COSC451: Artificial Intelligence
Lecture 15: How infants learn words

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Recap

Last lecture:
- How phonological representations are encoded in the brain
  - The idea of a mirror system for phonemes
  - The idea of phonological input and output buffers
- How words are encoded in the brain
  - As phonological units
  - As semantic units
  - As associations between phonological and semantic units
- Grammatical processing in the brain
  - Broca’s aphasia and Wernicke’s aphasia
Outline of today’s lecture

1. Development of phonological word representations
2. Development of object and action concepts
3. Development of knowledge of word meanings
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2. Development of object and action concepts

3. Development of knowledge of word meanings
Development of phonological word representations

There’s good evidence that infants can form representations of words as commonly-occurring phonological sequences by around 8 months (Saffran et al., 1996).

- In a training phase, an infant is played a stream of phonemes, where some phoneme sequences occur more often than chance. E.g. \textit{ga bi ro to ba di ga bi ro pa la ku to ba di}
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By 9 months, infants prefer to listen to nonwords which conform to the phonological rules of the exposure language (Jusczyk et al., 1994)
Development of phonological output representations

Infants produce sounds from birth.

- Children *imitate* the speech sounds they hear from very early. E.g. vowels are imitated from around 1 month old (Kuhl and Meltzoff, 1996).
- So the mirror system for phonemes starts to be learned very early.

Infants start to use *syllables* (‘babble’) around 6 months.

- To begin with, babbling is repeating a single syllable (*bababa*).
- By around 8 months, infants can produce short sequences of varied syllables (e.g. *baga*).
- Infants begin to *imitate* syllables at the time they start to babble (see e.g. Oller, 2000).
Outline of today’s lecture

1. Development of phonological word representations
2. Development of object and action concepts
3. Development of knowledge of word meanings
Development of object and action concepts

By 8 months:

- Infants can perform reach-to-grasp actions (Dimitrijevi and Bjelakovi, 2004).
- Infants are sensitive to the intended target of a reach-to-grasp action (Woodward, 1998).

![Diagrams showing reach-to-grasp actions]
Development of object and action concepts

By 8 months:

- Infants have a good understanding of the support/contact relations involved in grasping (Leslie, 1984).
- Infants have a good awareness of the spatiotemporal continuity of objects (Spelke et al., 1994).
- Infants can recognise common objects in a variety of poses (Ruff, 1978).

So at 8 months:

- Infants have well-developed phonological word representations;
- Infants (apparently) have well-enough developed SM concepts to serve as semantic representations of concrete words.
Outline of today’s lecture

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Some summary data from a well-normed study of US infants (Fenson et al., 1994):

- 8–12 months: infants acquire a small **passive vocabulary**.
- Active vocabulary really takes off at around 12 months.
Basic associationist model of word meaning learning

The basic model:

- An infant perceives an object or action, and evokes a semantic representation.
- An adult says the word which denotes this object/action, and the infant evokes a phonological representation.
- Associations are strengthened in the infant between the semantic and phonological representations. (Straight Hebbian learning.)

This simple idea is partly right. But there are a few problems.
Correlation problems

The stream of words infants hear is often very decorrelated from the stream of semantic representations they evoke.

Correspondences between word forms and word meanings take the form of weak statistical tendencies, reflecting the fact that parents talk about things the infant is attending to ‘more than chance’.
Cross-situational learning (Siskind, 1996)

Idea:

- The infant is in a situation, where only some of his semantic concepts will be activated.
- Assume that the infant is exploring the situation, and evoking a stream of semantic concepts.
- The situation also contains mature speakers, whose utterances are more likely than chance to contain words describing situation-related concepts.
- Assume the infant is processing these utterances phonologically, and activating a stream of word forms.
- *Any word form the infant hears in this situation is more likely than chance to denote the semantic concept he is currently evoking.*

So if we treat the set of word-concept pairs as training data, we’ll eventually learn word meanings.
Development of knowledge of word meanings

Refinements to cross-situational learning (1)

Cross-situational learning works. But it’s *slow*. (Because situation-based correlations are only very weak.)

Problem 1: the *sparseness* of good training data. It’s very unlikely that the child hears a word at *exactly* the time he activates the associated concept. We can alleviate this problem if the infant can maintain a sliding window of words, and associate *each word in this window* with the currently evoked semantic concept.

A ‘sliding window of words’ is the *phonological buffer*!

- We saw last lecture that phonological short-term memory correlates with word-learning abilities. Perhaps this is why.
Refinements to cross-situational learning (2)

There must be more clever, ‘directed’ ways of learning word meanings.

Problem (2):

- Nonhuman animals can do associative learning. But they can’t learn word meanings like human infants do.
- If human infants use simple associative learning to acquire word meanings, it’s surprising that they don’t learn faster from around 8 months.

Most current models of word learning assume there are mechanisms which go beyond simple associative learning.
An influential model by Michael Tomasello (2003) holds that infants need to acquire a set of social/pragmatic skills before they can learn words in any numbers.

