Conceptual Development
Last Class

- **How children’s object concepts change**
  1. Shift from categorizing objects (e.g., *island*) by characteristic features to categorizing by defining features
  2. Development of **superordinate** and **subordinate** categories (e.g., that a flower is also a **plant** and a **rose**)
  3. Development of **long-term memory for new categories** by learning how features are causally related to one another
Beyond Object Concepts

Concepts organize our experiences of the world

what or who we experienced
how many things were involved in the experience
where the experience occurred
when the experience occurred
why the experience occurred
**Beyond Object Concepts**

Concepts organize our experiences of the world

<table>
<thead>
<tr>
<th>Concepts</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>people concepts</strong></td>
<td>experience of people</td>
</tr>
<tr>
<td><strong>numerical concepts</strong></td>
<td>how many things were involved</td>
</tr>
<tr>
<td><strong>spatial concepts</strong></td>
<td>where the experience occurred</td>
</tr>
<tr>
<td><strong>temporal concepts</strong></td>
<td>when the experience occurred</td>
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<tr>
<td><strong>causal concepts</strong></td>
<td>why the experience occurred</td>
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<td>Numerical Concepts</td>
<td>Spatial Concepts</td>
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<td>--------------------</td>
<td>-----------------</td>
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<tr>
<td>1, 2, 3</td>
<td>near, far</td>
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<td>Phylogenetic Continuity</td>
<td>mice, pigeons, babies</td>
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<tr>
<td>Neuronal Specialization</td>
<td>PPC</td>
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<td>Lexical Items</td>
<td>“1, 2, 3”</td>
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<tr>
<td>“1, 2, 3”</td>
<td>“before, now, later”</td>
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<td>Math</td>
<td>Geometry</td>
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<tr>
<td>Advanced functions</td>
<td></td>
</tr>
</tbody>
</table>
Core Knowledge Theory of Concepts

- According to the core knowledge approach, all humans are born with domain-specific learning mechanisms that allow children to acquire skills that other animals do not possess.
  - Are there innate neural mechanisms for organizing our initial experiences of number, space, and time?
  - Do these mechanisms serve as the foundation for uniquely human capacities, such as lexicalized items, grammatical categories, and formal domains?
Number Concepts

- **Numerical equality:**
  - Sets of objects that differ in appearance can be equal in number
Numerical Equality

- Piaget’s studies initially suggested that children fail to recognize numerical equality, leading them to fail the number conservation task.
Fig. 1. The length of the rows in (a) was 7 inches (18 cm) for M & M's and 8 inches (20 cm) for clay pellets; in (b) 7 and 3 inches (18 and 8 cm) for M & M's and 8 and 5 inches (20 and 13 cm) for clay pellets. There was a 1½-inch (3-cm) space between each of the four clay pellets and a 2-inch (5-cm) space between each of the four M & M's. The clay pellets were ½ inch (1.3 cm) in diameter. The M & M candies were all of the same color.

Fig. 2. The proportion by age of responses choosing the row with more members in the situation shown in Fig. 1b. Numbers inside bars indicate total number of subjects of that age.
Concepts aren’t just recognition

- Do children really have a concept of One, Two, Three, ...
  - If so, they should be able to think with the concept
  - For this reason, elementary arithmetic provides an important test case
Infant ‘Math’

Initial transformation

Test trial outcomes
Possible

Arithmetically Impossible (Wynn)
Infant ‘Math’

Number of Objects Remaining

1 object

2 objects

1+1=2

2-1=1

1+1=2

2-1=1

"Addition"

"Subtraction"
Infant ‘Math’

- Still controversial
  - **Not clear whether addition is used:** most 5-year-olds can’t add 2+2
  - Other mechanisms may be used (e.g., subitization)
How many are there?
How many are there?
How many are there?
How many are there?
How many are there?
How many are there?
How many are there?
Explaining Wynn’s findings

- **Non-numerical mechanisms:**
  - Simon: subitizing
  - Mix: contour and area

- **Numerical mechanisms:**
  - Wynn & Gelman: counting
  - Dehaene: estimation
Subitizing

Is subitizing necessary?

