Recent Advances in Relational Complexity Theory & its Application to Cognitive Development

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Cromwell


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Changing conceptions of thinking

- In Piagetian theory, cognitive development culminates in formal operational *logic*
  - *"logic is the mirror of thought*" (Piaget, 1950)

- assumption that human thought is *logical* has been questioned
  - Information processing theories
  - Heuristics (Kahneman & Tversky, 1982)
  - Rational analysis (Anderson, 1990, 1991)
  - Mental models approach (Johnson-Laird & Byrne, 1991)

- If human reasoning is not “logical” then “normative logic” criteria are inappropriate for evaluating reasoning in children and adults

- reasoning can be considered in terms of the *complexity of the mental models* employed

Complexity as a criterion? Some requirements

- we need a *principled* method for analysing tasks and quantifying their complexity that is
  - applicable in different content domains
  - capable of making predictions in advance of data
  - supported by behavioural evidence
    - items with higher estimated complexity should be more difficult than comparable items with lower estimated complexity
    - sensitive to age related change
    - tests at a given complexity level form an equivalence class
    - consistency within individuals
  - consistent with evidence about brain function & development

Outline

- Describe Relational Complexity theory
- Demonstrate the approach by analysing complexity of some cognitive development tasks
- Evaluate whether requirements are met

Relational Complexity theory

(Halford, 1993; Halford, Wilson & Phillips, 1998)

- Higher cognitive processes involve processing of relations
- Relational representations have properties that underpin symbolic thought and are integral to analogical reasoning
- Relational complexity (RC) corresponds to
  - number of variables that are related in a cognitive representation
  - number of slots or *arity* of relations

RC metric

RC is defined by the number of slots

- Unary relations have 1 slot
  - e.g. class membership, as in *dog*(Fido)
- Binary relations have 2 slots
  - e.g. *larger-than*(elephant, mouse)
- Ternary relations have 3 slots
  - e.g. *addition*(2,3,5)
- Quaternary relations have 4 slots
  - e.g. *proportion*(2,3,6,9)

- each slot in a relation can be filled in a variety of ways
- a binary relation has two slots
  - *larger-than*(_____, _____)
  - *larger-than*(elephant, mouse)
  - *larger-than*(mountain, molehill)
  - *larger-than*(ocean-liner, rowing-boat)
- a slot corresponds to a variable or dimension

- More complex relations impose higher processing loads
  - ternary relations impose higher load than binary relations
  - quaternary relations impose higher load than ternary relations

- 2 strategies to reduce complexity and processing load
  - Segmentation
  - Conceptual chunking

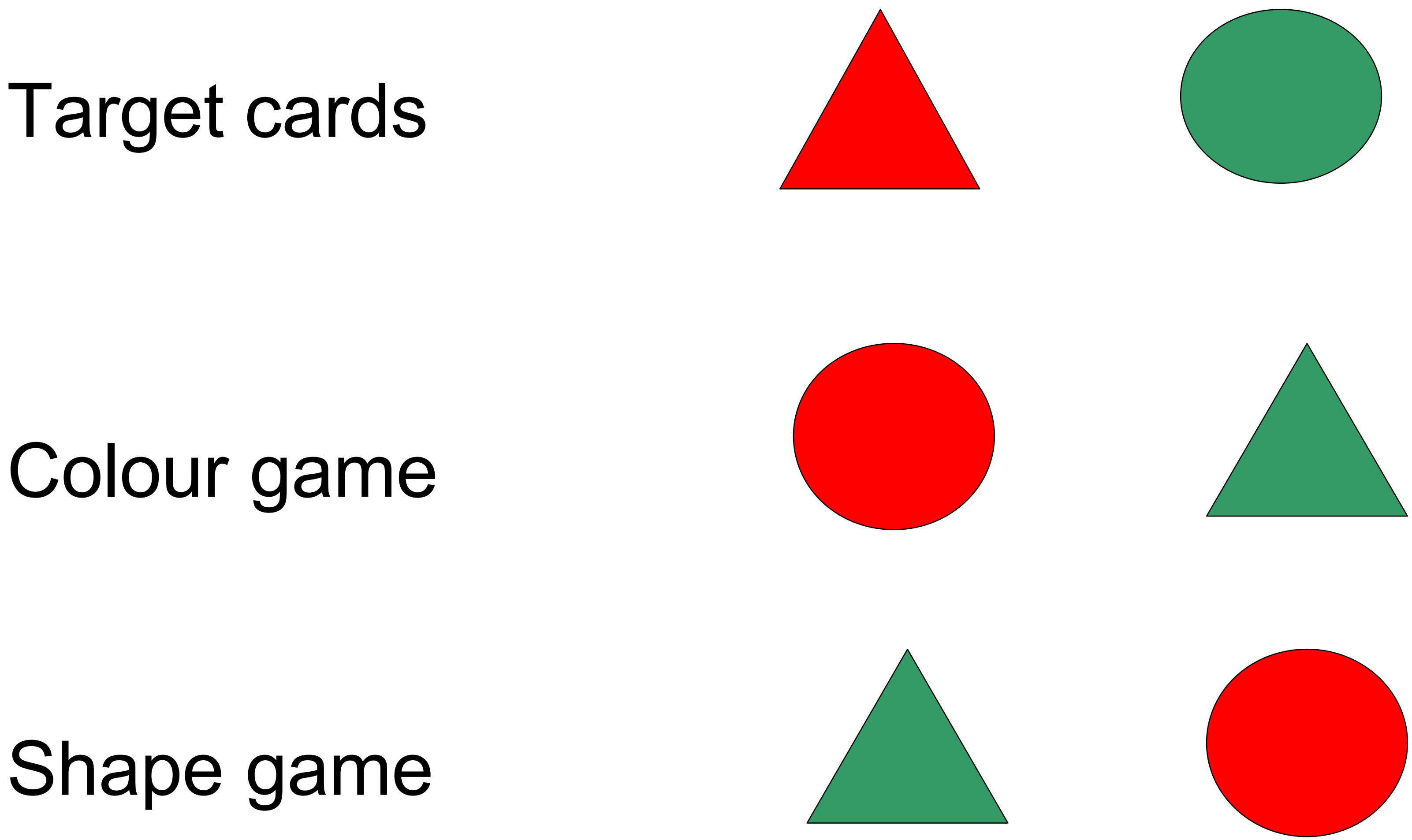
- *Segmentation*
  - complex tasks are decomposed into less complex components that do not overload capacity
- English relative clause sentences
  - *The clown that the teacher that the actor liked watched laughed* (difficult to segment)
  - *The actor liked the teacher that watched the clown that laughed* (easy to segment)

- *Conceptual chunking*
  - compression of variables
  - analogous to collapsing factors in a multivariate design
    - *Velocity = distance/time* (ternary-relational) can be recoded to binding between a variable and a constant, *Speed = 80 kph* (unary-relational)
  - reduces complexity and processing load, but chunked relations are inaccessible
    - with the chunked (unary-relational) representation, we cannot determine that velocity doubles if we travel the same distance in half the time
    - this is possible with the un-chunked (ternary-relational) representation

