An information seeking account of eye movements during word learning

Kyle MacDonald

Dissertation overview

Learning a first language should be hard. Consider that even concrete nouns are often used in complex contexts with multiple possible referents, which in turn have many conceptually natural properties that a speaker could talk about. This ambiguity creates the potential for an (in principle) unlimited amount of referential uncertainty in the learning task.[1]. Moreover, to find meaning in language requires rapdily establishing reference during real-time interaction where the incoming information is dynamic, multimodal, and transient. Remarkably, children's word learning proceeds despite these challenges, with estimates of adult vocabularies ranging between 50,000 to 100,000 distinct lexical concepts (P. Bloom 2002). How do learners infer and retain such a large variety of word meanings from data with this kind of ambiguity?

Statistical learning theories offer a solution to this problem by aggregating cross-situational statistics across labeling events to identify underlying word meanings (Yu and Smith 2007; Siskind 1996). Recent experimental work has shown that both adults and young infants can use word-object co-occurrence statistics to learn words from individually ambiguous naming events (Smith and Yu 2008; Vouloumanos 2008). For example, Smith and Yu (2008) taught 12-month-olds three novel words simply by repeating consistent novel word-object pairings across 10 ambiguous exposure trials. Moreover, computational models suggest that cross-situational learning can scale up to learn adult-sized lexicons, even under conditions of considerable referential uncertainty (K. Smith, Smith, and Blythe 2011).

While all cross-situational learning models agree that the input is the co-occurrence between words and objects and the output is stable word-object mappings, they disagree about how to best characterize the link between in-the-moment language comprehension and long-term retention of word-object labels. Moreover, researchers have only begun to understand these processes within spoken language learning for a narrow range of learning contexts. For example, the majority of prior work on language comprehension and cross-situational learning has used linguistic stimuli that come from a disembodied voice and a visual world that consists of concrete objects. As a result, we know much less about how learning unfolds in contexts that include a communicative partner who can modulate the ambiguity of the input to cross-situational learning mechanisms.

This gap is important to address since social-pragmatic theories of language acquisition have long emphasized the importance of the social context for first language acquisition (P. Bloom 2002; Clark 2009;

[1] This problem is a simplified version of Quine's *indeterminacy of reference* (Quine 1960): That there are many possible meanings for a word ("Gavigai") that include the referent ("Rabbit") in their extension, e.g., "white," "rabbit," "dinner." Quine's broader philosophical point was that different meanings ("rabbit" and "undetached rabbit parts") could actually be extensionally identical and thus impossible to tease apart.

Hollich et al. 2000). Moroever, experimental work has shown that even children as young as 16 months prefer to map novel words to objects that are the target of a speaker's gaze and not their own (Baldwin 1993). In an analysis of naturalistic parent-child labeling events, Yu and Smith (2012) found that young learners tended to retain labels that were accompanied by clear referential cues, which served to make a single object dominant in the visual field. And correlational studies have demonstrated strong links between early intention-reading skills (e.g., gaze following) and later vocabulary growth (Brooks and Meltzoff 2005; Carpenter et al. 1998).

In addition to the absence of work on the role of social contexts, we know little about how eye movements adapt to contexts where fixating on another person is critical for language acquisition as in the case of children learning a signed language. This developmental context creates a tradeoff where young signers must decide whether to look at their social partner to gather information about language or to look at the nonlinguistic visual world to gather information about objects. This channel competition potentially complicaties the link between the in-the-moment processes of establishing reference and long-term rentention of object labels.

My dissertation work directly explores how familiar language comprehension and novel word learning adapts to a wider variety of learning contexts, including sign language, language accompanied by social cues to reference, and language produced in noisy auditory contexts. To do this, I argue that it is useful to deconstruct the concrete word learning task into three parts (see M. Frank, Lewis, and MacDonald (2016) or McMurray, Horst, and Samuelson (2012)) and ask how each sub-component adapts to different contexts:

1. comprehending familiar words [in-the-moment]
2. following a social cue to reference [in-the-moment]
3. retaining a novel word-object link [across multiple moments]

In our previous work, we characterized how children and adults choose to allocate visual attention between a social partner and objects during familiar American Sign Language (ASL) comprehension (Chapter 1). We then compared the dynamics of eye movements during familiar ASL processing to those of spoken language learners, showing that ASL-learners gather more information about the linguistic signal before shifting away from a language source compared to spoken language learners. We proposed an information-seeking account to explain these modality-based differences and tested predictions of our account across a variety of language comprehension contexts. We found the same pattern of eye movements for English-speaking adults processing displays of printed text and for both children and adults processing speech in noisy auditory environments (Chapter 2). These results suggest that listeners flexibly adapt eye movements to the value of seeking higher value visual information to support their goal of rapid langauge comprehension.