There are two skills:

- **Joint attention**: the ability to follow an observed agent’s eye gaze.

- The ability to recognise **communicative intentions**.
Development of knowledge of word meanings

Social/pragmatic models of word meaning learning

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There are two skills:

- **Joint attention**: the ability to follow an observed agent’s eye gaze.
  We have already talked about the role of joint attention in the perception of hand actions.

- The ability to recognise **communicative intentions**.
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There are two skills:

- **Joint attention**: the ability to follow an observed agent’s eye gaze. We have already talked about the role of joint attention in the perception of hand actions.

- The ability to recognise communicative intentions. We have talked about the role of intention recognition in the perception of hand actions, and articulatory actions.
The role of joint attention in word meaning learning

Infants can acquire language by *overhearing* mature speakers.

In some cultures, people don’t talk much to children at all! (Pinker, 1994)

The joint attention model:

- The infant watches mature speakers talking, maybe to each other.
- While an observed speaker makes an utterance, the infant follows the speaker’s gaze, and evokes semantic representations of *what the speaker is attending to*. (Assumption: speakers often talk about what they’re attending to.)
- The infant associates *these* semantic reps with the speaker’s words.
The joint attention word-learning scenario

- infant
- attend to speaker
- adult
- cup
The joint attention word-learning scenario

infant → establish joint attention → cup

adult
The joint attention word-learning scenario

infant  establish jt attention  cup

adult
The joint attention word-learning scenario
The joint attention word-learning scenario
Infants’ ability to establish joint attention develops gradually.

- In simple contexts (where the angle the infant must traverse to establish joint attention is small), the ability is reliable around 10 months (Scaife and Bruner, 1975).
- In more complex contexts (where the angle is larger), it doesn’t become reliable until around 18 months (Butterworth and Jarrett, 1991).
Evidence for the role of joint attention in word learning

Infants’ ability to establish joint attention at 12 and 18 months is predictive of their language ability at 24 months (Mundy et al., 2007).

- Infants will follow the gaze of an observed speaker to determine the referent of a new word the speaker is using.
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- Bad learning:
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- Infants will follow the gaze of an observed speaker to determine the referent of a new word the speaker is using.

- Good learning:
Infants don’t only need to learn what words mean. They also need to learn what communication is.

‘Communication is where Agent1 gets Agent2 to attend to Thing, by performing a special type of action (an utterance).’
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The infant has to learn that words have an attention-directing function.
The role of communicative intention recognition in word learning

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‘Communication is where Agent1 gets Agent2 to attend to Thing, by performing a special type of action (an utterance).’

The infant has to learn that words have an attention-directing function. Joint attention is important in learning this.
The role of communicative intention recognition in word learning

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‘Communication is where Agent1 gets Agent2 to attend to Thing, by performing a special type of action (an utterance).’

The infant has to learn that words have an attention-directing function. Training: joint attention regularly co-occurs with observed utterances.
The role of communicative intention recognition in word learning

Infants don’t only need to learn what words mean. They also need to learn what communication is.

‘Communication is where Agent1 gets Agent2 to attend to Thing, by performing a special type of action (an utterance).’

The infant has to learn that words have an attention-directing function. After training, utterances actively direct an infant’s attention.
Infants begin following pointing gestures around 11–12 months (Butterworth, 2006; Carpenter et al., 1998).

Behne et al. (2005): infants had the task of looking for a hidden object.

- The experimenter helped them by giving them nonverbal ‘communicative gestures’ (alternately looking at the infant and the hiding place, with and without pointing at the hiding place).
- These gestures began to be understood at 14 months.
- ‘Non-communicative’ looking / pointing was not helpful.
We know that monkeys/great apes can recognise the intentions of other agents. And we know they can follow gaze.

Interestingly, great apes don’t seem able to recognise specifically communicative intentions (Call et al., 2004).

- E.g. They can’t make use of ‘communicative gestures’ (looking or pointing) in a hide-and-seek game.

Tomasello: nonhuman primates can’t represent communicative gestures. This is why they don’t have language.
Some questions about Tomasello’s model of word learning

Two questions:

1. How are communicative intentions represented in the brain? (Tomasello doesn’t say.)
   They involve ‘things in the world’ (the speaker, the hearer) and ‘things the utterance describes’ (the cup).
   How to represent these very different types of thing?
   E.g. ‘Agent1 wants me to notice the cup’
   E.g. ‘Agent1 wants me to notice the man grabbed the cup’

2. What’s the mechanism via which communicative intention recognition supports word meaning learning?
Development of knowledge of word meanings

Representing events and intentions

We’ve already got some ideas about how events and intentions are represented in the brain.

- Events involving actions (e.g. *The man grabbed a cup*) are represented (in working memory) as SM sequence plans in PFC.
- (So events are represented as *intentions*.)

So according to our model, communicative actions are probably represented in PFC somehow.

The question: what’s the difference between perceiving a regular physical action, and a communicative action?
An idea about how to represent communicative actions

If we buy the idea that semantic representations are sequential, then here’s one way we could represent communicative actions.