Principle 1

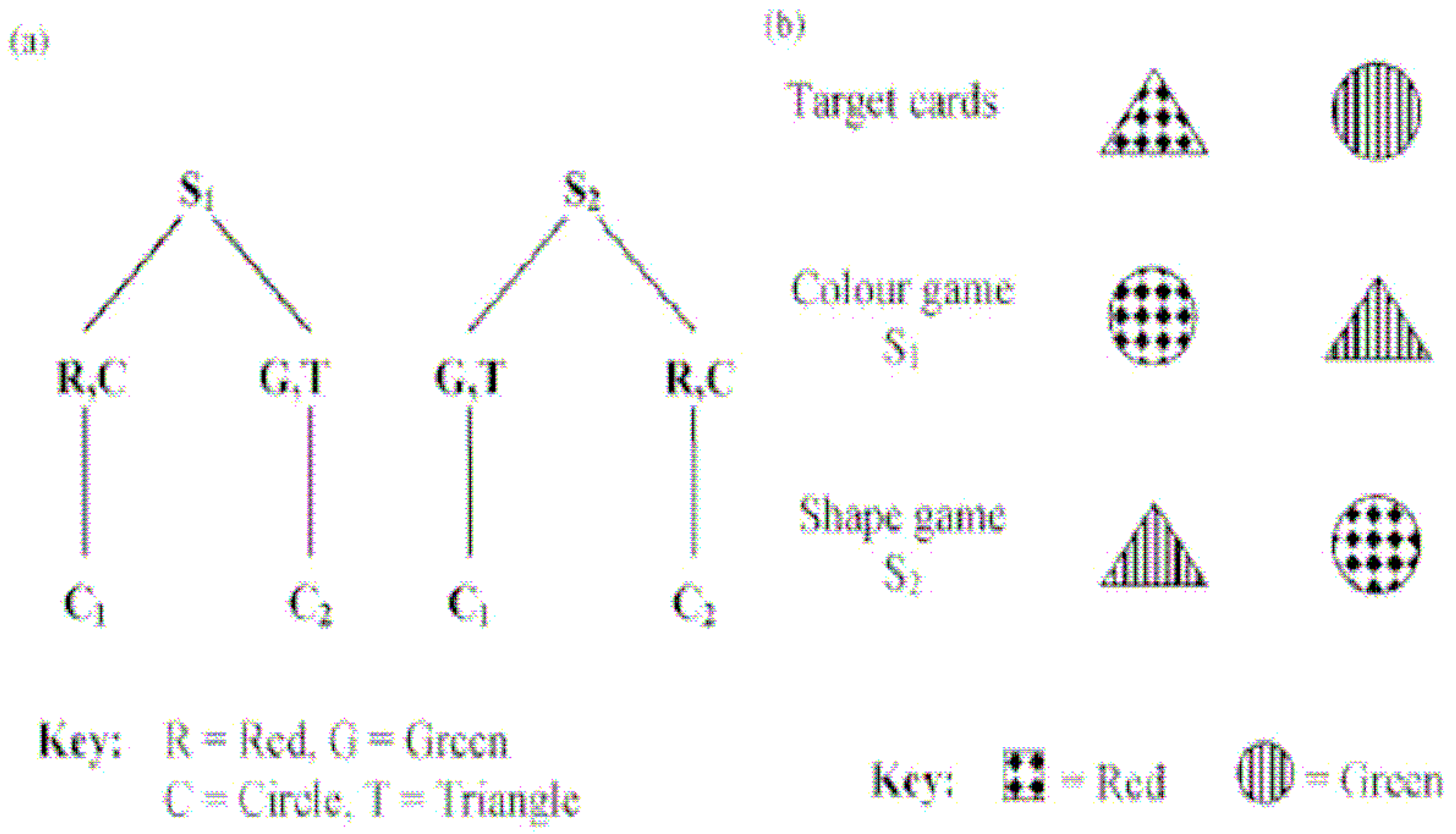
- Complexity analyses must take account of strategies to reduce complexity & processing loads
- Variables can be chunked or segmented only if the relations between them do not need to be processed
- Tasks that impose high processing loads are those in which chunking and segmentation are constrained

Dimensional Change Card Sort (DCCS) task



DCCS

- young children
  - sort correctly by the first dimension (e.g., colour),
  - experience difficulty switching between dimensions (e.g., from colour to shape)
- 2 complexity explanations
  - Cognitive Complexity & Control theory (Zelazo & Frye, 1998; Zelazo et al., 2003)
    - number of levels in rule hierarchy
  - RC theory
    - Involves a ternary relation that is difficult to decompose



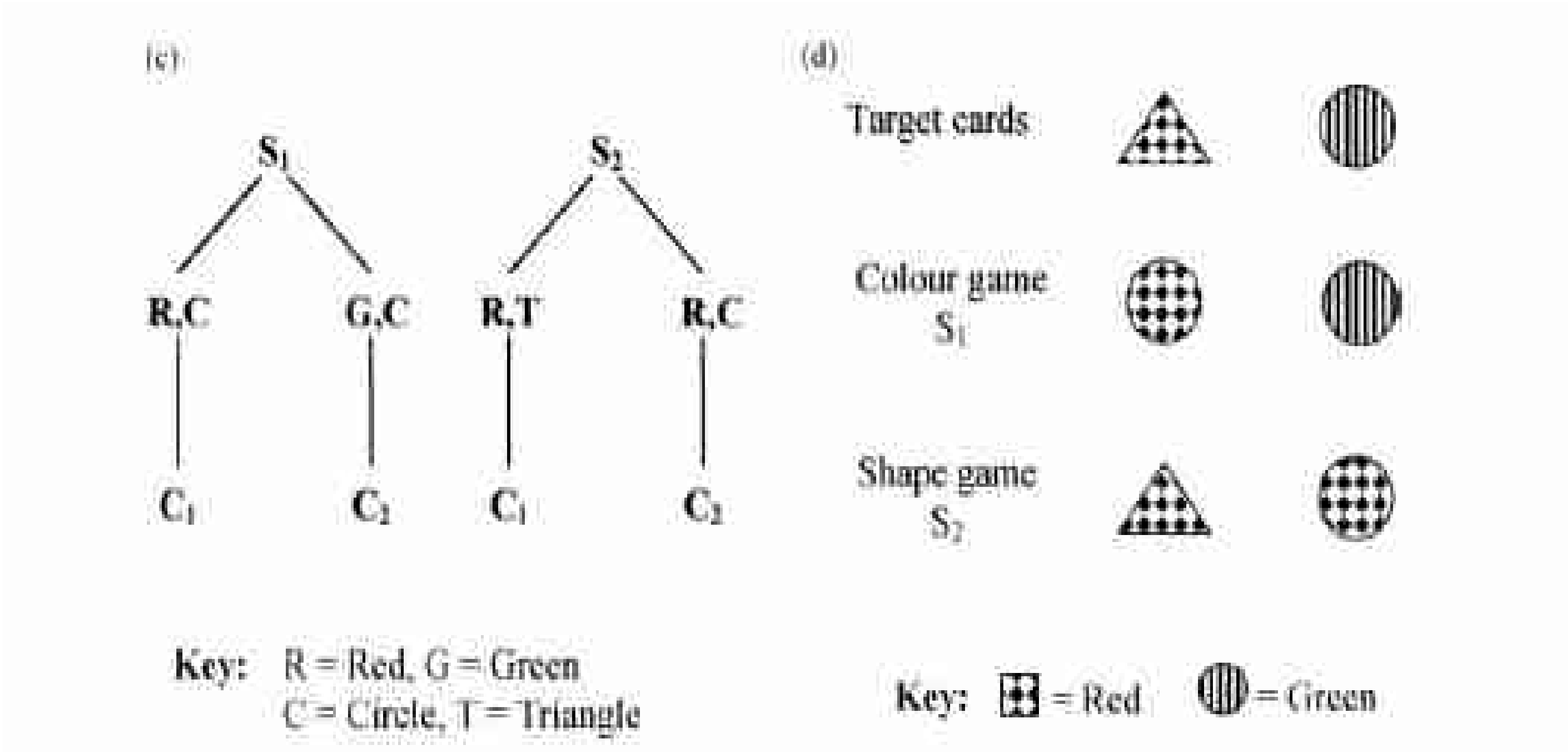
Setting condition (S_1 or S_2) indicates the sorting criterion

Antecedent condition (A_1 or A_2) assigns attributes (colors or shapes) to categories (C_1 or C_2)

- Task structure can also be expressed as

$$S_1\ A_1 \rightarrow C_1$$
$$S_1\ A_2 \rightarrow C_2$$
$$S_2\ A_1 \rightarrow C_2$$
$$S_2\ A_2 \rightarrow C_1$$

- Interaction between setting condition and antecedent determines category
  - Setting condition must be considered with attributes (colour, shape) to determine category
  - DCCS is ternary-relational
  - DCCS is difficult to decompose into 2 subtasks



Halford, Bunch and McCredden (2007)

- Decomposable version of DCCS
  - the setting condition can be processed first
- This binary-relational version was mastered earlier than standard version

Principle 2

- Complexity analyses should be based on the cognitive processes actually used in the task
  - the case of transitive inference
    - Tom is taller than Paul
    - Paul is taller than Jack
    - Therefore Tom is taller than Jack
  - premises are represented as an ordered array
    - Tom - Paul - Jack
  - integration of premises into an ordered array is the most demanding part of the task. The complexity analysis focuses on this.

Principle 3

- Complexity analysis applies to information that is being processed in the current step of the task
  - not to information that is being stored for future processing
  - for tasks with multiple steps, task complexity corresponds to most complex step

Other methodological requirements

- tasks must be appropriate to age of participants
- use training to ensure familiarity with materials, procedures, task demands
- include less complex control tasks with comparable materials, procedures
  - for ternary-relational tasks, include binary-relational tasks with comparable procedures.