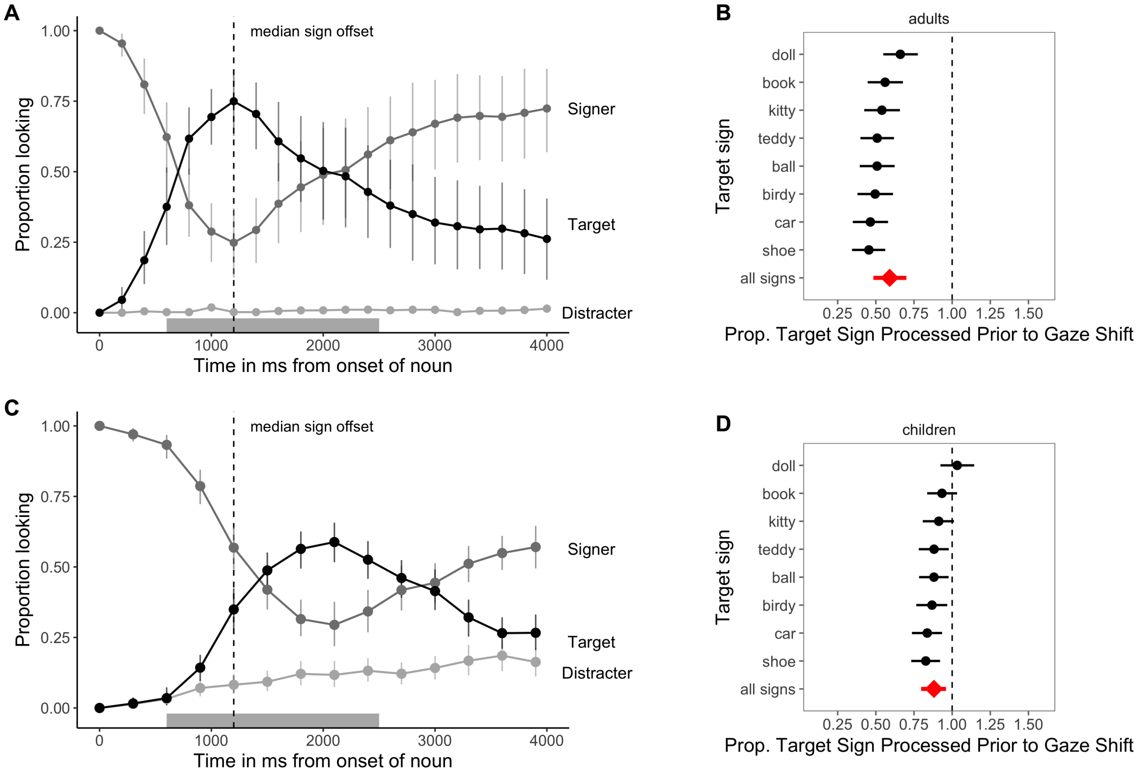
In a separate line of work, we have asked how the presence of a social cue to reference – a speaker's gaze – could change the representations that support novel word learning (Chapter 3). Our results suggest that word learneers stored representations with different levels of fidelity depending on the amount of ambiguity present during learning. In the absence of a referential cue to word meaning, learners tended to store more alternative word-object links. In contrast, when gaze was present learners stored less information, showing behavior consistent with tracking a single hypothesis. Thus, word learners flexibly respond to the amount of ambiguity in the input, and as referential uncertainty increases, they tend to store more information.

