CBCD turns 21: What have we learned about the mechanisms of learning and development?

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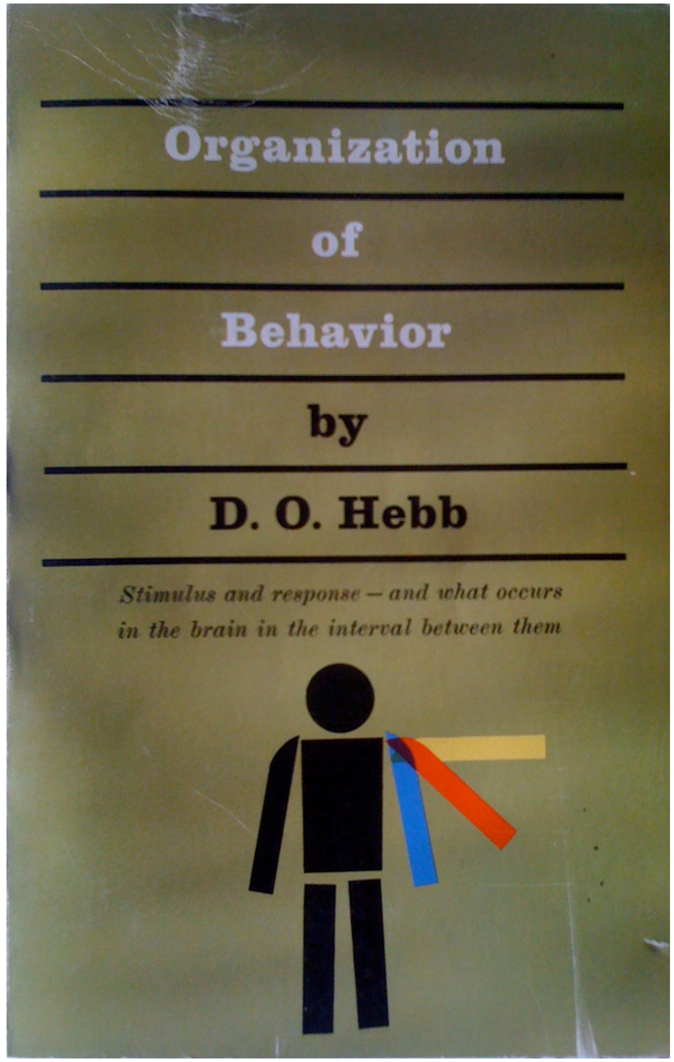
Linkages to my past

- Gyorgy Gergely: visiting professor at Rochester (1989-90)
- Mark Johnson and Annette K-S: McDonnell/PEW task force (1998-99)
- Denis Mareschal and Leslie Tucker
- Gergo Csibra and Sarah Lloyd-Fox: McDonnell Foundation eye-tracking/fNIRS consortium (2000-2007)
- 2006-07 CBCD sabbatical
- Natasha Kirkham: student of Scott Johnson (postdoc at Rochester)
- Rachel Wu: postdoc at Rochester


Organization
of
Behavior
by
D. O. Hebb
Stimulus and response — and what occurs in the brain in the interval between them

$3.95

(1949)

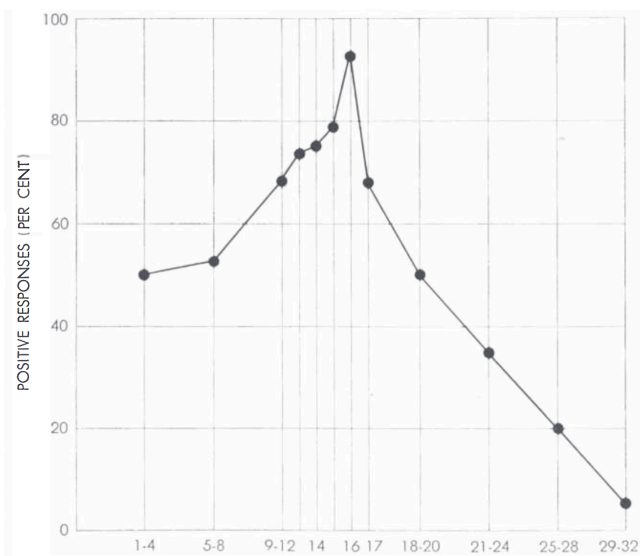
The Relation of Early to Later Learning: “It is of course a truism that learning is often influenced by earlier learning. Innumerable experiments have shown such a 'transfer of training'. Learning A may be speeded up, hindered, or qualitatively changed by having learned B before. . . . If the learning we know and can study, in the mature animal, is heavily loaded with transfer effects, what are the properties of the original learning from which those effects came? How can it be possible even to consider making a theory of learning in general from the data of maturity only? There must be a serious risk that what seems to be learning is really half transfer.” (pp.109-110)

Learning vs. Development

- Is development merely the historical outcome of learning at the age when developmental status is assessed?
- Is learning cumulative (i.e., bigger, better, faster) or does it lead to qualitative change, and by what mechanism?
  - Adding or deleting an underlying structure or process
  - Unmasking an existing structure or process (e.g., via noise reduction)
- What is special about development that is not captured by learning?
- **Early learning shapes later learning by facilitating or constraining it**

Classic example: Imprinting

- Konrad Lorenz: Nobel Prize in 1973



1 10 20 30

Age (Hours)

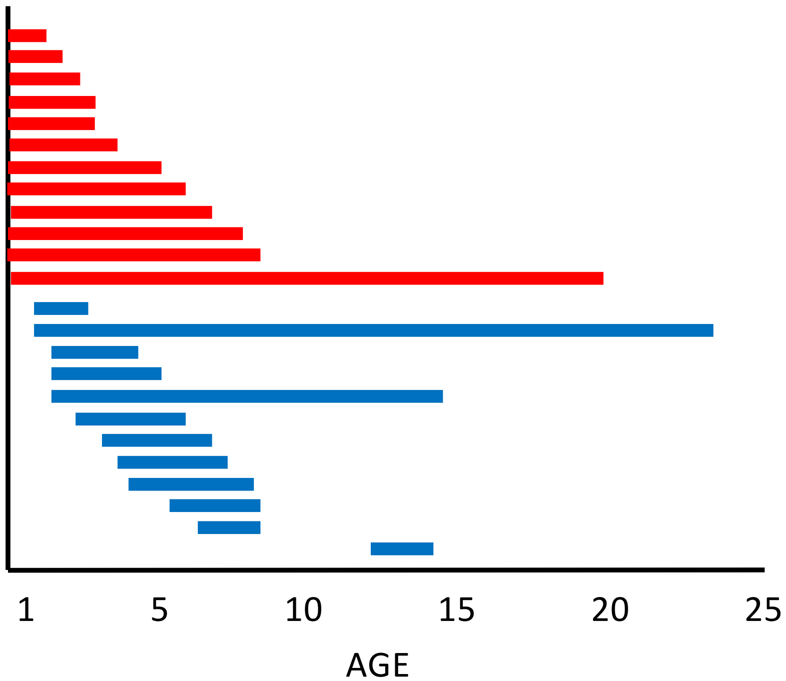
Sensitive period for perception in humans

3-D vision requires proper eye alignment

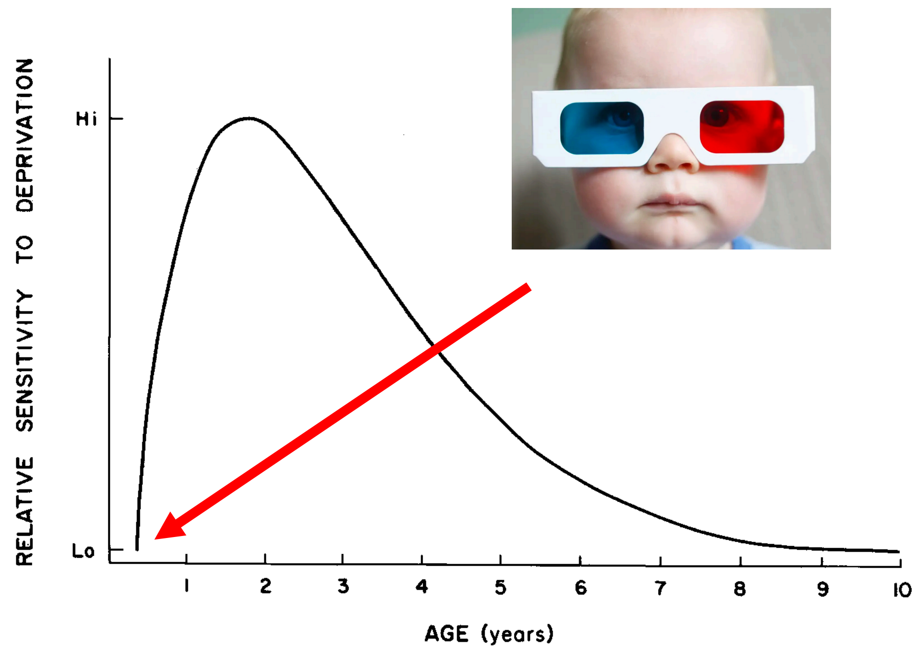
Strabismus

Early experience (eye-alignment) matters

- Banks, Aslin & Letson (*Science,* 1975)

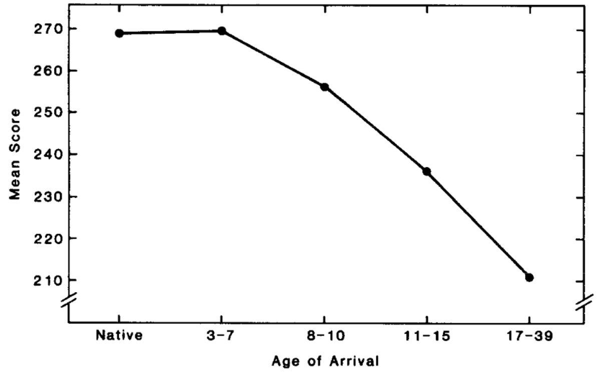


- Fox, Aslin, Shea & Dumais (*Science,* 1980)



Sensitive period for language?

- Henry Kissinger, b. Germany 1923
- Moved to U.S. in 1938
- Speaking English for 81 years
- Johnson & Newport (1989): speech errors made by people who learned English at different ages



Few

Many

The later you begin learning a second language, the more errors you make

The curse of developmental plasticity

- If early experience is atypical and plasticity declines with age, then learning mechanisms may not be able to recover from early errors
- Too much plasticity → only most recent input matters
- Too little plasticity → slow time-course of adapting to changing input
- Trade-off: *explore* the environment to gather new information vs. *exploit* what has already been learned to become an efficient user of that information
- Dilemma: the bias to exploit works well in a stationary world, whereas the bias to explore works well in a highly volatile world
- Complex generative models work best when stationarity/volatility is in balance → time-course of learning matches minimal epochs of stationarity

Outline

1. What are the dominant historical trends in infancy research?
2. Highlight the robustness and flexibility of learning in infants
3. What have measures of brain activity revealed about the mechanisms of development?
4. Do naïve learners integrate prior information with current input?