The complexity of relations that can be represented increases with age

- unary relations: 1 year
- binary relations: 2 years
- ternary relations: 5 years
- quaternary relations: 11 years

  – most adults can process 4 variables in parallel (quaternary relation)
  – some adults can process 5 variables (quinary relation) under optimal conditions (Halford et al., 2005)

- *Method for Analysis of Relational Complexity* demonstrated using three cognitive development tasks
  - Transitive inference
  - Class inclusion
  - Children’s Gambling task
- present empirical findings

Transitive inference

Premises a *R* b; b *R* c

Therefore a *R* c

where *R* is a transitive relation

Premises *Tom is taller than Paul*

Paul is taller than Jack

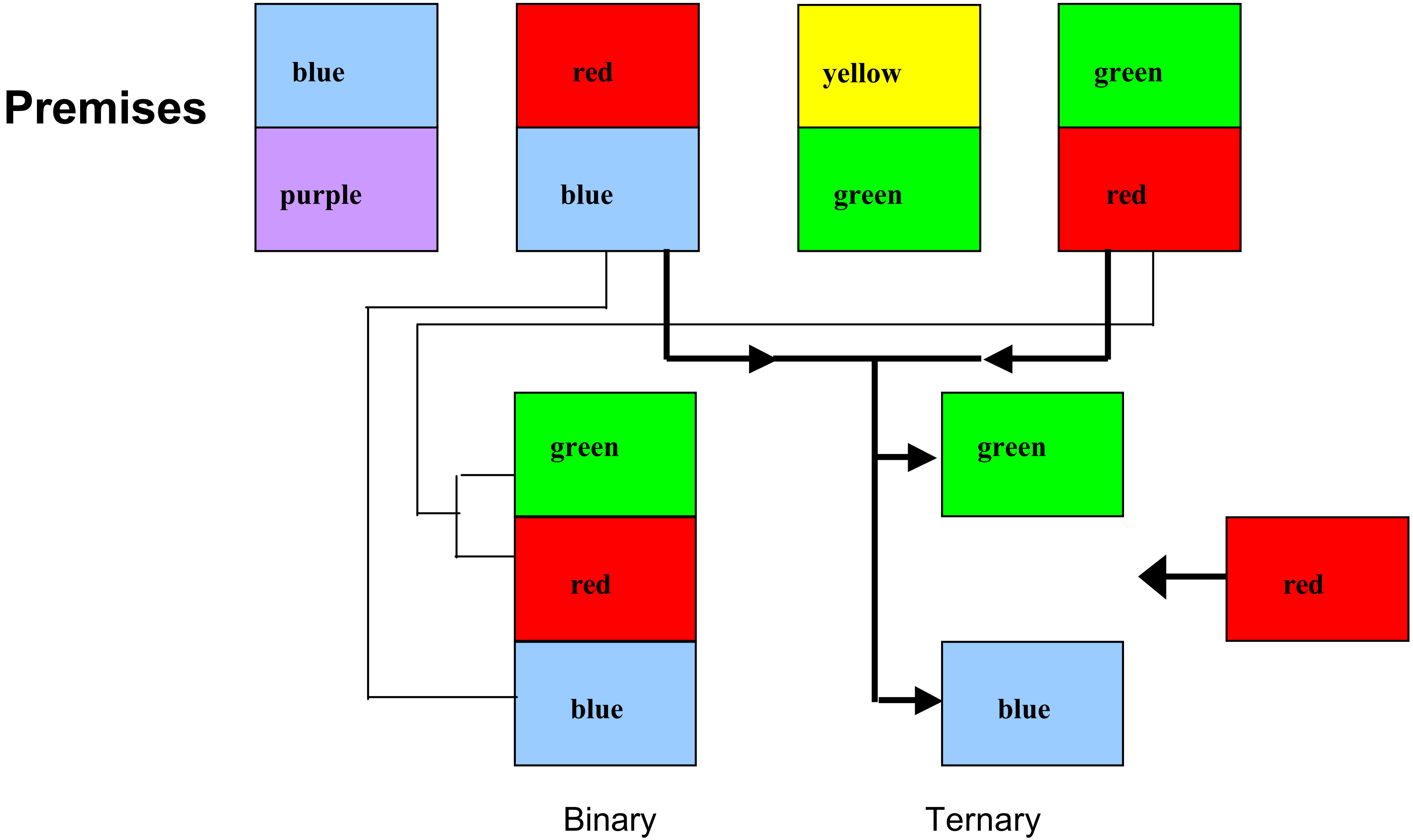
Therefore *Tom is taller than Jack*

5-element task precludes use of a labelling strategy

Premises a *R* b; b *R* c; c *R* d; d *R* e

Therefore b *R* d

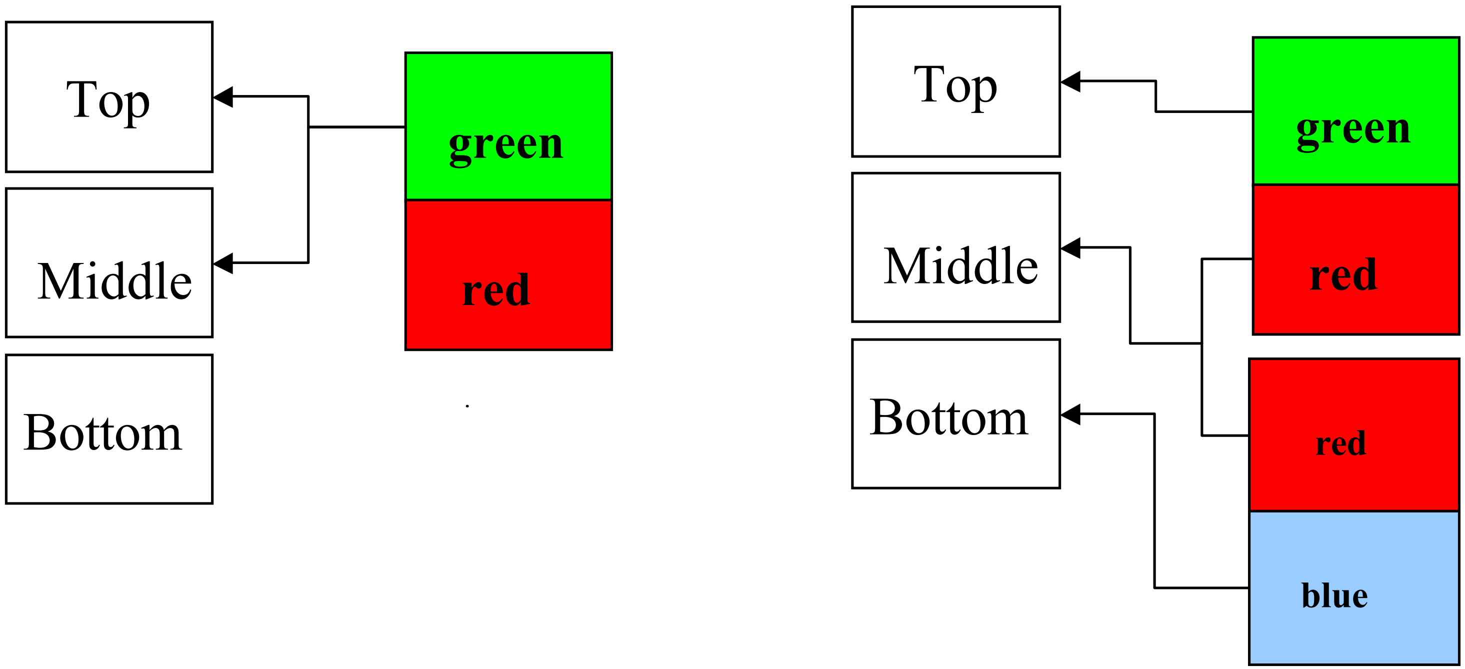
Transitive Inference Task (Andrews & Halford, 1998; 2002)