We first recognise a communicative action as a regular motor action.

- We attend to the agent (speaker), then to the patient (hearer), and then classify the action (communicate).

Recognising a communicate action has two special side-effects.

- We move into a special ‘verbal mode’, where links between words and concepts are turned on.
- We clear our working memory ‘event’ buffer.

Any words we now hear will create a brand new semantic rep.

In this model, the special relation between an utterance and its content is one of temporal adjacency.
PFC representation of communicative actions

We can imagine a stream of successive WM event representations in PFC.

PFC WM event representations

man  cup  grab  dog  cat  chase  mother  me  SAY  boy  girl  kiss  cat  man  bite

time
Development of knowledge of word meanings

PFC representation of communicative actions

We can imagine a stream of successive WM event representations in PFC.

PFC WM event representations

enter ’verbal mode’

<table>
<thead>
<tr>
<th>man</th>
<th>dog</th>
<th>mother</th>
<th>boy</th>
<th>cat</th>
</tr>
</thead>
<tbody>
<tr>
<td>cup</td>
<td>cat</td>
<td>me</td>
<td>girl</td>
<td>man</td>
</tr>
<tr>
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Communicative events are special, because they comprise a pair of successive event representations, with a switch to ‘verbal mode’ in between.
An idea about how communicative intention recognition supports word learning.

Recall: the stream of words infants hear is very decorrelated with the stream of semantic representations they evoke.

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But once the child has learned to establish *joint attention* with observed adults, there are some special moments where the two streams become well correlated.
An idea about how communicative intention recognition supports word learning

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These moments occur right after a *SAY* action has been observed.
An idea about how communicative intention recognition supports word learning

Idea:

- ‘Entering verbal mode’ is an action, which the infant can choose to do at any time.
- In verbal mode, if you can predict the next word you hear, you get a reward—otherwise you get a punishment.

In this scenario, the infant can learn by reinforcement to enter verbal mode after perceiving a communicative action.

- (The infant has to have a small vocabulary to kickstart the process.)
Reinforcement learning for entering verbal mode

Here’s the basic reinforcement learning paradigm.

- **S1**
- **S2**
- **S2**

- **R1**
- **R2**
- **R3**

- reward
- punishment

(Provided you get a reward for correctly-predicted word.)
Reinforcement learning for entering verbal mode

Here’s the basic reinforcement learning paradigm.

(S1) reward
(S2) punishment

(Provided you get a reward for correctly-predicted word.)
Here’s the basic reinforcement learning paradigm.

- **S1** (reward)
- **S2**
- **S2**
- **R1** (punishment)
- **R2**
- **R3**

(Provided you get a reward for correctly-predicted word.)
Reinforcement learning for entering verbal mode

Here's the basic reinforcement learning paradigm.

![Reinforcement Learning Diagram]
Here’s the basic reinforcement learning paradigm.

S1 \rightarrow R1
S2 \rightarrow R2
S2 \rightarrow R3

(reward)

(punishment)
Reinforcement learning for entering verbal mode

Here’s the basic reinforcement learning paradigm.

- reward
- punishment

\[ S_1 \rightarrow R_1 \]
\[ S_2 \rightarrow R_2 \]
\[ S_2 \rightarrow R_3 \]
Here’s the basic reinforcement learning paradigm.

- **S1**
- **S2**
- **R1**
- **R2**
- **R3**

- **reward**
- **punishment**
Reinforcement learning for entering verbal mode

Here’s the basic reinforcement learning paradigm.

○ reward
● punishment

S1

S2

S2

R1

R2

R3
Reinforcement learning for entering verbal mode

Here’s how it would look for learning to enter verbal mode.

(Provided you get a reward for correctly-predicted word.)
The network for learning word semantics

Here’s an extract from the phonological circuit I showed last time.
The network for learning word semantics

To learn words, we must learn how to *reproduce* an input word from a semantic rep.

```
Acoustic input

Actual next word  Err  Predicted next word

Word-learning netwk

Semantic reps
```

The error term can generate an 'internal' reward signal.
The network for learning word semantics

To learn words, we must learn how to reproduce an input word from a semantic rep.

The error term can generate an ‘internal’ reward signal.
Pragmatic bootstrapping

Here’s a model where word-learning and communicative action recognition bootstrap one another.

- The infant begins by learning a small vocabulary (inefficiently) using cross-situational learning. (No social/pragmatic skills needed here.)
- During development, the infant randomly experiments with entering verbal mode.
- Initially, it’s never a good idea.
- After a small vocabulary is learned, it’s sometimes a good idea, so the child tries it more often.
- This makes word learning more efficient.
A simulation (done by Greg Caza)
Summary

How infants learn words (empirical data):

- Preliminaries: word-sized phonological representations and concepts
- A small passive vocabulary
- Fast expansion of passive and active vocabulary size, perhaps correlated with development of social/pragmatic skills

Computational models of early word learning:

- Cross-situational learning is probably involved
- Joint attention is probably involved
- Perhaps vocabulary development bootstraps development of the concept of a communicative actions