- McCrink & Wynn tested whether addition and subtraction was restricted to the limit of 3 or 4
  - Same basic test but $5 + 5 = 10$ and $10 - 5 = 5$
Not just for small numbers either

Addition

- five objects drop down
- the occluder rises to cover them
- five additional objects emerge and go behind the occluder

The occluder drops to reveal an outcome of either:

- five objects (for half of the trials)
- ten objects (for the other half of the trials)
Not just for small numbers either

**RESULTS**

Baseline looking times to outcomes of 5 or 10 objects (9.12 and 9.68 s, respectively) were not significantly different, \( t(1, 25) = 0.48, p = .636 \). Preliminary analyses revealed no effects of sex (male, female), trial order (correct first, incorrect first), or test pair (first, second, third); our subsequent analyses collapsed over these variables. A 2 (outcome: 5 objects vs. 10 objects) \times 2 (operation group: addition vs. subtraction) repeated measures analysis of variance on infants’ mean looking times at test (see Fig. 2) demonstrated a significant interaction, \( F(1, 25) = 6.693, p = .012 \), \( \eta^2 = .22 \). Infants who saw an addition operation looked longer at the outcome of 5 (10.28 s) than at the outcome of 10 (7.35 s; mean looking-time difference \( 5 = 2.93 s \)), whereas infants who saw a subtraction operation looked longer at the outcome of 10 (9.13 s) than at the outcome of 5 (8.00 s; mean looking-time difference \( 5 = 1.13 s \)).

For nonparametric analyses, infants were categorized as preferring the incorrect test outcomes if their looking-time difference (average of incorrect trials – average of correct trials) was positive; a negative difference score characterized a preference for correct movies. Twenty of 26 infants (10 in each group) preferred the incorrect movie, and a \( \chi^2(1, N = 26) = 7.54, p < .01 \) chi-squared contingency test (Habituation Group vs. Test Trial Preference) was significant.

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**Subtraction**

- ten objects drop down
- the occluder rises to cover them
- five objects move from behind the occluder, and go offscreen
- the occluder drops to reveal an outcome of either:
  - five objects (for half of the trials)
  - ten objects (for the other half of the trials)
McCrink and Wynn (2004) found that babies as young as 9 months could recognize impossible addition and subtraction events.

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Fig. 2. Looking time to the outcome as a function of test pair (first, second, or third), operation group (addition, subtraction), and number of outcome objects (5, 10). Infants in the addition group saw a $5 + 5$ scenario, and infants in the subtraction group saw a $10 - 5$ scenario.
Numerical Mechanisms

- **An Hypothesis:**
  - Numerical equality and basic arithmetic can be recognized through two different numerical mechanisms—
    - **Estimation**, which is an innate ability
    - **Exact counting**, which must be learned
Estimation

- Beyond a small number, people can only approximately quantify objects without counting.
- To estimate, people and other animals seem to rely on a ‘number sense,’ i.e., a sense of numeric magnitude.
Size Effects
Distance Effects

4

19

9

14
Numerical Estimation

How many apples?

4, 9, or 19?
Size Effects
Symbols & Magnitudes

The basic idea:

- Numerals (1, 2, 3, ...) automatically activate an analog magnitude representation that stores numerosity information (🍎, 🍎🍎, 🍎🍎🍎) in memory
Analog Magnitude Representation

Spatial pattern: visual or tactile

Temporal Sequence: visual or auditory
Analog Magnitude Representation

Spatial pattern: visual or tactile

Temporal Sequence: visual or auditory
Analog Magnitude Representation

Spatial pattern: visual or tactile

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Spatial pattern: visual or tactile

Temporal Sequence: visual or auditory
Analog Magnitude Representation

Spatial pattern: visual or tactile

Temporal Sequence: visual or auditory
Stimuli

Perceptual Subsystem
Weber's Law

Analog Magnitude Representation
Fechner's Law

Symbols

Symbols

<table>
<thead>
<tr>
<th>one</th>
<th>two</th>
<th>three</th>
<th>four</th>
<th>five</th>
<th>six</th>
</tr>
</thead>
</table>

\[ p = k \ln \frac{S}{S_0}. \]

\[ dp = k \frac{dS}{S}, \]
Perception of Numerical Invariance in Neonates

Sue Ellen Antell; Daniel P. Keating


TABLE 1

Means and Standard Deviations of Last Two Habituation and First Two Posthabituation Trials, by Condition (in Seconds)

<table>
<thead>
<tr>
<th>CONDITION</th>
<th>LAST TWO HABITUATION TRIALS</th>
<th>FIRST TWO POST-HABITUATION TRIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEAN</td>
<td>SD</td>
</tr>
<tr>
<td>2 to 3</td>
<td>15.3</td>
<td>5.6</td>
</tr>
<tr>
<td>3 to 2</td>
<td>15.9</td>
<td>7.6</td>
</tr>
<tr>
<td>4 to 6</td>
<td>14.9</td>
<td>5.9</td>
</tr>
<tr>
<td>6 to 4</td>
<td>15.3</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Fig. 1.—Simulus array for conditions 1–4
Newborn infants perceive abstract numbers