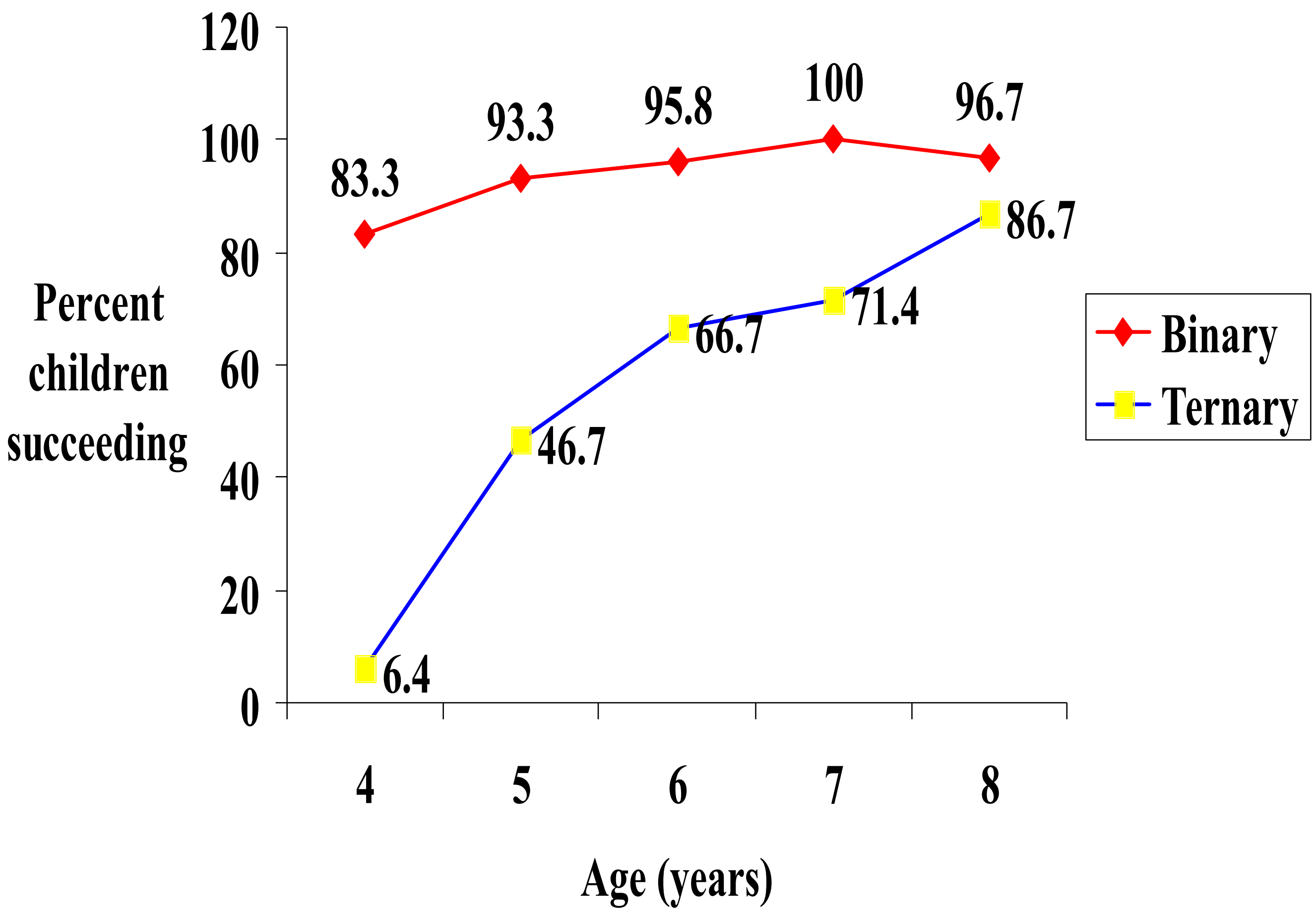
Transitive inference

- Transitive reasoning requires that the relations "GREEN above RED" and "RED above BLUE" be integrated to form an ordered triple, "GREEN above RED above BLUE".
- GREEN above BLUE can be deduced from this.
- Premise integration is ternary-relational because premise elements must be assigned to three slots.

There is a <u>constraint on segmentation</u> because both premises must be considered in the same decision.



Children's transitive inference performance

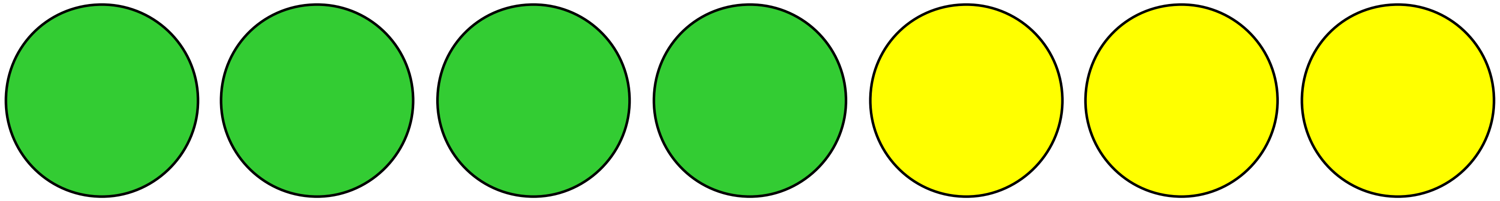


Binary-relational items were easier than ternary-relational items, especially for younger children.

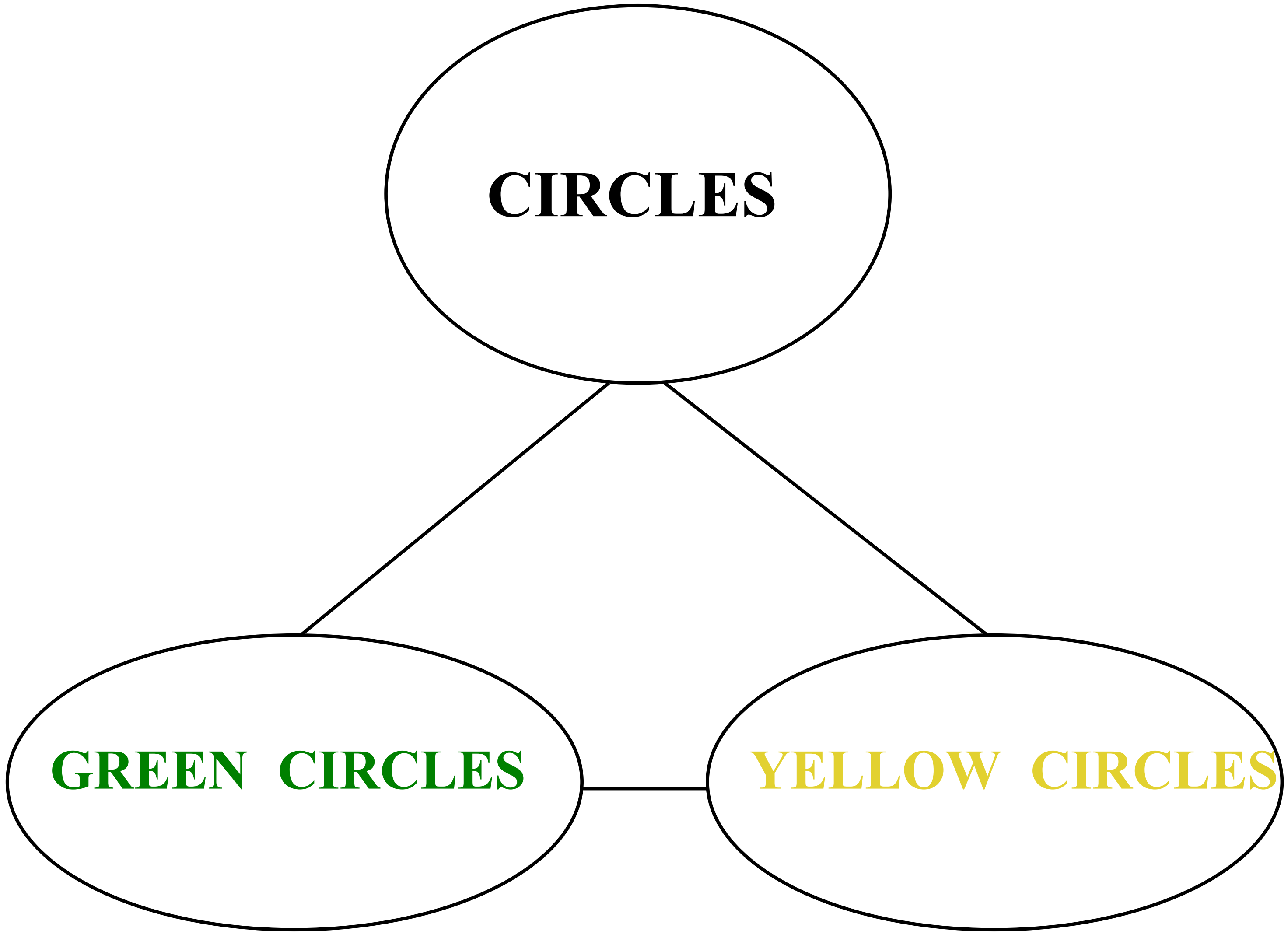
Ternary-relational items were more sensitive to age.

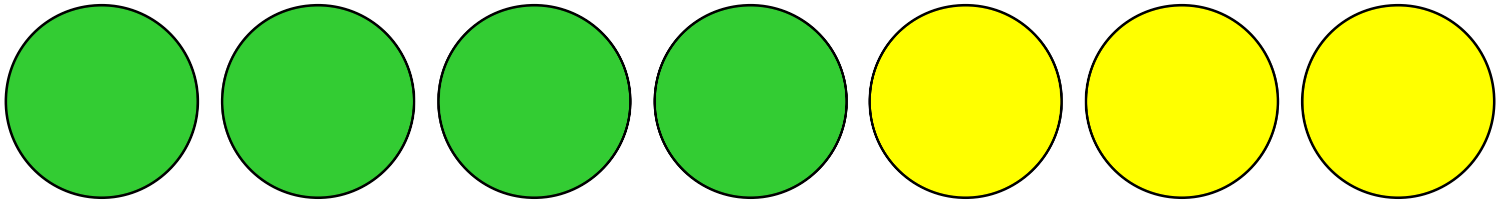
Andrews & Halford (2002). Experiment 1

Class Inclusion



- In the set {4 green circles, 3 yellow circles} green things and yellow things are included in circles.
- This is a ternary relation between three classes; green, yellow, circles.


