *J. Cog. Neuroscience (*2004)

- **A : B :: C : D or D' Verbal Analogies**
- **Manipulate how associated C : D are relative to C : D'**
- **Collected association ratings for each C:D and C:D' pair from UCLA undergraduates**
- **Calculated a Semantic Facilitation Index (SFI) for each problem**

**SFI = assoc (C:D) - assoc (C:D')**

# Analogy in the Brain

Morrison et al. (2004)

## Neutral SFI

**lake : ocean :: big : _____ 1) bigger* 2) small**

- *association of big:bigger = association of big:small*

## Positive SFI

**motor : engine :: middle : _____ 1) center* 2) end**

- *association of middle:center > association of middle:end*

## Negative SFI

**play : game :: give : _____ 1) party* 2) take**

- *association of give:party < association of give:take*

* correct relational answer

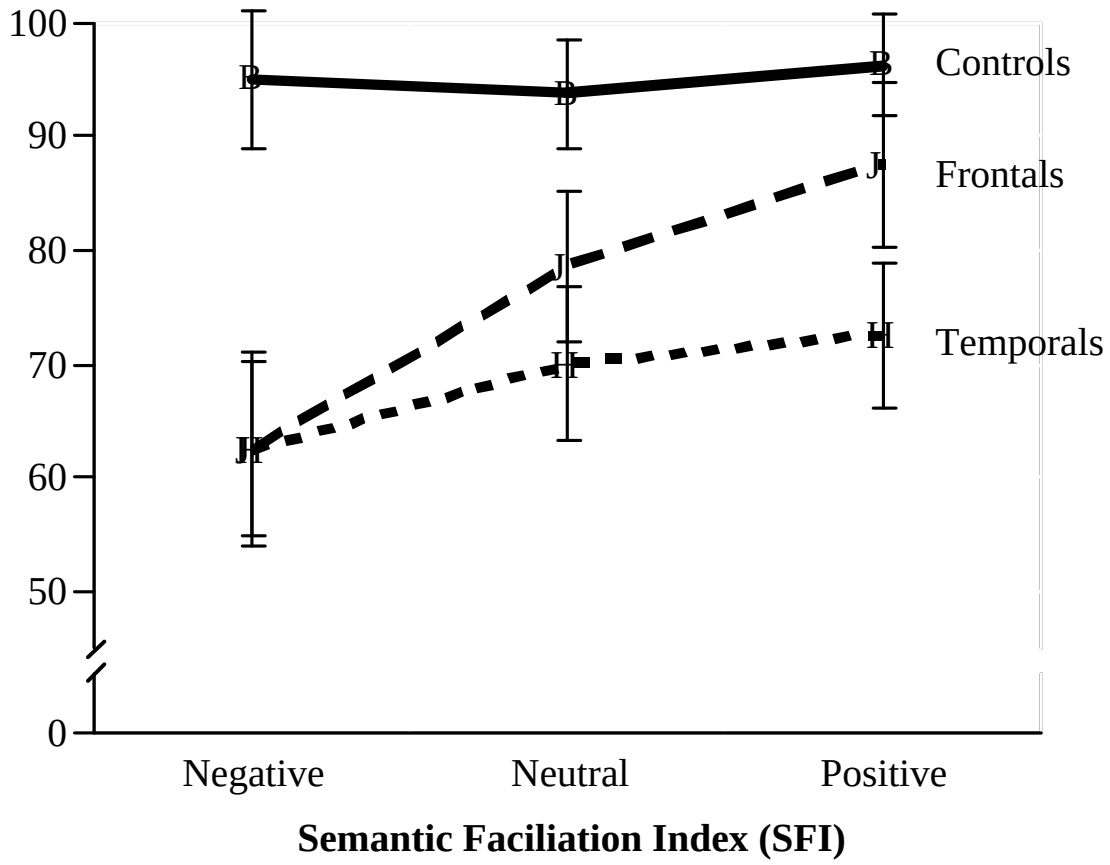
# Analogy in the Brain

Morrison et al., 2004

- **Frontal patients**
  - **Negative SFI worse than Neutral or Positive SFI**
  - **Difficulty suppressing competing alternatives in WM**