Birkbeck
UNIVERSITY OF LONDON

Centre for Brain and Cognitive Development

1. What are the dominant historical trends in infancy research?

Scientists discover the “competent infant”

- In the 1950’s, most major textbooks in Opthalmology stated that newborns were “blind”
- Most major textbooks in Audiology stated that newborns were ”deaf”
- Over the subsequent 30 years, infants were found to have remarkable, although limited, perceptual abilities
- Over the past 30 years, it was confirmed that infants have amazing abilities to learn their native language, the properties of objects, and how other people think and reason in social settings
- Are “modern” babies just smarter than their ancestors?

What drove this increase in knowledge about infants?

What's in a look?

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Abstract

The most common behavioral technique used to study infant perception, cognition, language, and social development is some variant of looking time. Since its inception as a reliable method in the late 1950s, a tremendous increase in knowledge about infant competencies has been gained by inferences made from measures of looking time. Here we examine the logic, utility, and future prospects for further gains in our understanding of infant cognition from the use of looking time measures.

Development is rapid and transformational

William Kessen, Marshall Haith & Philip Salapatek

Chapter on Infancy in *Carmichael's Manual of Child Psychology (1970)*

"Whether one sees the newborn child as neurologically insufficient (Flechsig, 1920), cognitively confused (James, 1890), narcissistic (Freud, 1905), solipsistic (Piaget, 1927), or merely ugly (Hall, 1891), the distance between the new child and the walking, talking, socially discriminating, and perceptive person whom we see hardly 500 days later is <u>awesome</u>."

Historical trends in infancy research

1965 – 1985: what are infants' c*apacities*?

1985 – 2005: how are capacities *utilized*?

2005 – 2025: how do infants form causal (*generative*) models and apply them in the natural environment?

Discovery of latent variables allows a learner to *transfer* knowledge (generalize) to novel contexts

Learning by action and by observation

85%

Why 15% failure?
Jammed mechanism
Late restock delivery
Power failure
Pounding/shaking

Learning is fundamentally an *inference* problem

- Events are probabilistic
- Associations are only one source of information and are often spurious
- Causes are often hidden
- Ambiguity is ubiquitous
- 1 3 5 7 __
- sum2+1, sum2-1, etc. = 13

How do infants form causal (generative) *models*?

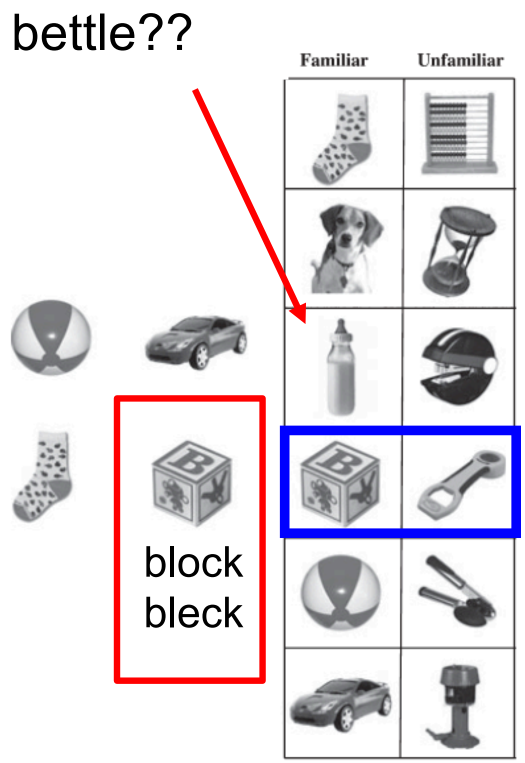
Alison Gopnik: blicket detector

Other examples of infants' flexibility and transfer of learning

2. Highlight the robustness and flexibility of learning in infants

White & Aslin (2011)

Known-word object labeling pre-test phase



18-month-olds

Look longer at match

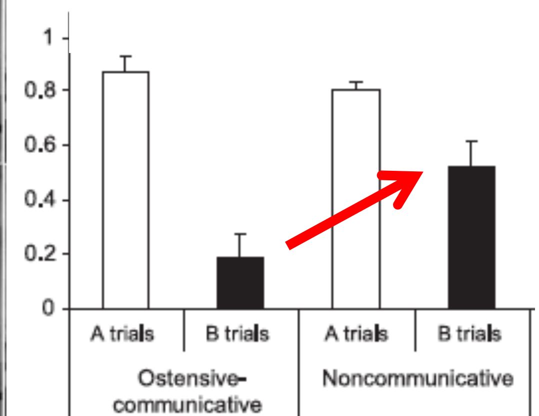
Even if match was just mispronounced

Same for Unlabeled

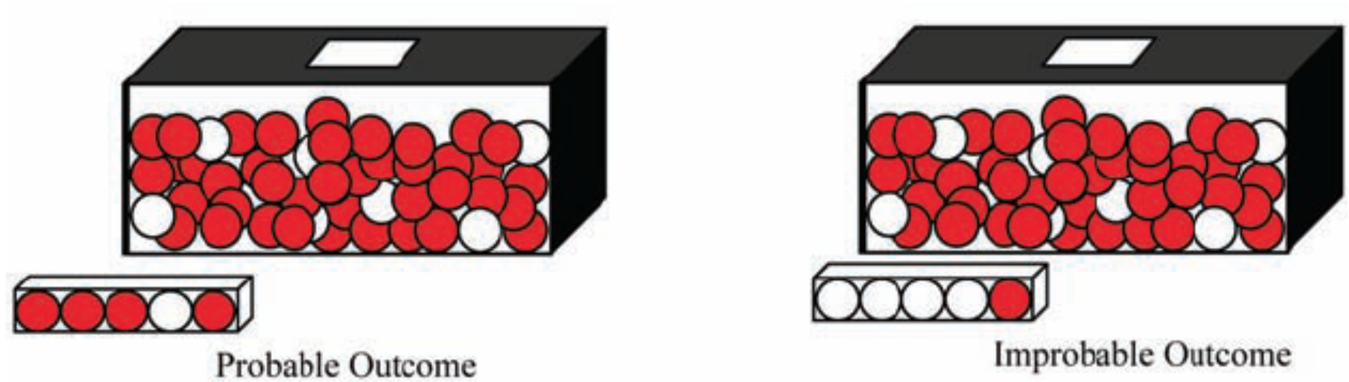
Topál, Gergely, Miklósi, Erdőhegyi, Csibra (2008)

Ostensive-communicative   Noncommunicative

A-not-B task
10-month-olds



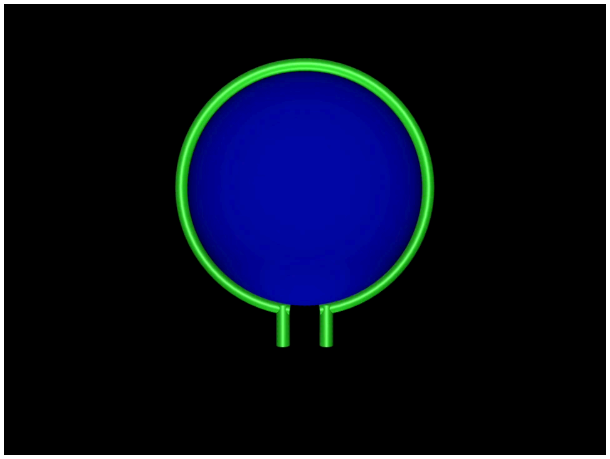
Xu & Garcia (2008)

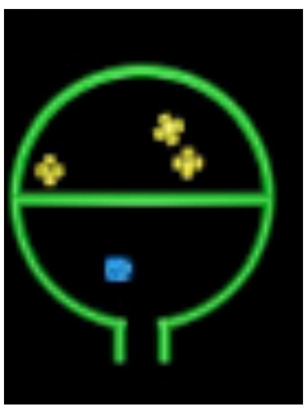


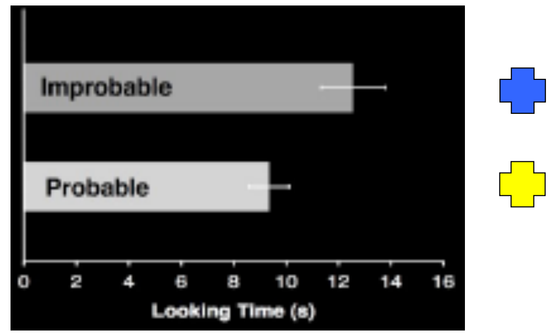
Xu & Denison (2009)

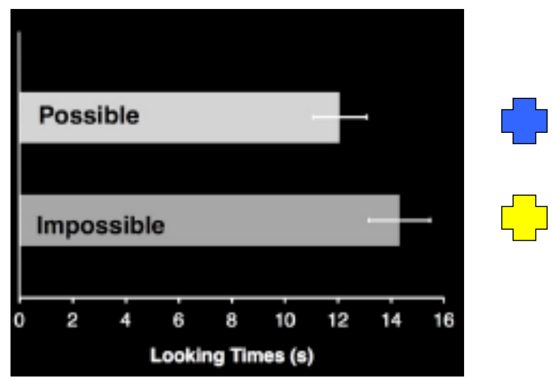
If person drawing samples has a strong preference for white balls (i.e., less likely outcome), then looking pattern is reversed

Téglás, Girotto, Gonzalez, & Bonatti (2007)









Choosing the “right” inference

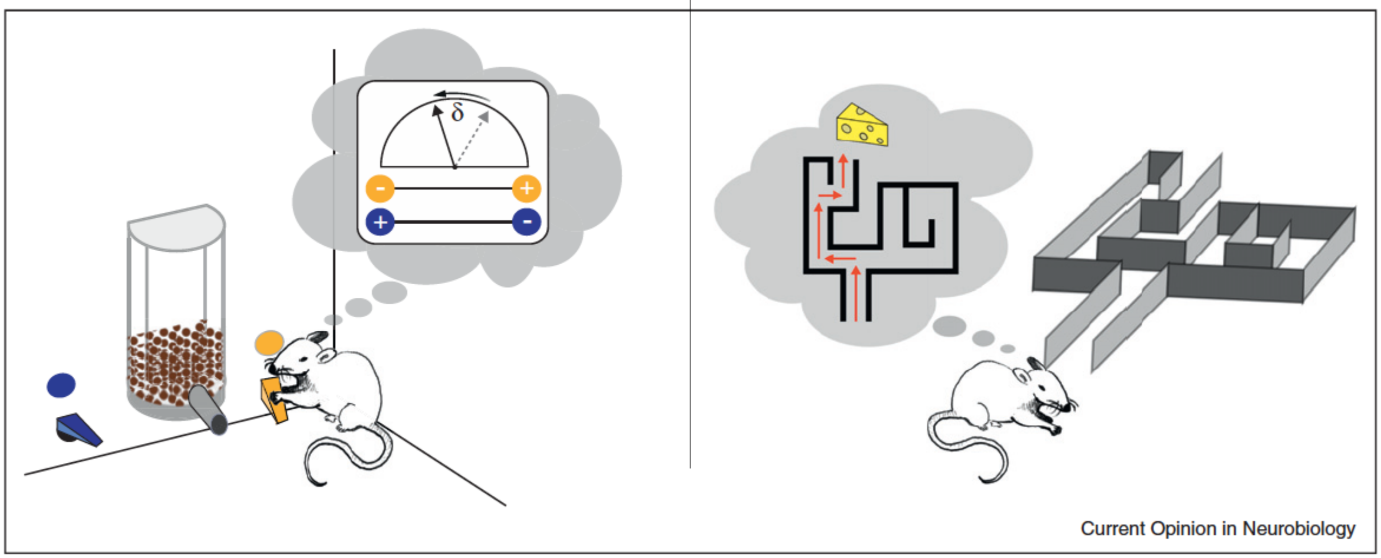
Occam’s Razor: *Among competing hypotheses, the one with the fewest assumptions should be selected.*

Wikipedia

This does not ensure that the simplest explanation is the correct explanation, but if you have no other basis for preferring explanation #1 over explanation #2, go with simplicity.