CIRCLES
GREEN CIRCLES
YELLOW CIRCLES



There are also three binary relations:

- green to circles,
- yellow to circles,
- green is the complement of yellow

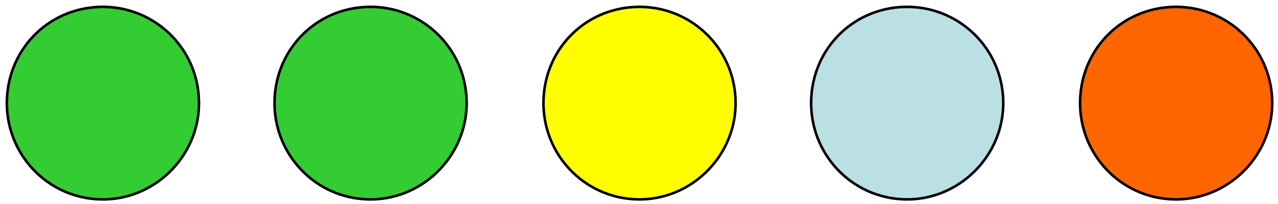
- No single binary relation is sufficient for understanding inclusion
- The inclusion hierarchy cannot be decomposed into a set of binary relations without losing the essence of the concept.

The processing load is due to the need to allocate classes to all 3 slots in the same decision.

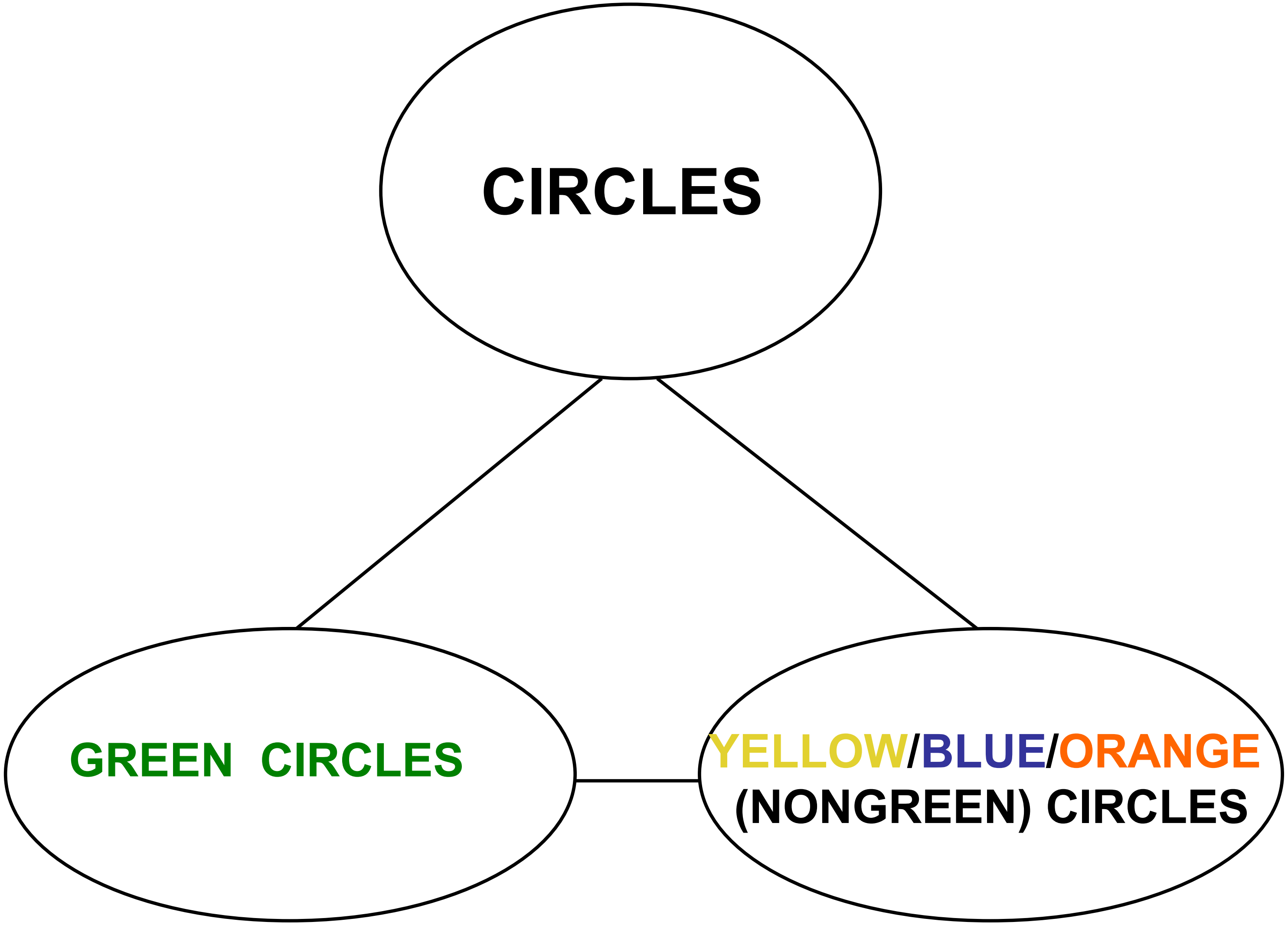
- To determine that circles is the superordinate class we must consider relations between circles, green elements and yellow elements.
- Circles is not inherently a superordinate class
  - It is the superordinate because it includes at least two subclasses.
- Green is a subordinate class because it is included in circles, and because there is at least one other subordinate class.

<u>Conceptual chunking</u>

- circles, with subclasses: green, yellow/blue/orange



- yellow/blue/orange can be chunked into the single class: non-green circles

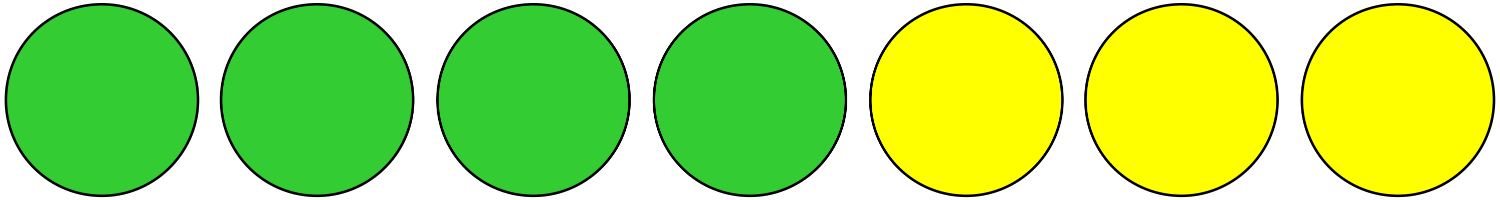

CIRCLES
GREEN CIRCLES
YELLOW/BLUE/ORANGE
(NONGREEN) CIRCLES

- Why not chunk green, yellow, blue and orange into a single subclass?

- We would lose the inclusion hierarchy

- At least 3 classes are needed to represent an inclusion hierarchy and it cannot be reduced to less than a ternary relation.