- **Temporal patients**
  - **Uniform decrease in performance because of semantic memory loss**

# Verbal Analogies

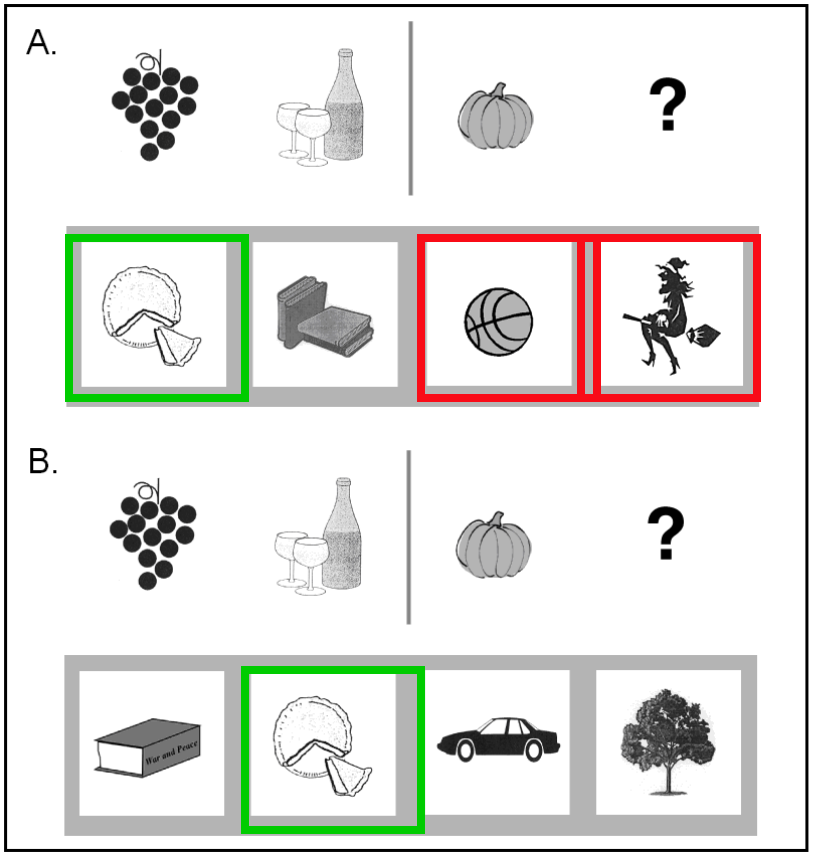


# Role of Inhibition with Picture Analogies

Krawczyk et al. (*Neuropsychologia*, 2008)