Caveat: *Simple could be wrong* – Michael Maratsos

Model-free   Model-based



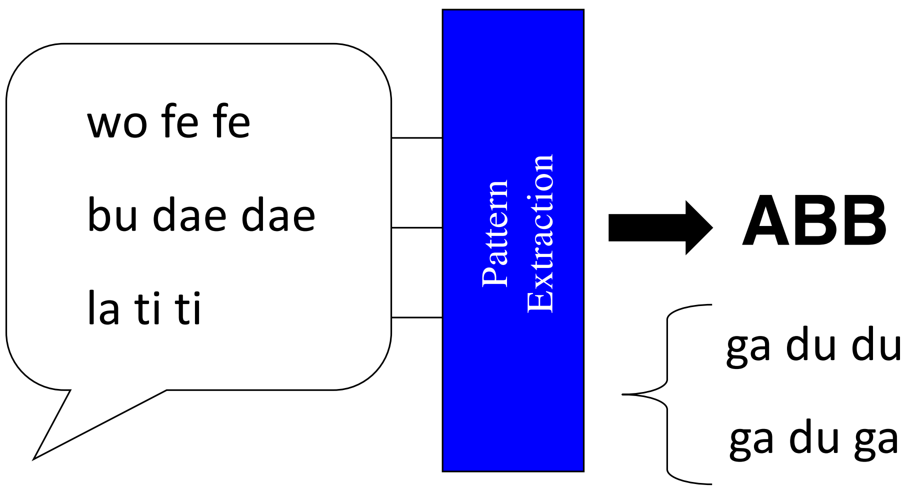
Doll, Simon & Daw (2012)

Team Smart vs. Team Dumb

- Model-based (e.g., Rule learning) or Model-free (e.g., Statistical learning)
- How does Smart emerge from Dumb?
- Two separate mechanisms or a continuum?
- What patterns of input license "abstraction"?
  - Specialized triggers (innate or maturational)
  - General principles (domains, modalities, species)

Marcus et al. (1999): rule learning

- 3-element *strings*
- Pauses between strings enable encoding of position
- Syllable 'identity' used to define category



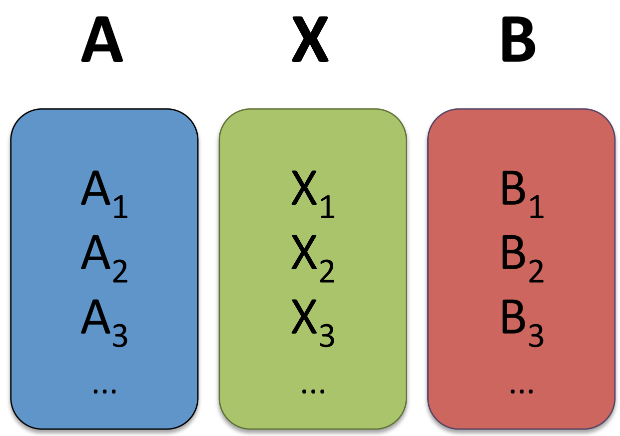
Gerken (2006): Context-specific generalization (broad vs. narrow)

	Syllable B			
Syllable A	Di	Je	Li	We
Le	LeLeDi	LeLeJe	LeLeLi	LeLeWe
Wi	WiWiDi	WiWiJe	WiWiLi	WiWiWe
Ji	JiJiDi	JiJiJe	JiJiLi	JiJiWe
De	DeDeDi	DeDeJe	DeDeLi	DeDeWe

6-year-olds can learn word-category rules

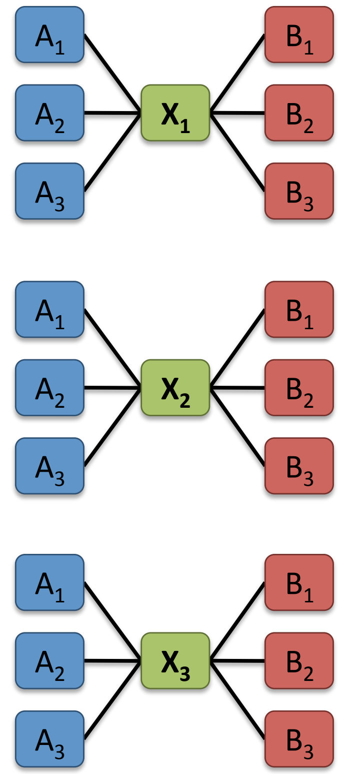
Schuler, Reeder, Kissinger, Aslin & Newport (2017)

- Listen to a set of 3-word sentences
- Words are assigned to 3 categories (3 words per category)

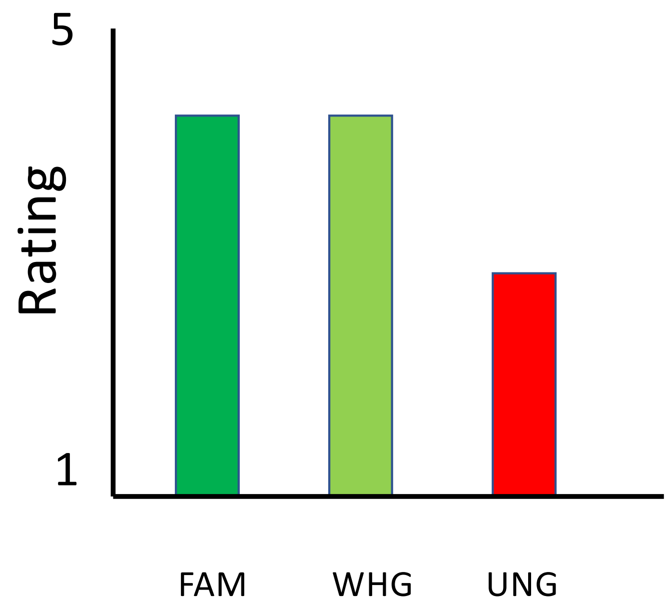


"klidum bleggin glim."   "mawg fluggit zub."

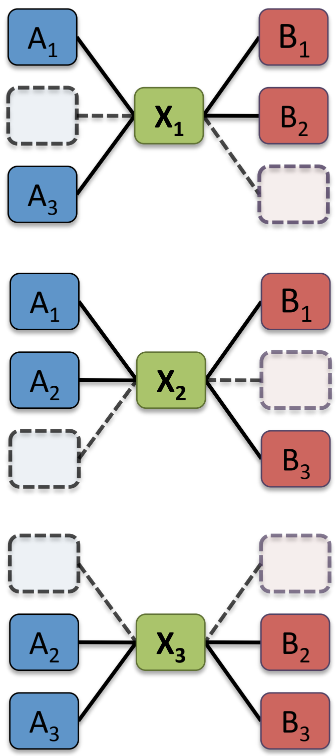
Space Alien language

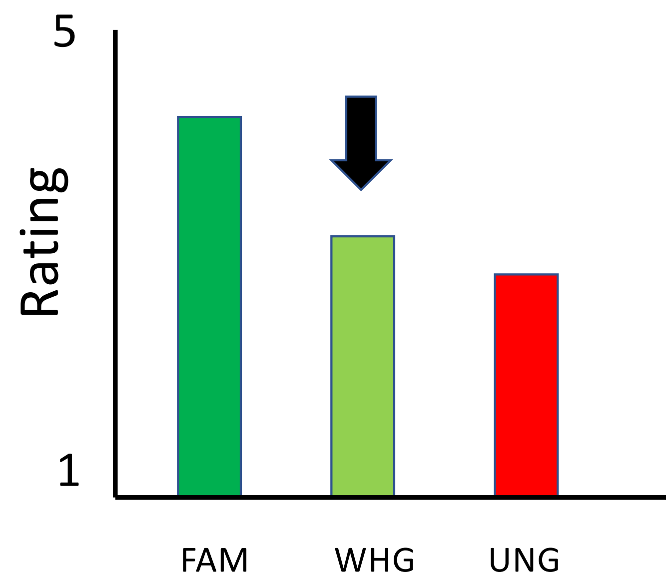


Test on novel (withheld) sentences



6-year-olds can learn rules and <u>exceptions</u>





Learning is not limited to observables

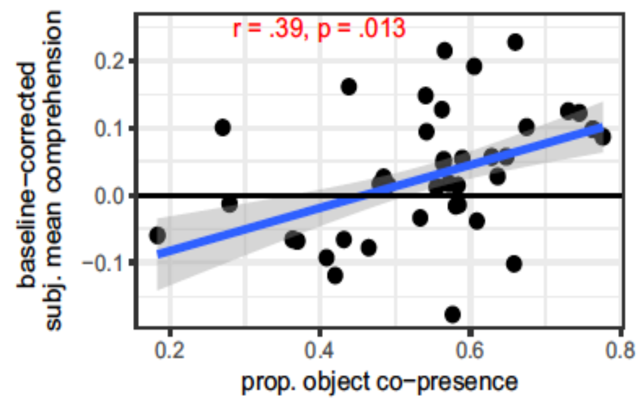
Bergelson & Aslin (2017)

6-month-olds looked significantly more at named target images when the competitor images were semantically unrelated (e.g., milk and foot) than when they were related (e.g., milk and juice)

David Pisoni: “One replication is worth 1000 t-tests”

SeedLings Project: Duke University

Word recognition



Number of times that word is spoken while <u>infant is looking at object</u>

3. What have measures of brain activity revealed about the mechanisms of development?

What is the "value added" of brain over behavior?

- Development of behavior typically <u>lags</u> brain development → earlier diagnosis and more sensitive assessment of treatment effectiveness
- Behavioral development exhibits <u>qualitative</u> change → implies a fundamental change in brain structure or function

✓ At 9 months, begin to search for hidden object

✓ At 18 months, begin to produce 2-word sentences

What are the brain recording techniques?