Class Inclusion task



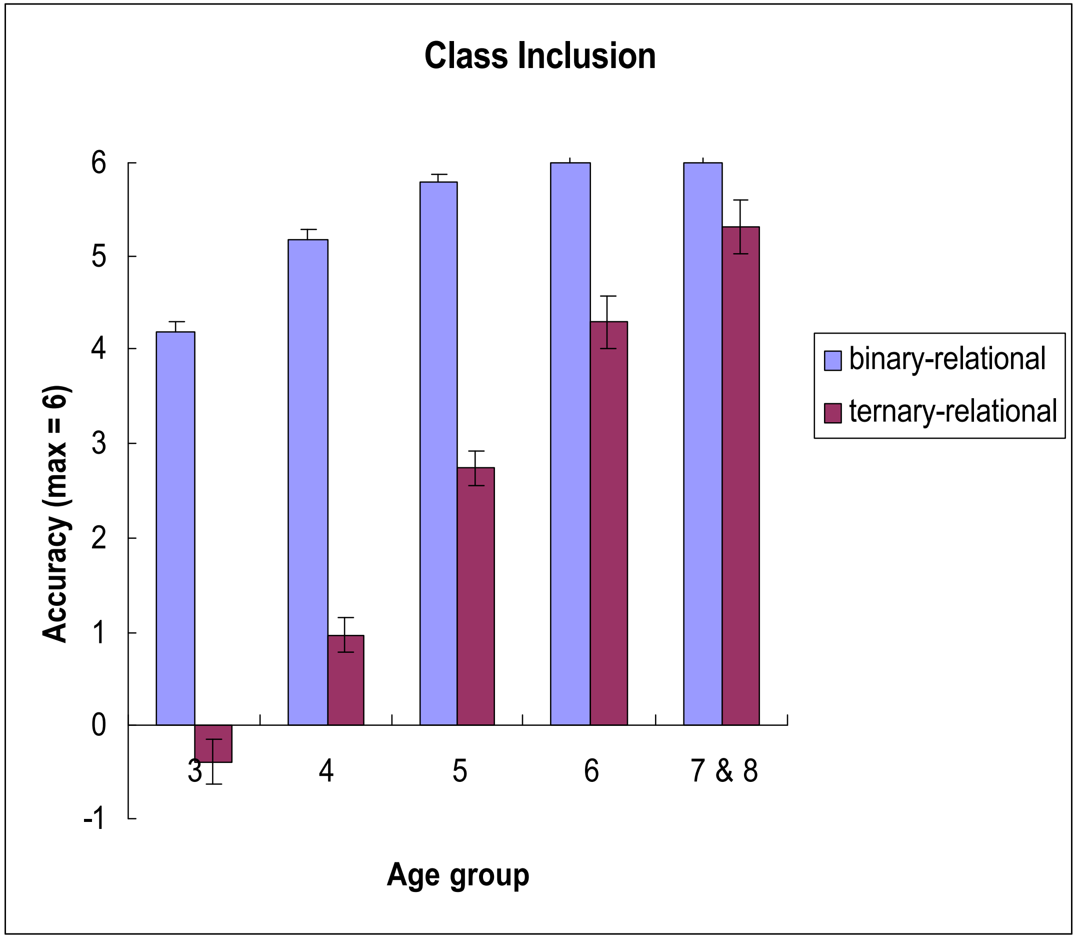
A. Are there more green things or more yellow things?

B. Are there more yellow things or more circles?

C. Are there more green things or more circles?

Children's Class Inclusion performance

(N = 442)



- Binary-relational items easier than ternary-relational, especially for younger children
- Ternary-relational items were more sensitive to age

Iowa Gambling Task

(Bechara et al 1994)

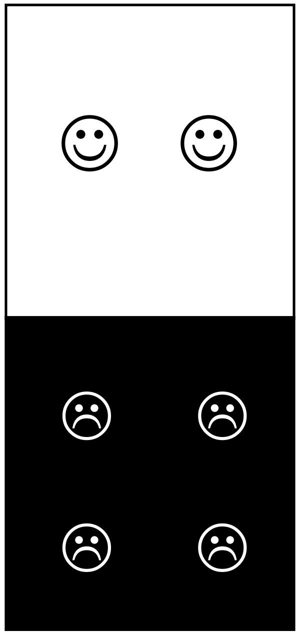
- initial stake of play money
- goal: to win as much money as possible by choosing cards from 4 decks
  - 2 “disadvantageous” decks yield high gains, higher losses => net loss over trials
  - 2 “advantageous” decks yield low gains, minimal losses => net gain over trials

- Unimpaired adults quickly learn to identify the advantageous decks and select from them, while avoiding the disadvantageous decks.
  - improvement across trial blocks

- Patients with frontal brain lesions continue to select from the disadvantageous decks
  - no improvement across trial blocks

Children's Gambling Task

(Kerr & Zelazo, 2004)



- 2-deck version
- rewards were M&Ms
- Cards display happy & sad faces indicating the numbers of M&Ms won & lost
- 5 blocks of 10 trials
- 3-year-olds: choices from advantageous deck decreased across blocks
- 4-year-olds: choices from advantageous deck tended to increase across blocks

- Cognitive Complexity & Control (CCC) theory
  - 3 year-olds can use a pair of arbitrary rules
    - can learn the initial discrimination
      - striped deck has high gains, dotted deck has low gains
    - have difficulty coordinating this with emerging evidence about losses
      - striped deck has high losses, dotted deck has low losses
  - older children can integrate two incompatible pairs of rules into a single rule system via a higher-order rule (Zelazo, Jacques, Burack & Frye, 2002)
    - can formulate a higher-order rule and this allows them to appreciate net gains

Relational Complexity

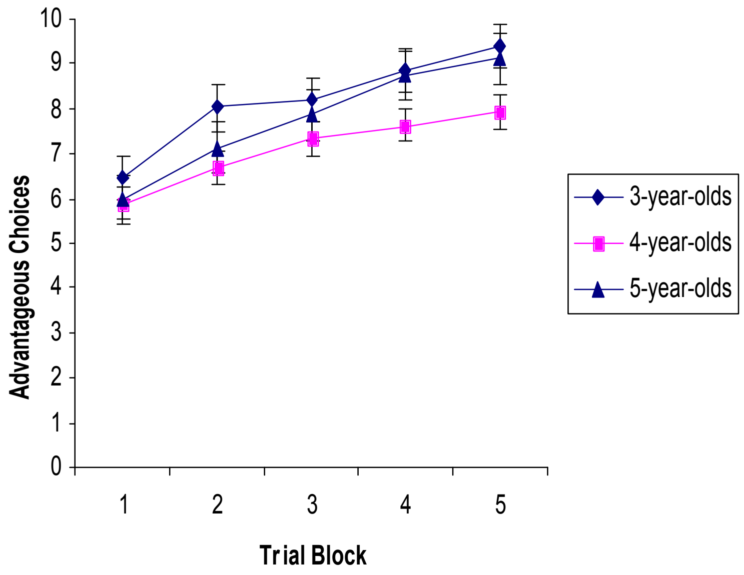
(Bunch, Andrews & Halford, 2007)

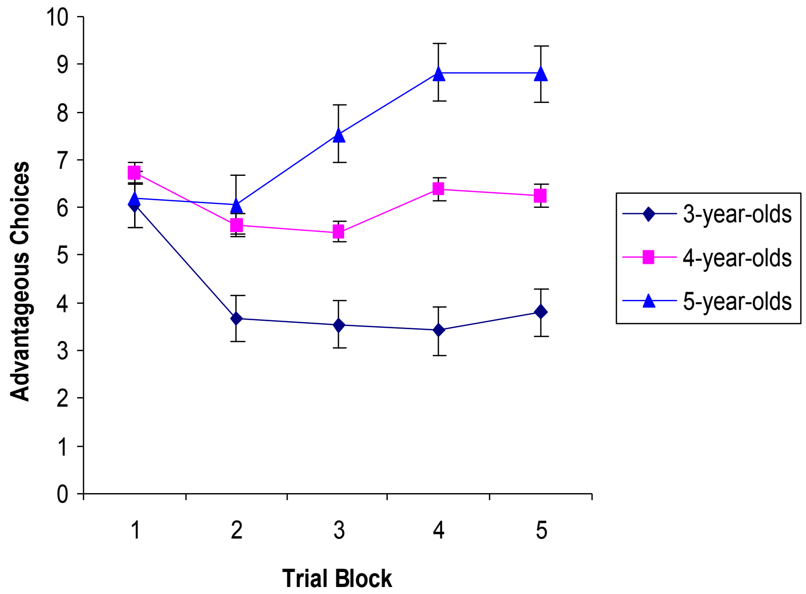
- CGT requires integration of the differences between the decks in gains and losses
- 2 binary relations must be integrated into a ternary relation involving 3 variables
  – (deck, magnitude of gain, magnitude of loss)
- Prediction
  – by 5 years, children will process the ternary relations required for success on the CGT
  – 3-year-olds will be
    - able to process the component binary relations,
    - unable to integrate these binary relations into a ternary relation

Bunch, Andrews & Halford (2007)

- designed 2 less complex (binary-relational) versions
- *binary-gain*
  - decks differed in gains, with losses held constant across decks
  - (deck, magnitude of gain)
- *binary-loss*
  - decks differed in losses, with gains held constant across decks
  - (deck, magnitude of loss)
- 3-, 4-, and 5-year-olds completed all 3 versions
  - ternary CGT (as in Kerr & Zelazo, 2004)
  - binary-gain
  - binary-loss
- procedures were closely matched

- Binary-relational
  - choices from advantageous decks increased across blocks for all age groups
- Ternary-relational
  - Choices from advantageous decks increased across blocks for 5-year-olds, but not for 3- or 4-year-olds
- Younger children dealt with each component of the task in isolation, but they did not integrate information about gains and losses to identify the advantageous deck