Véronique Izarda,1, Coralie Sannb, Elizabeth S. Spelkea, and Arlette Sterrib

aDepartment of Psychology, Harvard University, 33 Kirkland Street, Cambridge, MA 02138; and bUniversité Paris Descartes, Laboratoire Psychologie de la Perception, Centre National de la Recherche Scientifique Unité Mixte de Recherche 8158, Paris, France

Edited by Charles R. Gallistel, Rutgers, The State University of New Jersey, Piscataway, NJ, and approved May 5, 2009 (received for review November 28, 2008)

Newborn infants were familiarized with auditory sequences containing a fixed number of syllables, and were then tested with images of the number of items (here 4 or 12). Auditory sequences were equated across numbers on extensive parameters (total duration), and visual array intensive parameters (size of each item, density of the array).

Fig. 2. Newborns looked consistently longer at the displays that were congruent in number with the auditory sequences presented during familiarization, when the numbers to discriminate were separated by a ratio of 3:1 (4 vs. 12, 6 vs. 18), but not for a smaller ratio (4 vs. 8; ratio 2:1). Error bars represent standard errors.
Nieder & Miller (2003)

A

131 neurons

111 neurons

352 neurons

Monkey T

Monkey P
Nieder & Miller (2003)

Neural Activation

Stimuli

(Nieder & Miller, 2003)
Nieder & Miller (2003)

Neural Activation

Stimuli

(Nieder & Miller, 2003)
Nieder & Miller (2003)

Neural Activation

Stimuli

(Nieder & Miller, 2003)
Nieder & Miller (2003)

Neural Activation

Number of items (log scale)

Stimuli

Apple Apple Apple Apple
Scaling of Numerical Information in Monkey Cortex

Figure 3. Quantification of Behavioral Performance Curves
The behavioral performance for both monkeys indicated whether they judged the first test stimulus (after the delay) as containing the same number of items as the sample display (% same as sample). Colors represent performance curves for a given sample numerosity. Behavioral filter functions are plotted on linear (A) and logarithmic (B) scales. The functions are asymmetric when plotted on a linear scale (note the shallower slope toward higher numerosities) (A), but are symmetric when plotted on the nonlinear logarithmic scale (B). (C and D) Individual distributions for all tested numerosities for both monkeys. Columns to the left in (C) and (D) show data plotted on a linear scale, contrasted by the same functions plotted on a logarithmic scale. To evaluate the symmetry of the behavioral and filter functions in the monkeys, a normal distribution (Gaussian, indicated by dotted lines) was fitted to the measured data, and the goodness-of-fit was derived as a quantitative measure (error bars, SEM). Memory over a short delay. Performance on sets of sively better as numerical distance between two displays increased (numerical distance effect). For larger control stimuli confirmed that the monkeys were relying on abstract quantity information rather than on the exact quantities, the two numerosities had to be numerically more distant for performance to reach the level obtained appearance of the displays or lower-level visual features (area, circumference, density, or geometric arrangement with smaller quantities and closer numerical distance (numerical size effect). Of the dots) (Nieder et al., 2002). In a new set of behavioral experiments, we tested the monkeys' performance. The distributions of both monkeys' performance were asymmetric when plotted on a linear scale (Figure 3A); to an expanded range of nonmatch numerosities (Figures 3A and 3B). Monkeys made more errors when the slopes were shallower for numerosities higher than the sample numerosity (i.e., the center of each distribution) numerosities were adjacent and performed progressively better as numerical distance increased.
Nieder & Miller (2003)

Behavioral Response
delayed match-to-sample

Idealized Neural Activation

Stimuli

(Nieder & Miller, 2003)
Numerical Estimation

Logarithmic Representation

Number-to-Position Task

Position-to-Number Task

"10"
Numerical Estimation

Logarithmic Representation

Linear Representation

Number-to-Position Task

Position-to-Number Task

“200”
Second Graders’ Median Magnitude Estimates

Fourth Graders’ Median Magnitude Estimates

(Siegler & Opfer, 2003)
Siegler & Opfer, 2003
How Does This Change Occur?
“Hollywoodized version of cognitive development”

Logarithmic Stage

Linear Stage
Kindergarten

Estimate vs. Actual Magnitude

\[ y = 14.508 \ln(x) + 8.7421 \]

\[ R^2 = 0.75 \]

First Grade

Estimate vs. Actual Magnitude

\[ y = 19.29 \ln(x) - 14.978 \]

\[ R^2 = 0.95 \]