EEG

MEG

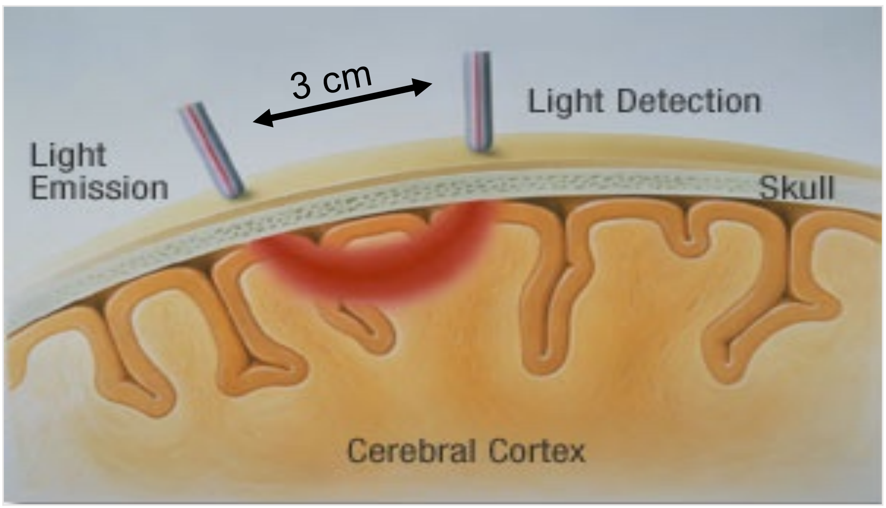
Courtesy of Patricia Kuhl

NIRS

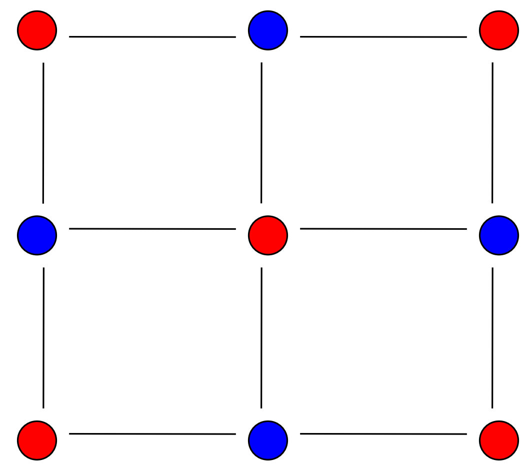
MRI

Courtesy of John Richards

fNIRS



Emitter-Detector Array



Diffuse optical imaging of relative changes in oxy- and deoxy-hemoglobin concentrations

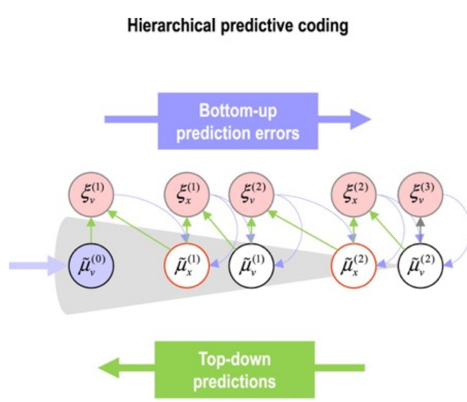
Pros and Cons

- No acoustic noise from pulse sequences
- Tolerates considerable head motion (emitters and detectors fixed to a cap)
- Allows upright posture and a variety of natural responses
- Limited to cortical surface (sub-cortical and ventral cortical areas not accessible)
- Coarse spatial resolution (~ 1 cm^2; not 3D voxel)
- Deoxy-hemoglobin (BOLD) signal is weak
- Surface vasculature creates non-cortical "systemic noise"

The Predictive Coding Perspective

- Sensory signal that is transformed in a feed-forward hierarchy
- Biased interpretation (via priors) of sensory signal → <u>prediction</u>
- Discrepancy between sensory signal and prediction → <u>prediction error</u>

Sensory input



Bastos et al. (2012)

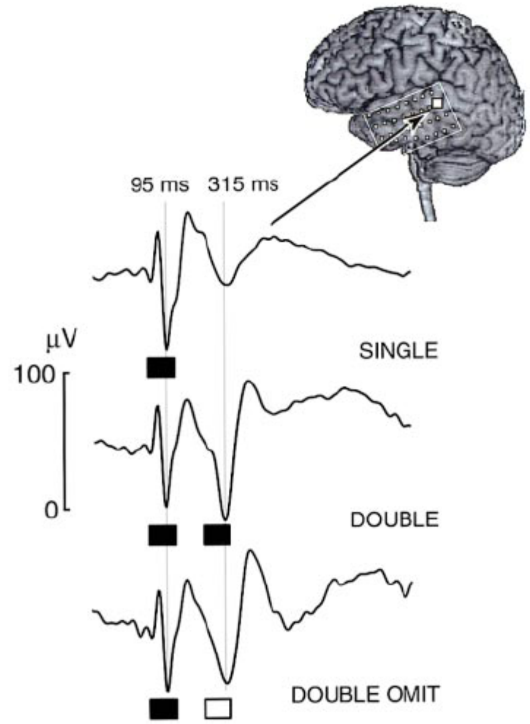
- How close to sensory signal does top-down prediction propagate?

Benefits of Predictive Coding

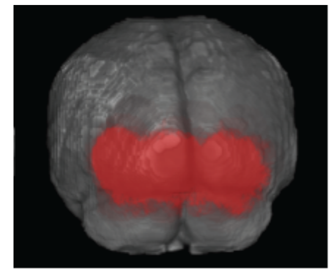
- Time-critical events (e.g., speech, reading) benefit from a reduction of alternatives during on-line processing
- Motor planning and execution requires learning a Forward-Model to compensate for time delays and kinematic constraints
- Updating of a generative model requires efficient brain pathways that can be flexibly deployed depending on context, particularly in a non-stationary (volatile) environment

Stimulus Omission Paradigm

- Hughes et al. (2001)
- ECoG from presurgical epilepsy patients using cortical electrode arrays
- 2-tone pairing with occasional 1-tone (unexpected omission) test trials

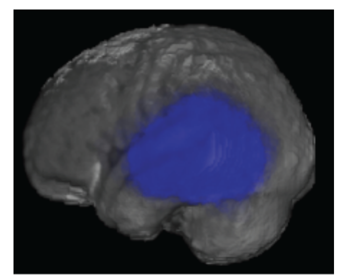


Emberson, Richards & Aslin (2015)