Distractors present

No distractors



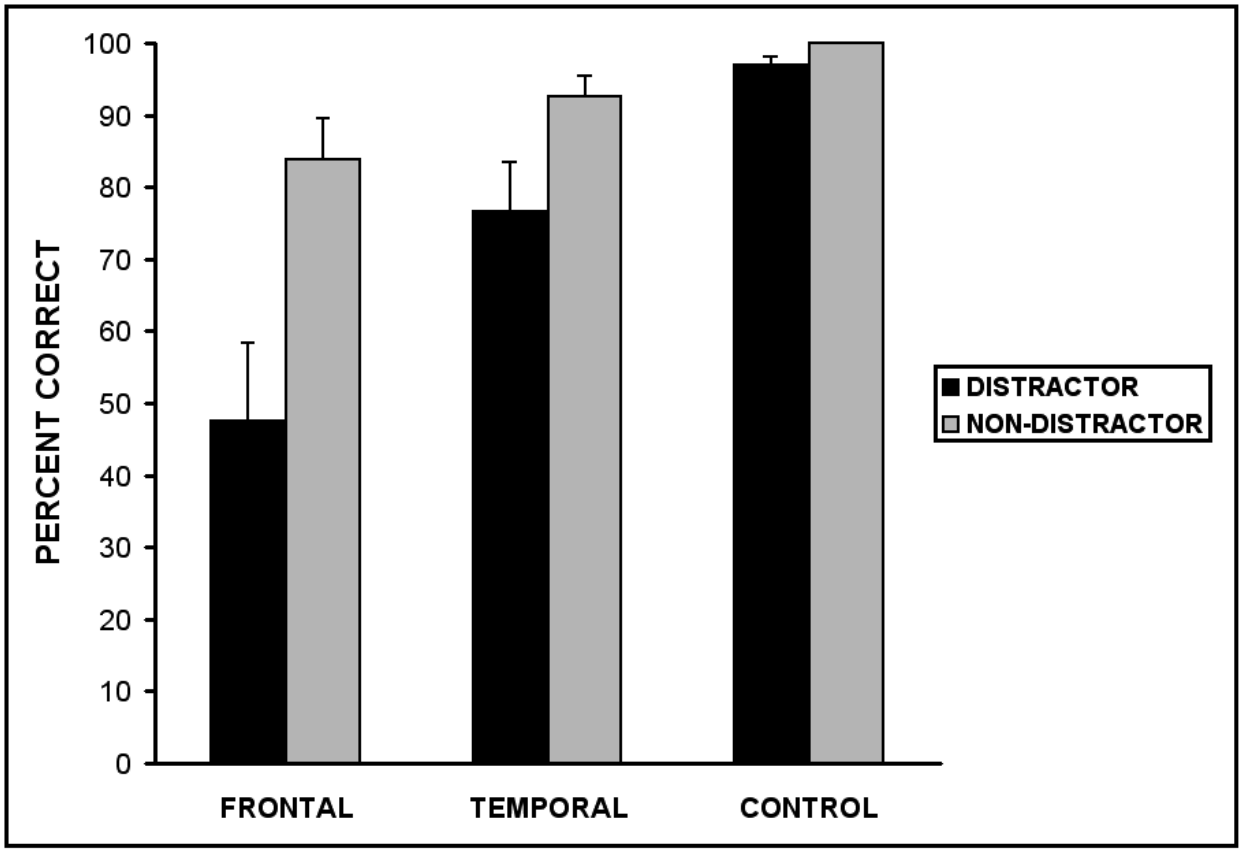
# Predictions
## Krawcyzk et al. (2008)

- Frontal patients
  - Reasoning impaired by presence of semantic and perceptual distractors
  - Difficulty suppressing competing alternatives in WM

- Temporal patients
  - Impairment with semantic distractors due to semantic memory loss