Second Grade

Estimate vs. Actual Magnitude

\[ y = 0.6412x + 19.457 \]

\[ R^2 = 0.95 \]
2.5- to 4-year-olds

\[ y = 2.82 \ln(x) + 0.95 \]
\[ R^2 = 0.79 \]

4- to 5.5-year-olds

\[ y = 1.04x - 0.07 \]
\[ R^2 = 1.00 \]

Opfer & Thompson (2006)
Selectionist Theory

- At any given age, multiple representations co-exist and compete for selection (Siegler & Opfer, 2003)
- Experience-based selection (Opfer & Siegler, 2007)
Log or Linear? Distinct Intuitions of the Number Scale in Western and Amazonian Indigene Cultures

Stanislas Dehaene, Véronique Izard, Elizabeth Spelke, Pierre Pica

Fig. 1. Number mapping task with numbers from 1 to 10. A horizontal segment, labeled with a set of 1 dot on the left and a set of 10 dots on the right, was constantly present on screen. Numbers were presented visually as sets of dots or auditorily as sequences of tones (24). Mundurucu numerals, or Portuguese numerals. For Mundurucu numerals, a rough translation into Arabic numerals is provided (for example, “pūg pōgbī xe xp xep bōdī” = “one handful (and) two on the side” = 7; “xe xep pōgbī” = “two handfuls” = 10). For each stimulus, participants pointed to a place on the line, and the experimenter clicked it with the computer mouse, which made a small bar appear.
Estimation

- The neural mechanisms for estimating appear in the intraparietal sulcus across several species, including humans

**Numerical neurons.** Cerebral networks that may underlie the sense of number in mammals (11). The brain areas that are activated when we compute a simple subtraction, such as 11 – 5, may encompass areas homologous to those in the monkey and cat brain, where neurons tuned to a specific number have now been recorded.
Counting

- Counting is more difficult and is learned relatively slowly
  - Most 3-year-olds can count ten objects.
  - Most 6-year-olds can count to 100.
  - There are cultural differences in the counting level attained by young children.
But do counting children understand counting?

- Simply reciting a list of numbers while touching objects is not necessarily real counting.
  - For example, duck-duck-goose is like the counting procedure, but it’s based on different principles.
## Counting Procedures

### (a) Incorrect counting

<table>
<thead>
<tr>
<th>Number stated:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
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<tr>
<td>Pointing:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Objects:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### (b) Unusual but correct counting

<table>
<thead>
<tr>
<th>Number stated:</th>
<th>3</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pointing:</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Objects:</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Principles of Counting

- **One-to-one correspondence:**
  - Each object should be labeled by a single number word.

- **Stable order:**
  - The numbers should always be recited in the same order.

- **Order irrelevance:**
  - Objects can be counted left to right, right to left, or in any other order.

- **Abstraction:**
  - Any set of discrete objects or events can be counted.

- **Cardinality:**
  - The number of objects in the set corresponds to the last number stated.
Cardinality

- Wynn's *Give-a-Number Task*
  - Children who can count past 10 are given a pile of objects and asked to give $N$ objects
  - Over 18 months (3 to 4.5 years), skill develops rapidly
    - One knowers
    - Two knowers
    - Three knowers
    - Cardinality
Number Concepts

- Concepts of number have a uniquely human aspect that is slow to develop (counting) as well as an aspect that is innate and shared with other species (estimating)
Spatial Concepts

- Like concepts of number, concepts of space have a uniquely human aspect that is slow to develop as well as an aspect that is innate and shared with other species.
Space Concepts

- Specific brain areas seem to be devoted to the processing of spatial information.
  - Represent space relative to oneself (Egocentric representation)
  - Represent space relative to the external environment (Allocentric representation)
Egocentric Representations

- As soon as infants can reach, they show they can code spatial location
  - They prefer to reach for close vs far objects
- Forming a bigger mental map of the world starts with the self and how things look to you
  - During the first year, when infants find they can reach an object on the right, they will continue to reach to the right when they are rotated
  - Once children can move on their own, they begin to form non-egocentric mental maps
Benson & Uzgiris (1985)
Non-egocentric Representations

- **Landmark-based representations**
  - 12-month-olds (and rats) use landmark locations but not landmark indicators (Hermer & Spelke, 1996)
Allocentric Representations

- **Dead reckoning**
  - ability to keep track continuously of one’s location relative to one’s starting point in the absence of landmarks (Gallistel, 1990)
  - even adults are not very good at dead reckoning
  - children in some cultures are very good at dead reckoning for mysterious reasons
Scale Errors

- When interacting with toy objects, children normally realize that the small toys aren’t real.
- But after interacting with large toys, object concepts can interfere with spatial reasoning.