- Complexity effects, Age × Complexity interactions have been observed in many content domains
  - Transitive inference; Class Inclusion; Hierarchical classification; hypothesis testing, counting and cardinality; sentence comprehension (Andrews & Halford, 2002)
  - Property Inferences based on categorical hierarchies (Halford, Andrews & Jensen, 2002)
  - Balance-scale reasoning (Halford et al., 2002)
  - Theory of Mind tasks (Andrews et al., 2003)
  - Children's Gambling task (Bunch et al, 2007)

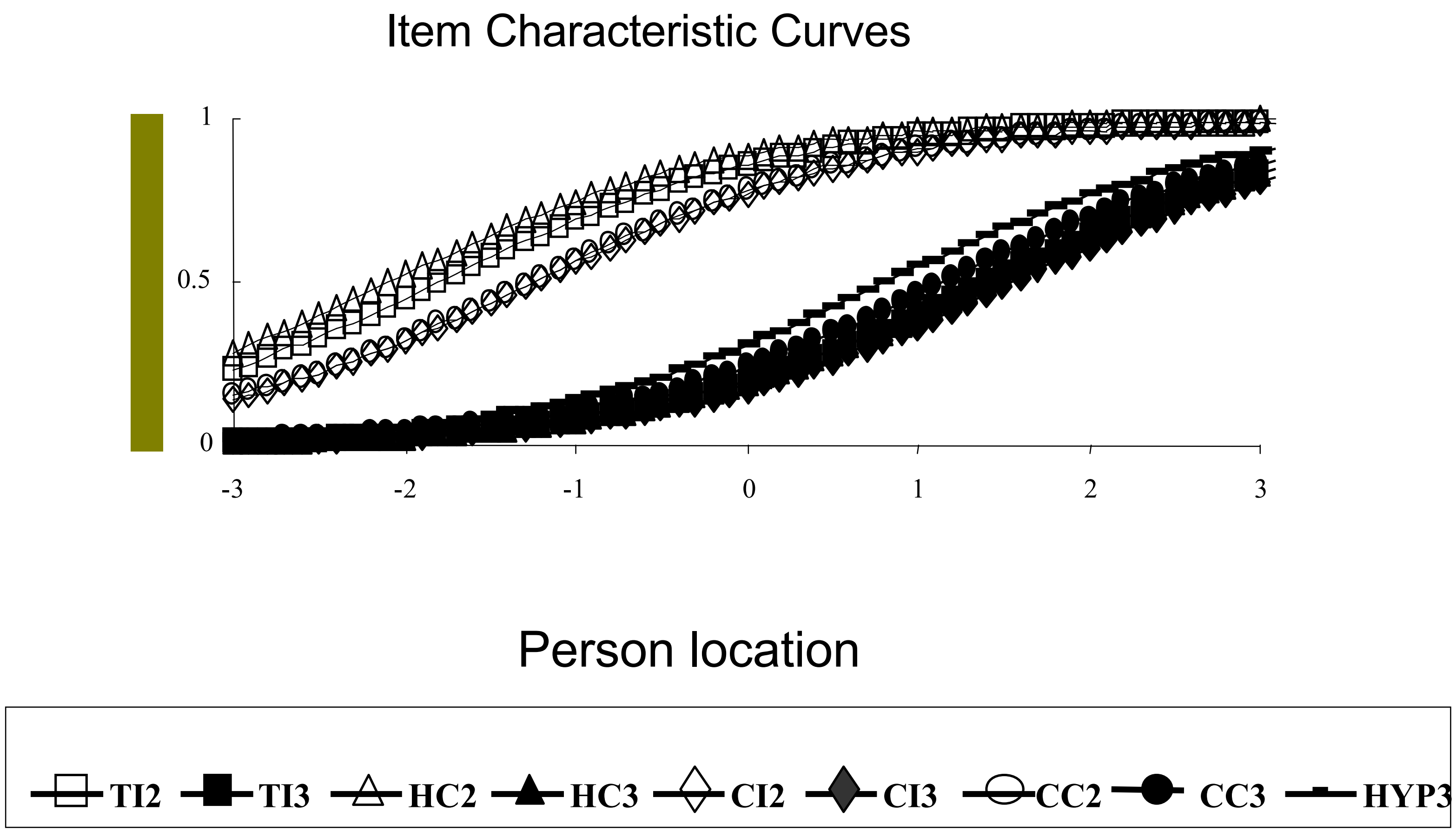
General finding

- children succeed on ternary-relational tasks from median age of 5 years
- younger children succeed on comparable binary-relational versions
- predictions were made in advance of data

Equivalence classes

- Andrews & Halford (2002)
  - transitive inference; class Inclusion; hierarchical classification; hypothesis testing, counting and cardinality
  - 4 binary, 5 ternary
  - *N* = 241 (Exps. 1, 2)

Equivalence classes for tests of the same complexity



Andrews & Halford (2002)

Within-person consistency

- Andrews & Halford (2002)
  - Tasks were strongly inter-correlated and loaded on a single factor which accounted for
    - 43% of the variance (Exp 1)
    - 55% of the variance (Exp 2)
  - RC factor scores were correlated with
    - age (r = .80); fluid intelligence (r = .79) (Exp.1)
    - age (r = .85); compositionality of sets (r = .68) (Exp. 2)

- Bunch (2006)
  - 3-, 4-, 5-, 6-year-olds completed 7 tasks, with binary- and ternary-relational items within each
    - Transitive inference
    - Class Inclusion
    - DCCS
    - Children's Gambling Task
    - Theory of mind
    - Delay of Gratification (choice paradigm)
    - Conditional Discrimination & Reversal learning
  - Age $\times$ Complexity interactions for all tasks
  - Significant cross-task correlations

Zero-order correlations: ternary-relational items

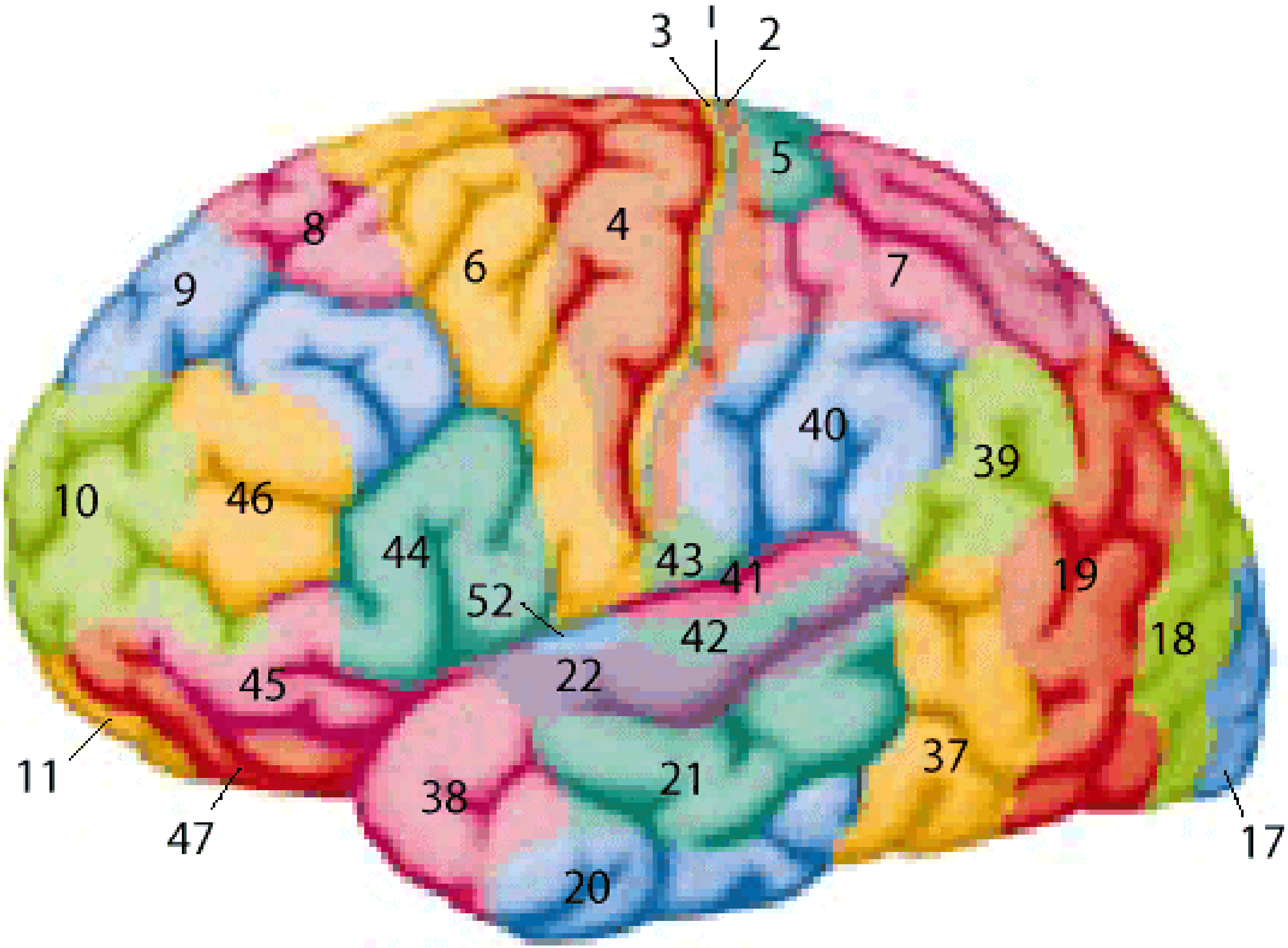
	DoG	*CGT*	*CD*	*ToM*	*CI*	*TI*	*DCCS*
DoG	**1.00**						
CGT	**.68*** **	**1.00**					
CD	**.60*** **	**.54*** **	**1.00**				
ToM	**.73*** **	**.65*** **	**.77*** **	**1.00**			
CI	**.70*** **	**.68*** **	**.70*** **	**.77*** **	**1.00**		
TI	**.68*** **	**.60*** **	**.71*** **	**.72*** **	**.71*** **	**1.00**	
DCCS	**.67*** **	**.59*** **	**.58*** **	**.66*** **	**.68*** **	**.65*** **	**1.00**
Age	**.77*** **	**.69*** **	**.76*** **	**.85 *** **	**.80*** **	**.82*** **	**.71*** **