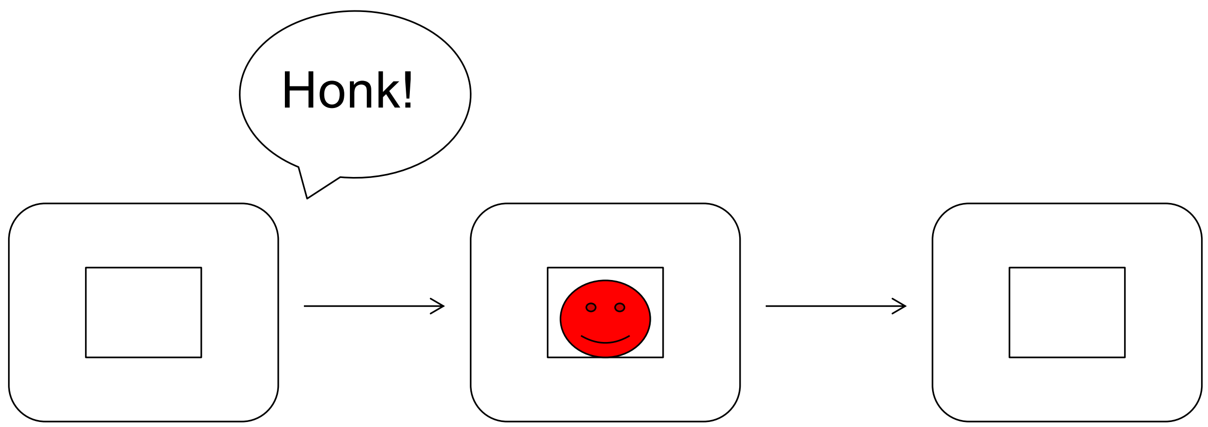


Occipital cortex

Temporal cortex

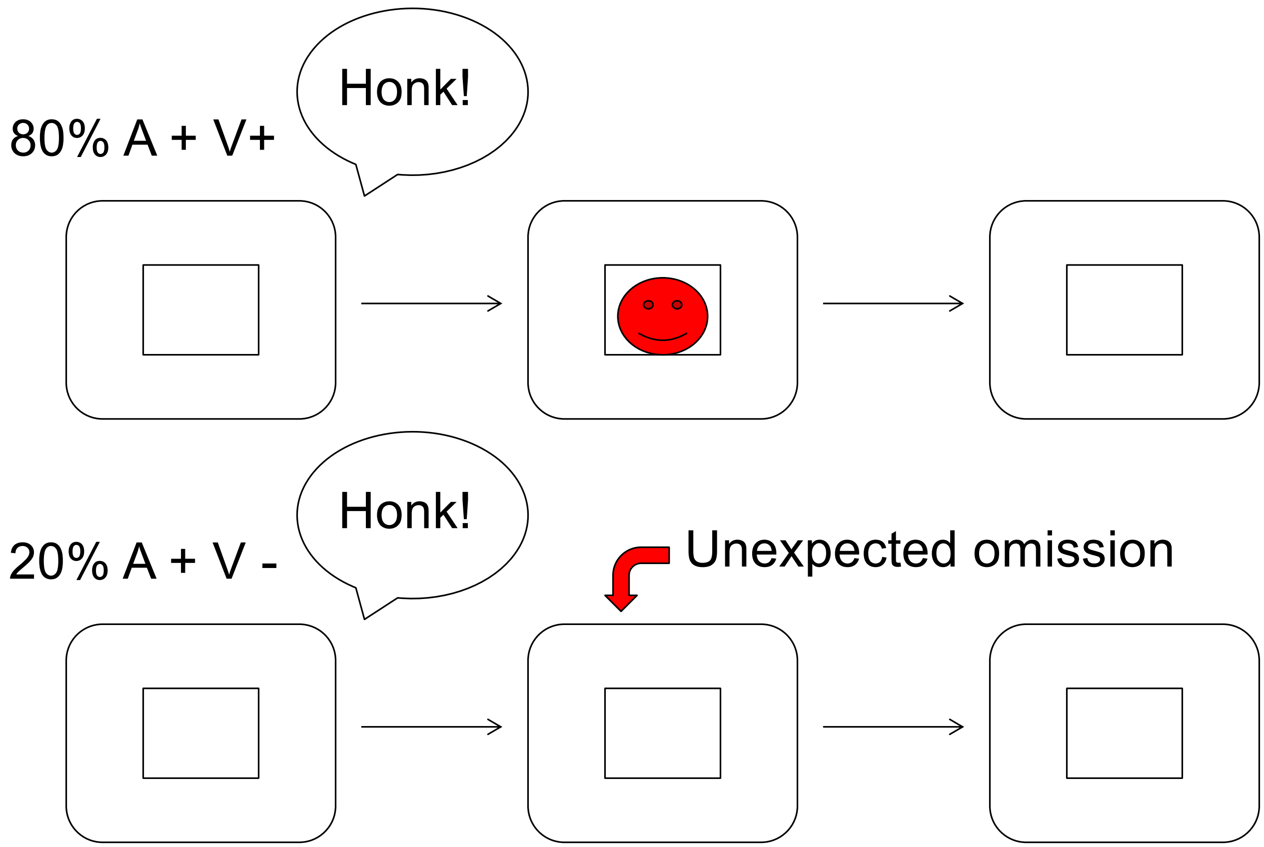


Learning Phase: Auditory-Visual Pairing

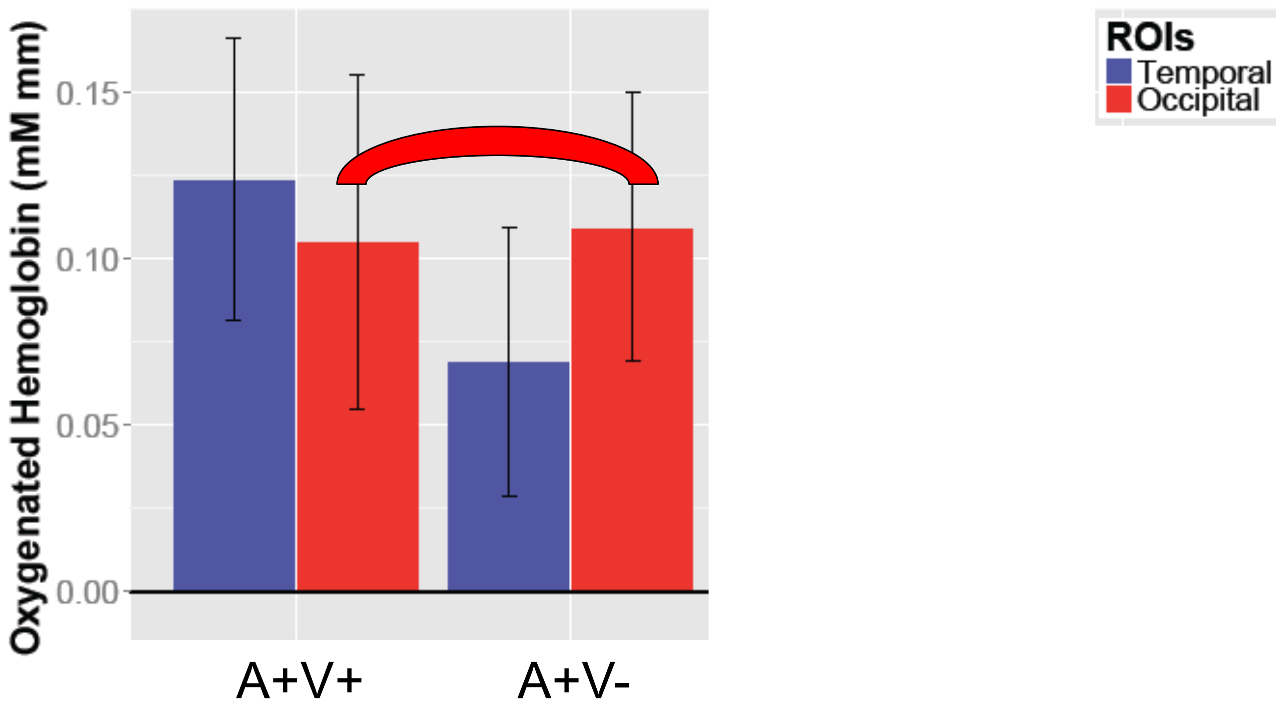


18 trials of A + V pairings

Test Phase: Expected Pairs and Visual Omissions

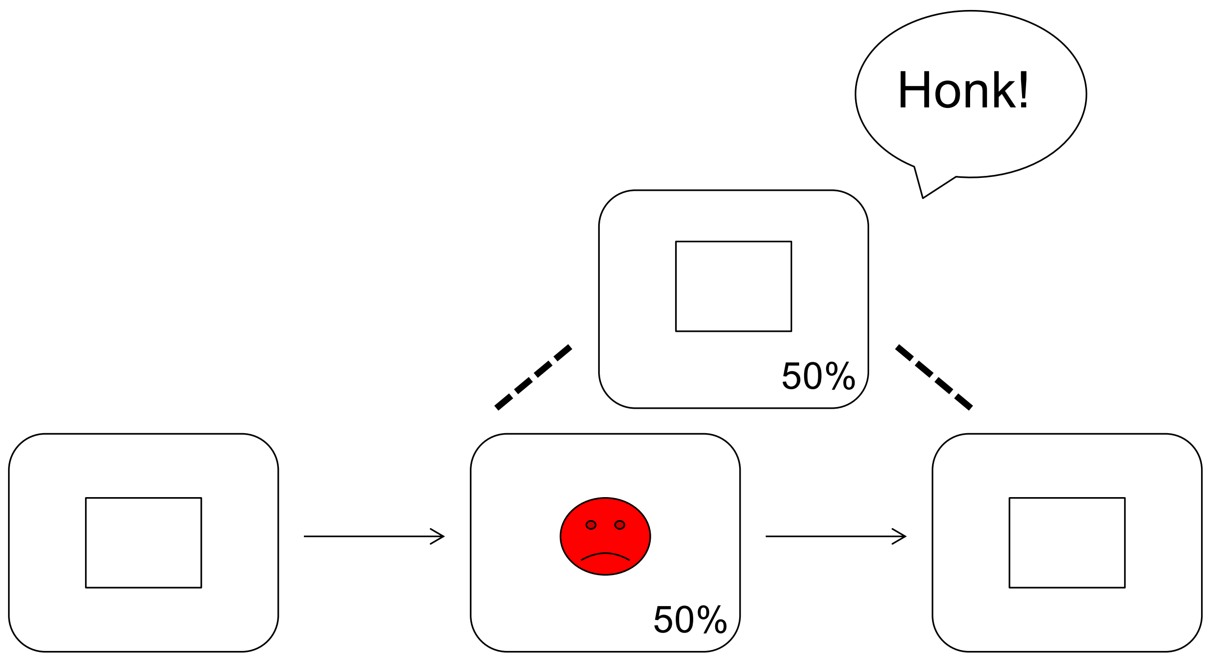


Results

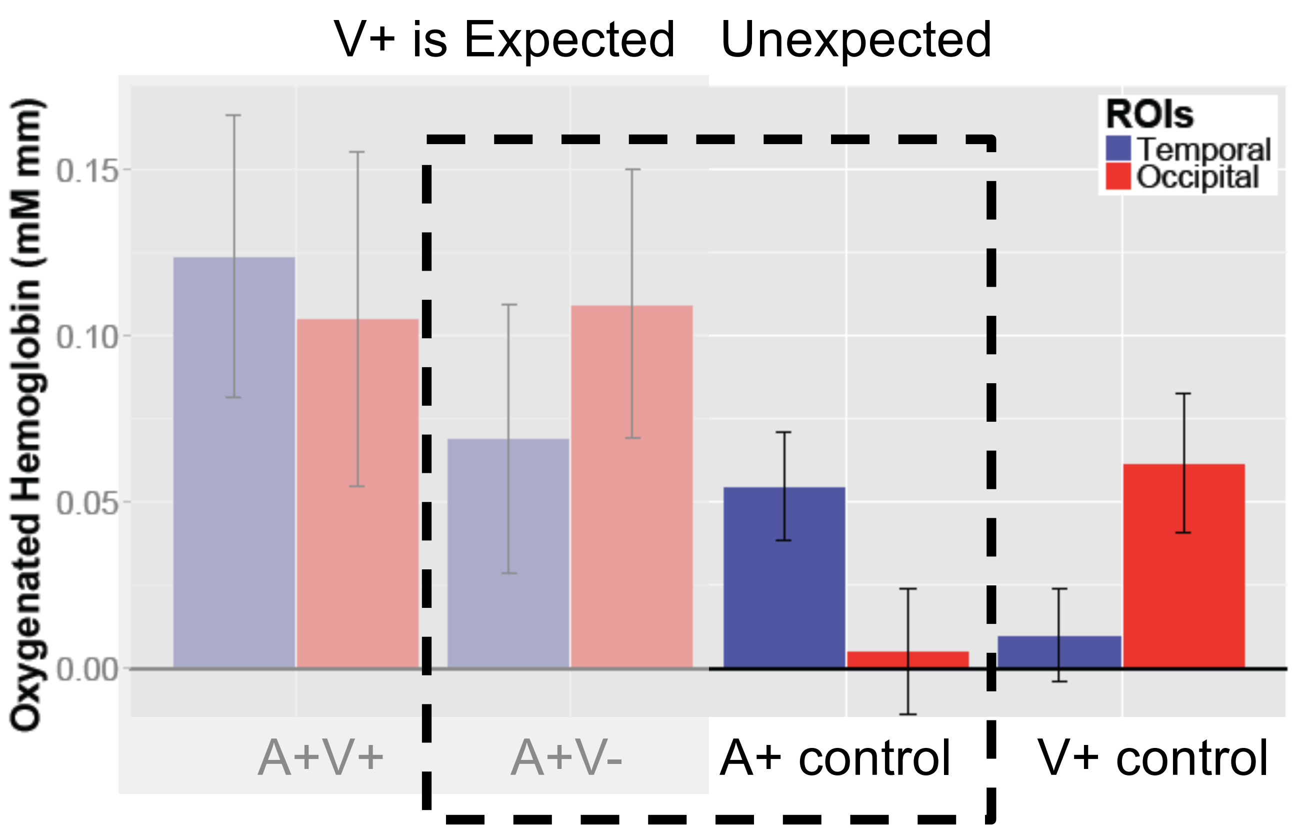


Oxygenated Hemoglobin (mM mm)
0.15
0.10
0.05
0.00
A+V+
A+V-
ROIs
Temporal
Occipital