Here, I propose a study that will connect our prior work on eye movements for information seeking during familiar language comprehension with our work on the effects of social cues on cross-situational word learning. The goal of this study is to test how predictions of our information seeking account generalize to the novel word learning context. Testing these preditions will increase our understanding of how listeners flexibly adapt the dynamics of eye movements to seek higher value information to support word learning. Overall, these results will synthesize ideas from research on social-pragmatic theories of language acqusition and work on goal-based vision to increase our knowledge of how in-the-moment decisions about how to allocate visual attention affect word learning over time.

Completed work

Chapter 1: Dividing visual attention to language and objects during real-time American Sign Language comprehension

When children interpret spoken language in real time, linguistic information drives rapid shifts in visual attention to objects in the visual world, which can provide insights into the development of efficiency in lexical access. But how does language influence visual attention when the linguistic signal and the visual world are both processed via the visual channel? We developed precise measures of eye movements during real-time comprehension of a visual-manual language, American Sign Language (ASL), by 29 native, monolingual ASL-learning children (16-53 mos, 16 deaf, 13 hearing) and 16 fluent deaf adult signers. All signers showed evidence of rapid, incremental language comprehension, initiating eye movements prior to sign offset. Deaf and hearing ASL-learners showed remarkably similar gaze patterns, suggesting that the in-the-moment dynamics of eye movements during ASL processing are shaped by the constraints of processing a visual language in real time and not by differential access to auditory information in day-to-day life. Finally, variation in children's ASL processing was positively correlated with age and vocabulary size. Thus, despite channel competition, allocation of visual attention during ASL comprehension reflects information processing skills that are fundamental for language acquisition regardless of language modality.

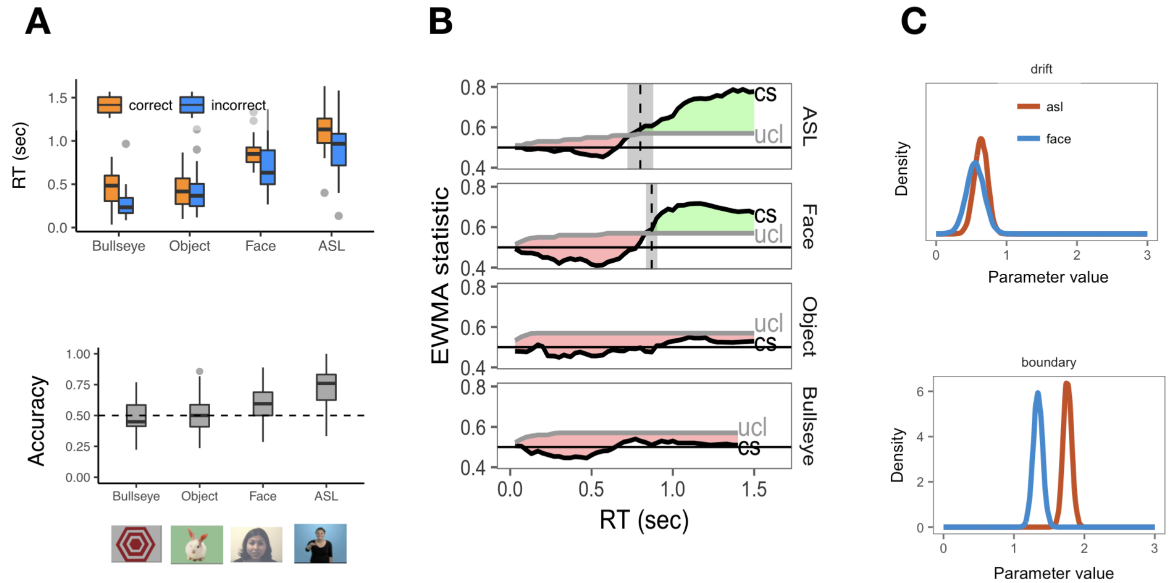


Chapter 2: An information seeking account of differences in eye movements between spoken and signed language during real-time language processing

The study of eye movements during language comprehension has provided fundamental insights into the interaction between conceptual representations of the world and the incoming linguistic signal. For example, research shows that adults and children will rapidly shift visual attention upon hearing the name of an object in the visual scene, with a high proportion of shifts occurring prior to the offset of the word (Allopenna, Magnuson, and Tanenhaus 1998; Tanenhaus et al. 1995). Moreover, researchers have found that conceptual representations activated by fixations to the visual world can modulate subsequent eye movements during language processing (Altmann and Kamide 2007).