Deloache, Uttal, & Rosengren (2004)

Fig. 1. Three examples of scale errors. (A) This 21-month-old child has committed a scale error by attempting to slide down a miniature slide; she has fallen off in this serious effort to carry out an impossible act. (B) This 24-month-old child has opened the door to the miniature car and is repeatedly trying to force his foot inside the car. (C) This 28-month-old child is looking between his legs to precisely locate the miniature chair that he is in the process of sitting on.
Scale Errors

Scale Errors:
Slide
Scale Errors: Car
Scale Errors

Scale Errors:
Chair
## Concepts

<table>
<thead>
<tr>
<th></th>
<th>core</th>
<th>not core</th>
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</thead>
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<tr>
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<td>?</td>
</tr>
<tr>
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<td>estimation</td>
<td>counting</td>
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<tr>
<td>space</td>
<td>egocentric</td>
<td>allocentric</td>
</tr>
<tr>
<td>time</td>
<td>experienced</td>
<td>logical</td>
</tr>
<tr>
<td>causality</td>
<td>physical</td>
<td>non-physical</td>
</tr>
</tbody>
</table>
"What then is time? I know well enough what it is provided nobody asks me; but if I am asked and try to explain, I am baffled." (Augustine)
What is time?

• **Three aspects to time**
  • *Order* of events (first, second, third; before, now, after)
  • *Duration* of events (e.g., 2s, 2m, 2h of sound)
  • *Intervals* between events (e.g., duration of pauses between sounds)
Time Concepts

- **Good candidate for core knowledge**
  - Like number and space, selection pressure for encoding time
    - A minute, an hour, a day--does it matter how long you leave your baby unattended?
  - Like number and space, time is a grammatacized category
    - Tense: walk-walked, bod-bodded
  - **Like number and space, time has**
    - a dedicated neural architecture (fronto-striatal network),
    - is tracked in other species (e.g., interval timing in rats)
    - is selectively impaired in populations with abnormal dopaminergic functioning (e.g., Parkinson’s, ADHD, Schizophrenia)
Early Temporal Coding

- **Temporal order**
  - 3-month-olds can detect a repetitive sequence of events over time (R, R, L) and expect the sequence to continue (Haith et al., 1993).
  - 4-month-olds can discriminate between ordered and disordered causal events (Friedman, 2002)

- **Temporal duration**
  - For durations of 5s or less, 4-mo-olds also accurately discriminate between durations of sound or light (subject to Weber’s law)
The Innate “Clock”

FIG. 1. A summary of the information-processing model of timing proposed by Gibbon, Church, & Meck (1984).
Beyond the Innate Clock

- Beyond about 5s, ability to estimate temporal durations declines markedly in every age, though older children typically outperform younger children.
- Estimating how long ago a certain event occurred, say Christmas, is not very well developed until about the age of 9.
# Beyond the Innate Clock

## Table 1

Specific Response and Percentage of Correct Answers Predicted by Each Rule for Each Problem Type on Time Concept

<table>
<thead>
<tr>
<th>Rule</th>
<th>Problem type</th>
<th>Train A</th>
<th>Train B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A longer (100)</td>
<td>0 f 1 6</td>
<td>0 f 2 9</td>
</tr>
<tr>
<td></td>
<td>Equal (0)</td>
<td>2 f 5</td>
<td>4 f 9</td>
</tr>
<tr>
<td></td>
<td>B longer (100)</td>
<td>0 f 6</td>
<td>0 f 4</td>
</tr>
<tr>
<td>2</td>
<td>A longer (100)</td>
<td>A longer (100)</td>
<td>A longer (100)</td>
</tr>
<tr>
<td></td>
<td>B longer (0)</td>
<td>B longer (0)</td>
<td>B longer (0)</td>
</tr>
<tr>
<td>3</td>
<td>A longer (100)</td>
<td>A longer (100)</td>
<td>A longer (100)</td>
</tr>
</tbody>
</table>

*a Numbers in the problems correspond to the number of seconds since the beginning of the trial. The letter f indicates which train traveled at a faster speed. Lengths and relative positions of lines correspond to distances traveled and spatial positions. Thus, in the example in problem-type 1, Train A starts at the beginning of the trial and travels for 6 seconds, while Train B starts 2 seconds after the trial begins and also stops at second 6. The two trains would start from parallel points, but Train A would finish farther up the track.*

*b Numbers in parentheses refer to the predicted percentage of correct answers.*
Beyond the Innate Clock

“Logical time”

On Piaget’s train problem, children often show a failure to mark “logical time” until about age 9.

Children as young as 5 years old can reason and make logical inferences about time, as in predicting that a doll that “fell asleep” last will wake up last.