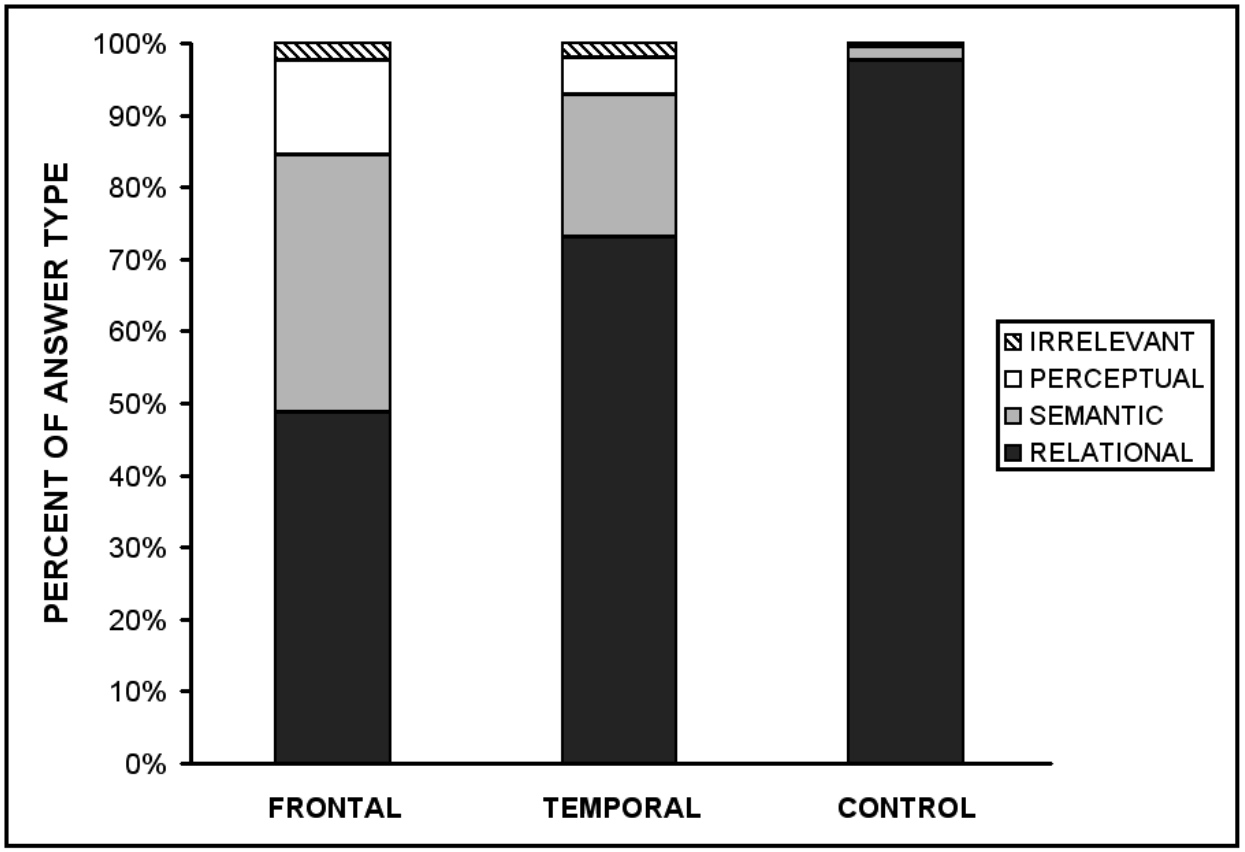
# Overall accuracy

## Krawczyk et al. (2008)



# Responses in Distractor Set

## Krawczyk et al. (2008)

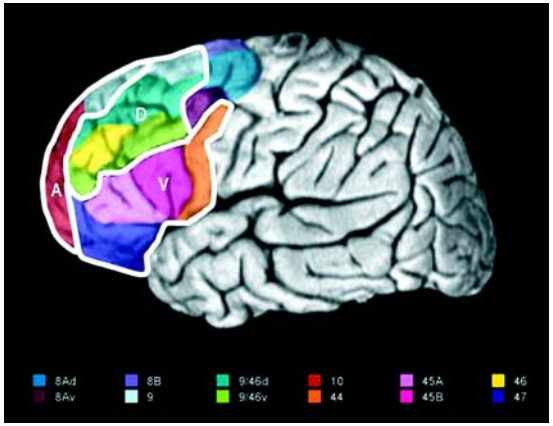


# Evidence from Neuropsychology

- Prefrontal cortex required to
  - integrate multiple relations (Waltz et al., 1999, 2001)
  - inhibit responses to salient distractors (Morrison et al., 2004; Krawczyk et al., 2008)

# Prefrontal Regions of Interest for Analogical Reasoning

- Anterior (BA 10)
  - relational integration (Ravens, analogy)
  - coordinating goals
- Dorsolateral (BA 46, 9/46)
  - working memory (e.g., *n*-back task)
- Ventrolateral (BA 44,45)
  - inhibition of motor response
  - proactive interference
  - semantic retrieval
  - control of belief bias in deductive reasoning



# Summary of fMRI Findings

- Relational complexity activates anterior PFC ≠

  *Prabhakaran et al. (1997); Christoff et al. (2001); Kroger et al. (2001); Luo et al. (2003); Bunge et al. (2004); Green et al. (2006)*

*New study manipulating both complexity and interference with pictorial analogy problems (Cho et al., under review):*

- Interference activates regions of ventrolateral PFC associated with control of interference in other tasks

- Relational complexity yields broader activation, overlapping with interference in ventrolateral PFC

# Overall Conclusions

Relational integration and interference resolution are key processes in analogical reasoning:

- undergo cognitive development
- impaired with aging or frontal damage
- associated with specific subareas of PFC
- result in uniquely human analogical abilities