Control: Auditory and Visual Stimuli never Paired

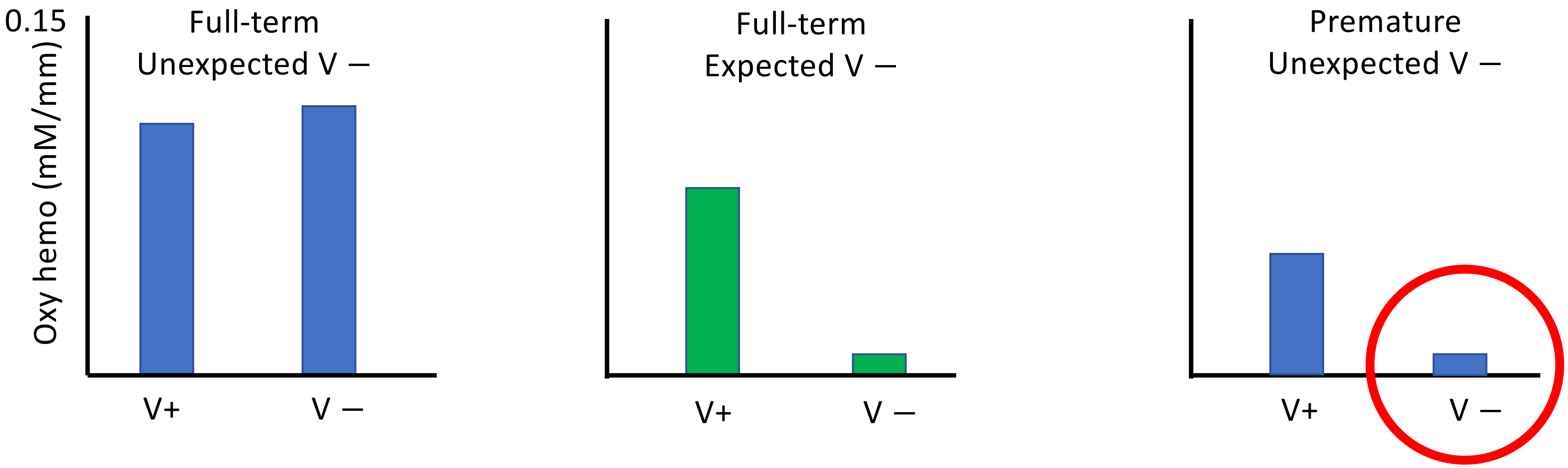


Overall Results

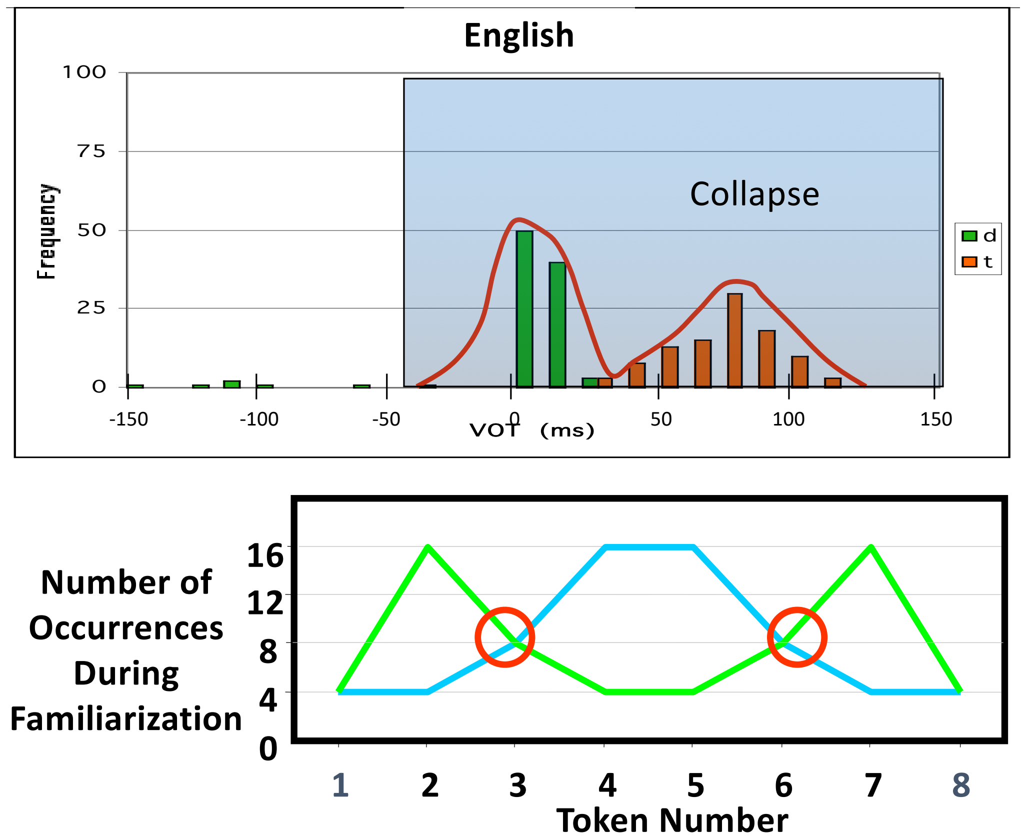


Emberson et al. (2017)

- At-risk infants: extremely premature (27-33 weeks gestation)
- Tested at 6 month corrected age on visual omission task

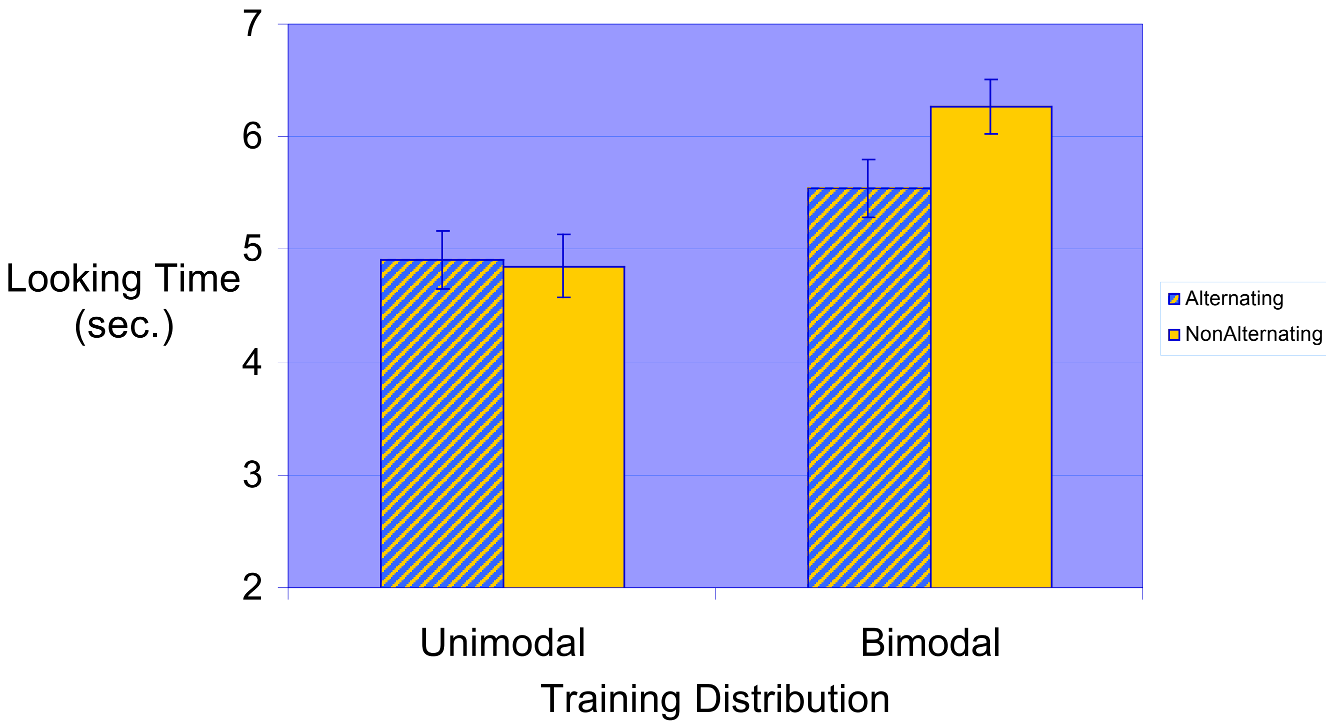


4. Do naïve learners integrate prior information with current input?

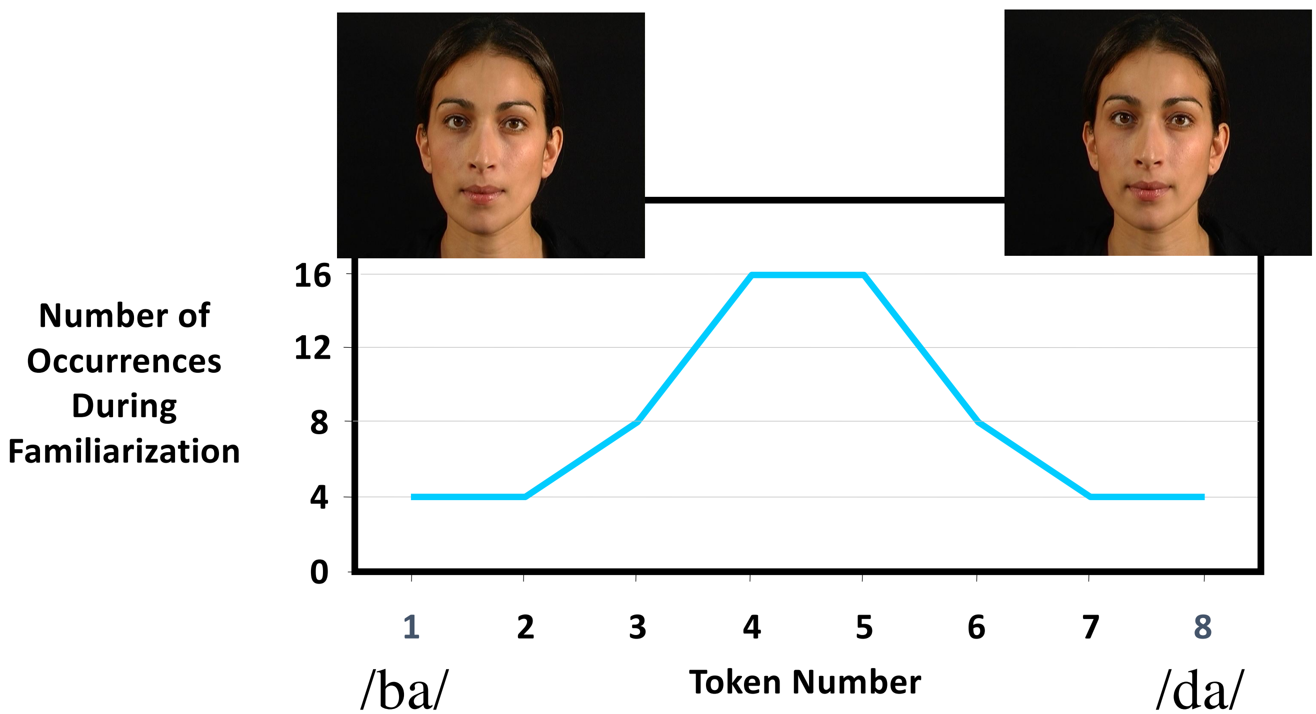


English
100
75
50
25
0
Frequency
Collapse
d
t
-150
-100
-50
0
50
100
150
VOT (ms)
Number of Occurrences During Familiarization
16
12
8
4
0
1
2
3
4
5
6
7
8
Token Number