Cross-domain findings suggest we are tapping a common underlying relational processing ability that undergoes considerable development between 3 years and 8 years

Brain research

- Prefrontal cortex (PFC) appears suitable for representing relations (Robin & Holyoak, 1995)
  - especially lateral PFC regions (BA9; BA10; BA46)

- fMRI studies of analogy have indicated activation of the
  - left frontopolar cortex (Bunge et al. 2005),
  - left frontal pole, BA 9, BA10 (Green et al., 2006)
  - right BA11/47 and left BA45 (Luo et al., 2003)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Brain research

- Selective activation of the PFC with tasks of high relational complexity
  - Kroger et al. (2002) parametrically varied RC of modified Ravens matrix problems and found selective activation of the left anterior PFC.
  - Waltz, et al., (2004). PFC dysfunction was associated with impaired relational integration in Alzheimer's patients. ". . . *intact PFC is necessary for the on-line integration of relational representations …*"
  - Christoff & Owen, (2006). Functions of the rostrolateral prefrontal cortex (BA10) are related more to cognitive complexity than to a cognitive domain

Transitive inference & PFC

- Waltz et al (1999)
  - Prefrontal patients were seriously impaired in ability to integrate relations, but were unimpaired in episodic memory and semantic knowledge
  - Temporal patients showed the opposite pattern
  - Double dissociation
- Goel (2007) reviewed 5 recent PET and *f*MRI studies of explicit transitive inference
  - activation patterns varied as a function of task variables
  - all studies reported increased activation relative to baseline in left DL-PFC
    - either BA9, BA46 or both regions

Transitive inference

- Fangmeier, Knauff, Ruff, & Sloutsky (2006)
  - event-related fMRI study
    - distinguished activation associated with premise encoding vs premise integration
    - premise integration => additional activation in BA10 and cingulate (BA32)
- Brain research on adults provides converging support for complexity as a criterion for evaluating reasoning

Brain development

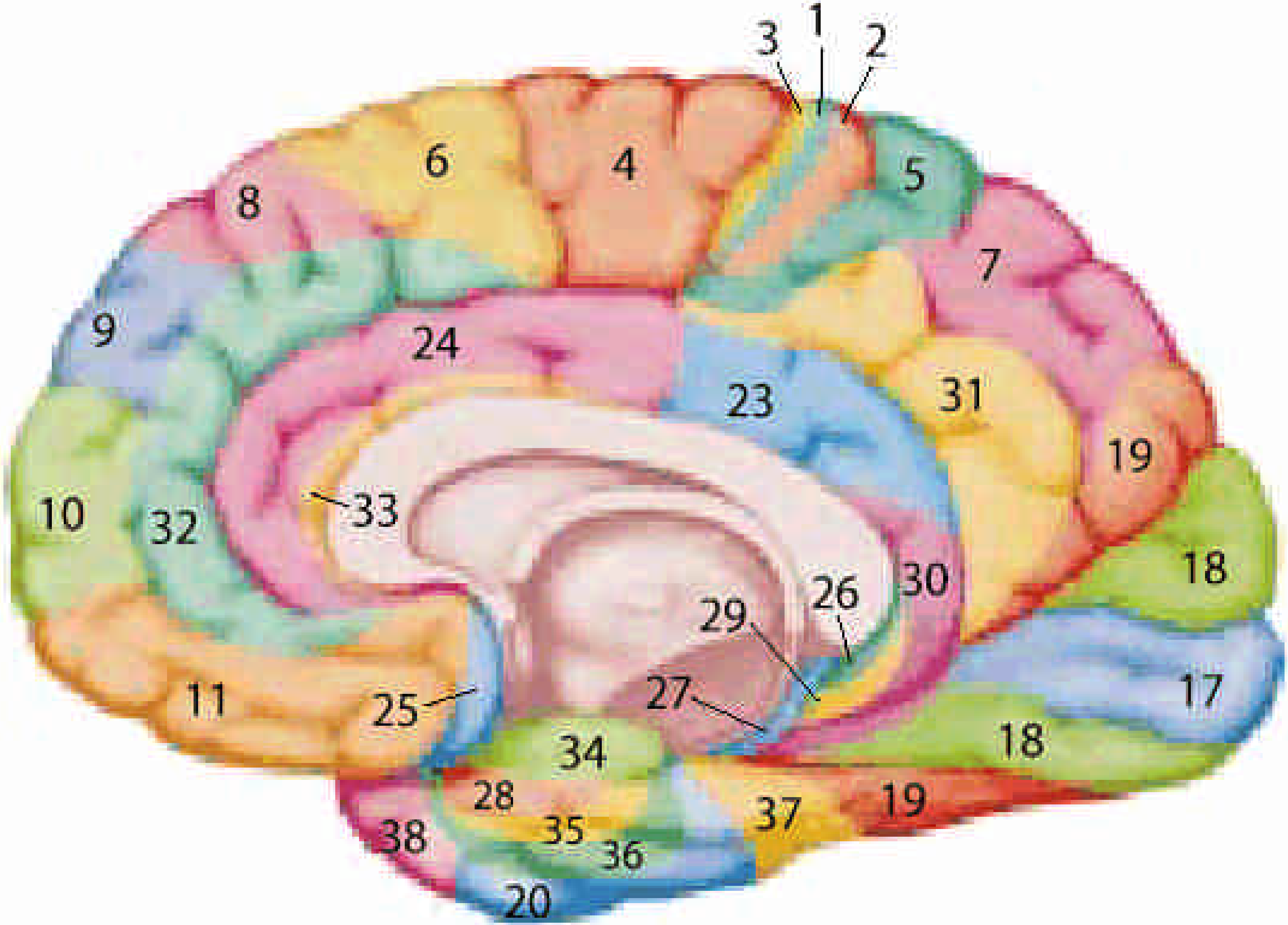
- prefrontal regions are the last to reach maturation
  - synaptic density & elimination (Huttenlocher & Dabholkar, 1997)
  - myelination (Paterson, et. al., 2006)
- myelination continues in the dorsal, medial, and lateral regions of the frontal cortex during adolescence (Nelson, Thomas, & De Haan, 2006)
- in frontal lobes grey matter maturation occurs
  - earliest in orbitofrontal cortex (BA11)
  - later in ventrolateral (BA44, BA45, BA47)
  - and later still in dorsolateral PFC (BA9; BA46) coinciding with its later myelination (Gogtay et al., 2004)

- Processing of complex relations might depend on the functional maturity of these brain regions

Complexity as a criterion for reasoning

- RC theory provides a principled way to analyse tasks and quantify their complexity
  - RC metric; Chunking and segmentation strategies
  - Principles for complexity analysis
- Some degree of domain generality
  - RC approach has been applied to many content domains
- Predictions based on the RC theory have received empirical support
  - Complexity effects
  - Age of acquisition
  - Equivalence classes
  - Within-person consistency
- Consistent with research on functions of PFC in adults, and the protracted maturation of these regions

Thank you



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Resources construct

- Nature of the resource
  - active processing, rather than maintenance
  - dynamic binding to a coordinate system
    - early examples
      - object-location bindings
      - avoidance of A-Not-B error in infancy
    - assigning elements to slots in ordered array or other mental model
  - tests of relational processing capacity should incorporate a relational complexity manipulation