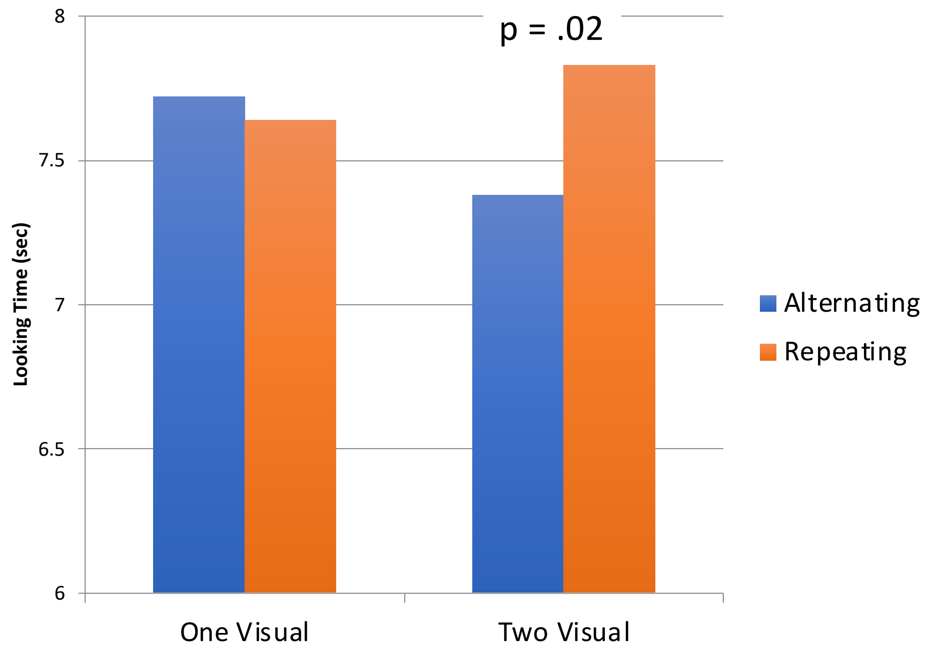
Maye, Werker & Gerken (2002)



Teinonen, Aslin, Alku & Csibra (2008)

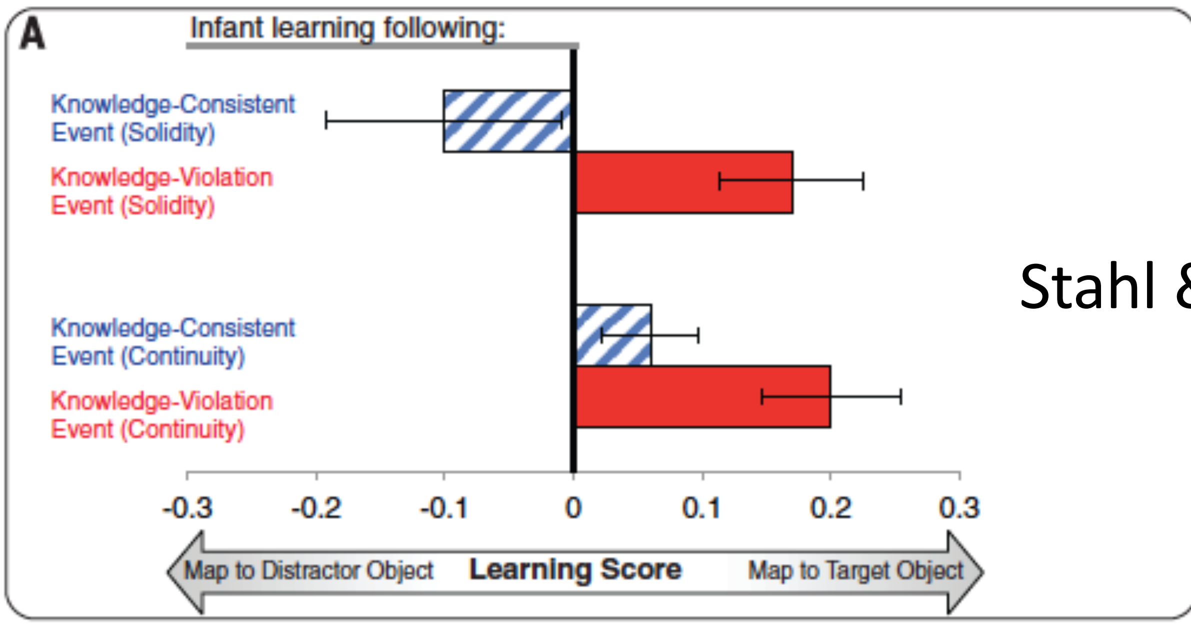


Two visual-articulatory gestures override unimodal distribution



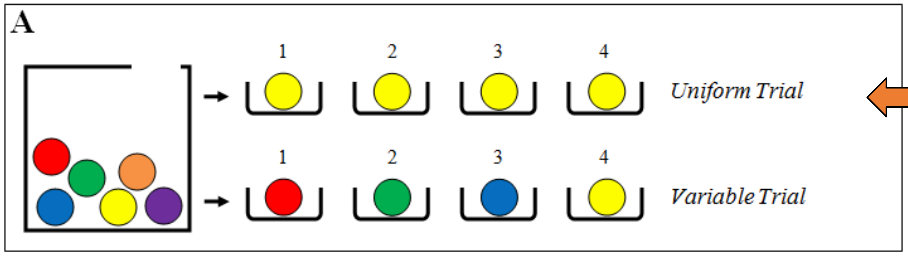
What do infants do with prior information?

- Learning more/better/faster
- Explore to learn or verify hypotheses



Stahl & Feigenson (2015)

Sim & Xu (2017)

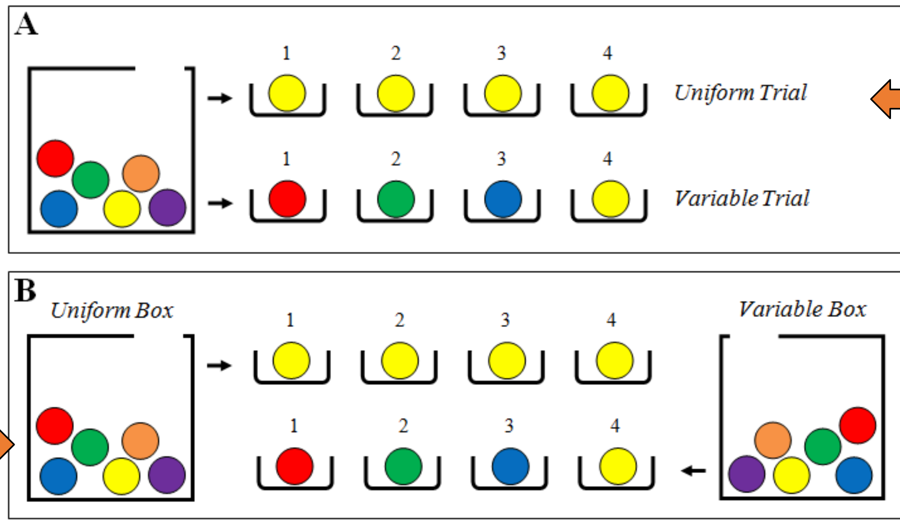


Look

13-month-olds

Sim & Xu (2017)

Look

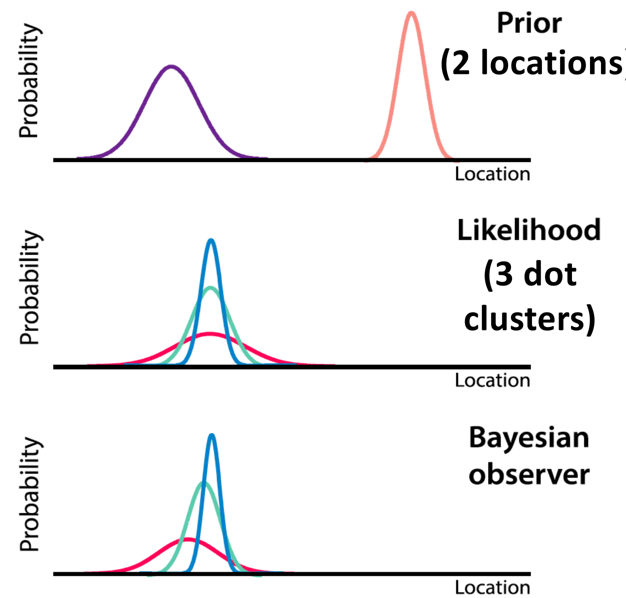


Explore

13-month-olds

Why do children do with prior information?

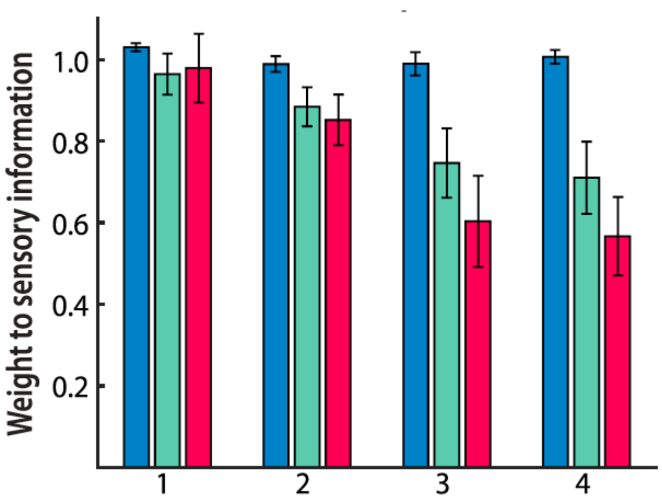
- Limited computational mechanism: fail to update priors
- Domain-general constraints: show adult-like integration if simple task
- Bejjanki, Murphy & Aslin (2019)



Weights for sensory and prior information

Adults

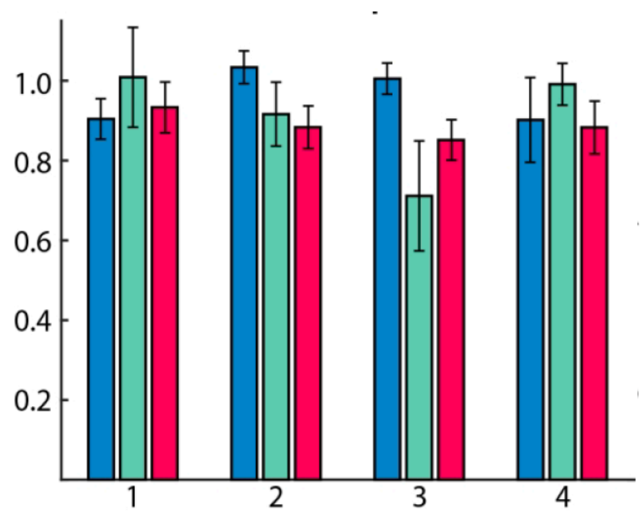
Double prior



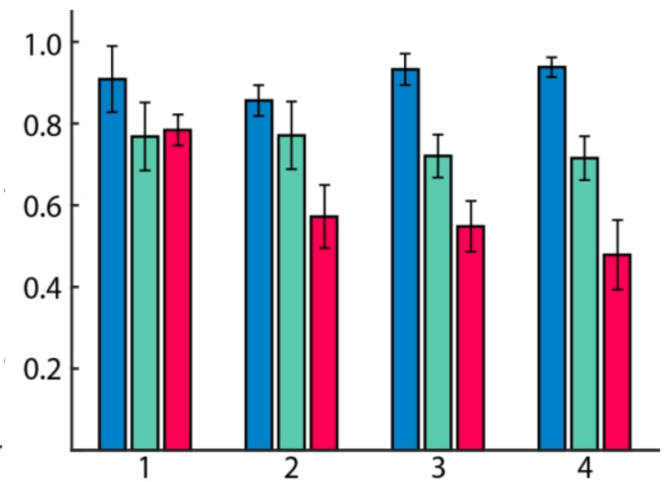
Block of 400 trials

6-8 year olds

Double prior

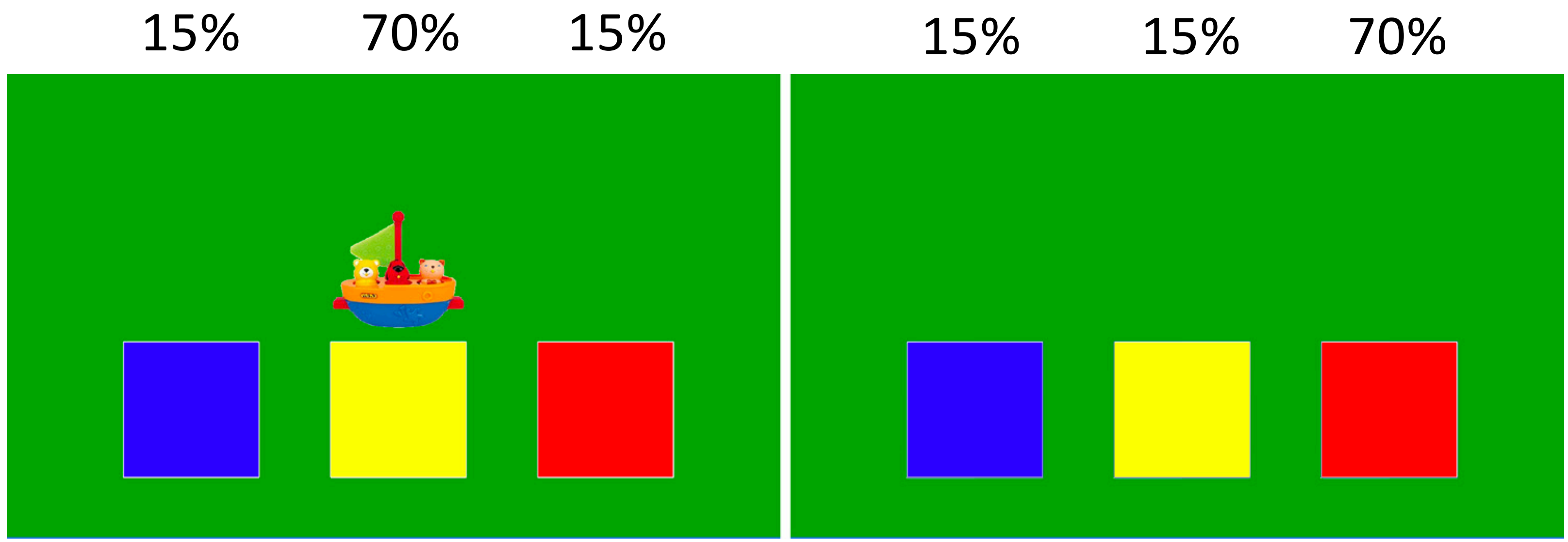


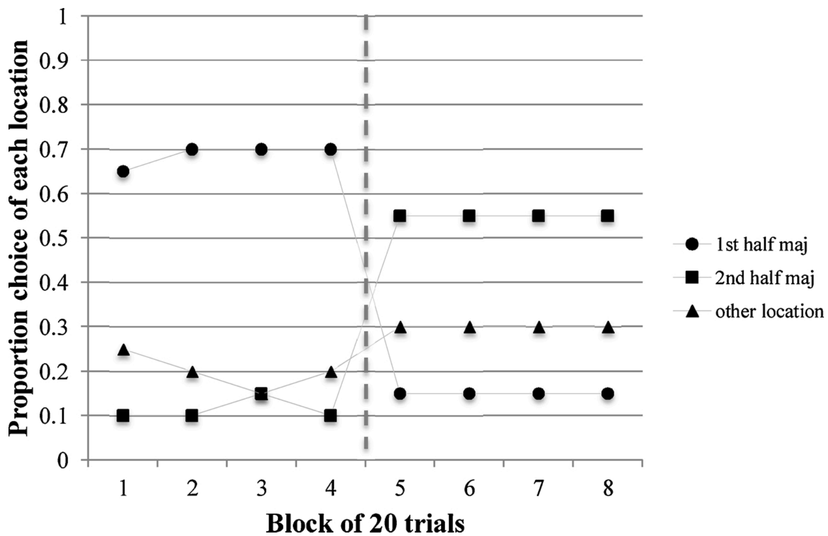
Single prior

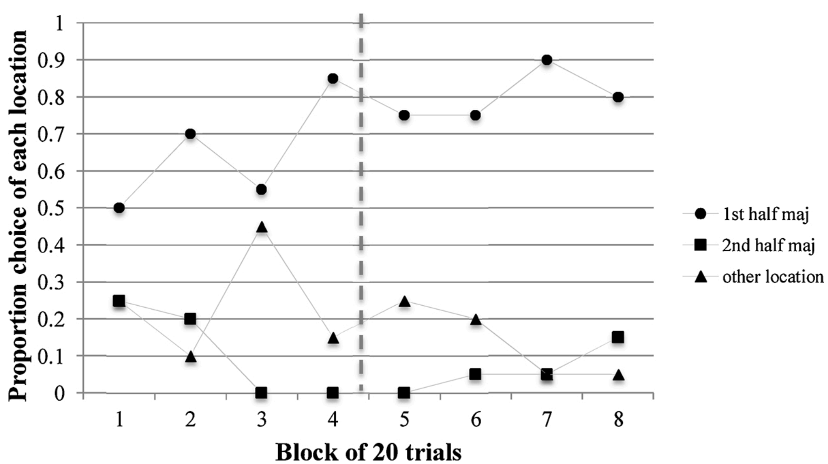


4-year-olds fail to update: stationarity bias

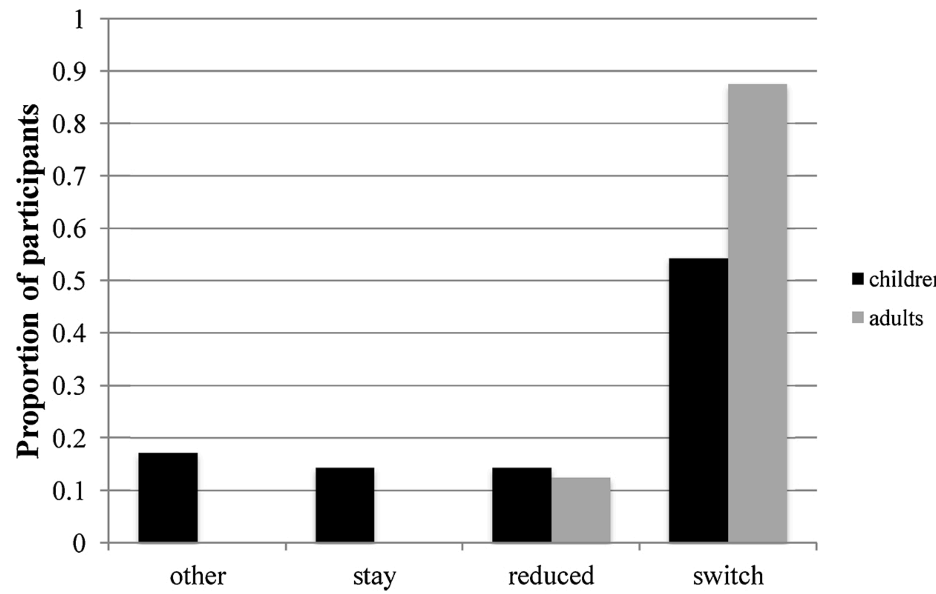
- Starling, Reeder & Aslin (2018)





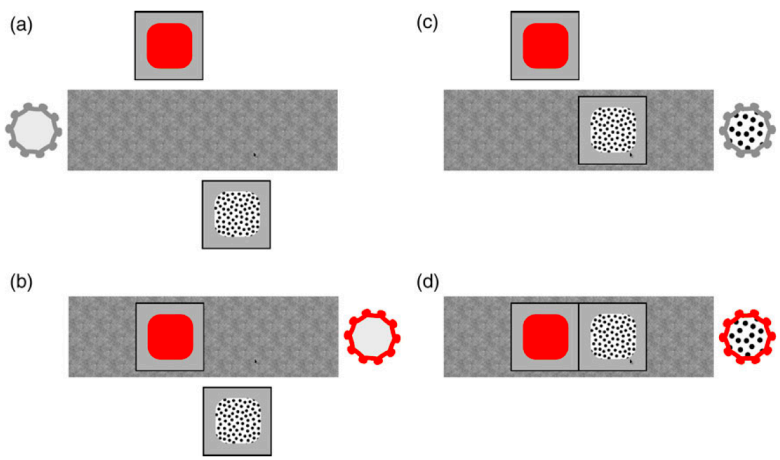


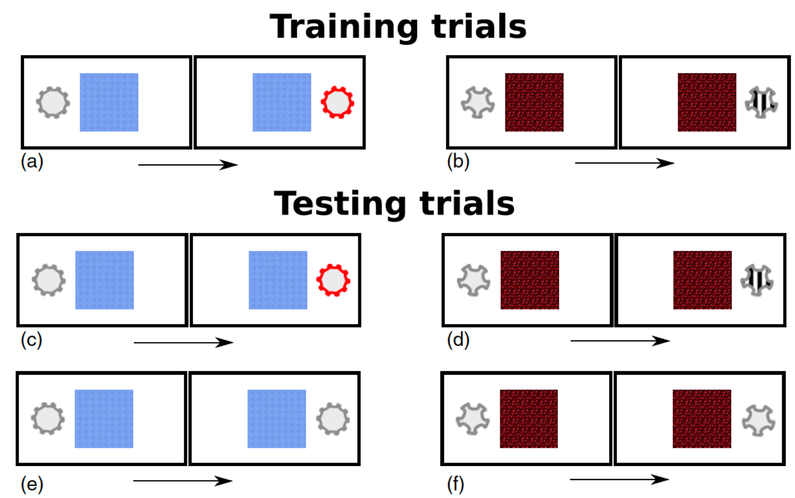
- Stationarity bias (simplicity)
- Reduces memory demand
- Explain away volatility as noise



Compositional bottleneck: WM

- Piantadosi, Palmeri & Aslin (2018)





The Future

- Machine-learning techniques and classification-learning paradigms

  fNIRS: Emberson, Zinszer, Raizada & Aslin (2017)

  EEG: Bayet, Zinszer, Pruitt, Aslin & Wu (2018)

- Big data: Many Babies 'X' Project
- Connectomics (whole-brain functional connectivity during rest and movie watching): Sanchez-Alonso, Rosenberg & Aslin (revision under review)
- Portable MEG

Hill, …. & Brookes, 2019
Nature Communications

Summary

- Pay attention to history (search literature from the past, not just from the present)
- Development = constrained learning
- fNIRS reveals top-down predictive architecture in infants
- Efficient and flexible learning is a balance of: simplicity, domain-general cognitive limitations, and task-related pressure to generalize beyond the input
- **See you in 2029!!**

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