The majority of this work has used eye movements as a measure of the output of the underlying language comprehension process, often using linguistic stimuli that come from a disembodied voice. But in real world contexts, people also gather information about the linguistic signal by fixating on the language source. Consider a speaker who asks you to “Pass the salt” but you are in a noisy room, making it difficult to understand the request. Here, comprehension can be facilitated by gathering information via (a) fixations to the nonlinguistic visual world (i.e., encoding the objects that are present in the scene) or (b) fixations to the speaker (i.e., reading lips or perhaps the direction of gaze). But, this situation creates a tradeoff where the listener must decide what kind of information to gather and at what time. How do we decide where to look? We propose that people modulate their eye movements during language comprehension in response to tradeoffs in the value of gathering different kinds of information.

We test this adaptive tradeoff account using two case studies that manipulate the value of different fixation locations for language understanding: a) a comparison of processing sign vs. spoken language in children (E1), and b) a comparison of processing printed text vs. spoken language in adults (E2). Our key prediction is that competition for visual attention will make gaze shifts away from the language source less valuable than fixating the source of the linguistic signal, leading people to generate fewer exploratory, nonlanguage-driven eye movements.



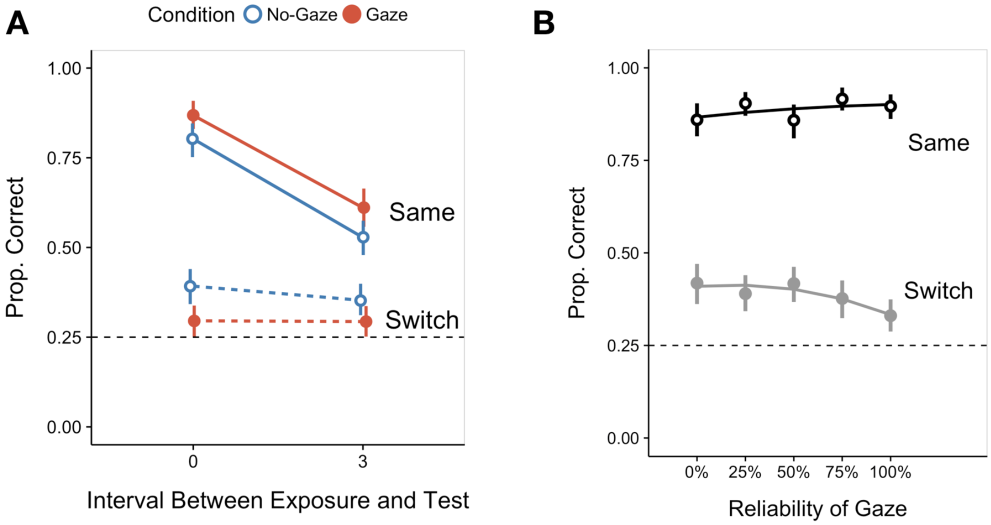
Some of our work has explored how the presence of another person changes the set of information seeking behaviors available (MacDonald et al. 2017). Inspired by theories of natural vision that characterize eye movements as an information seeking mechanism, we asked whether children and adults would allocate more visual attention to a speaker when the linguistic signal was noisy to support the goal of rapid language understanding. We used an eye-tracking task to measure participants' gaze patterns while they processed clear or degraded speech (speech with brown noise added). Both children and adults spent more time fixating on the speaker in the degraded speech context. Interestingly, children and adults were also more accurate in word recognition even though the speech was noisy and difficult to process. This result suggests that listeners were compensating for the uncertainty in the auditory channel by gathering visual information from the speaker. Critically, listeners would not have been able to gather this information if the speaker was not present (e.g., listening to a noisy recording) and in clear view.

Chapter 3: Social cues to reference modulate attention and memory during cross-situaitonal word learning

Some of our own work provides evidence that the social context can modulate the content of the learner's hypothesis space (MacDonald, Yurovsky, and Frank 2017). Inspired by ideas from Social-pragmatic theories of language acquisition that emphasize the importance of social cues for word learning (Clark 2009; Hollich et al.

2000; P. Bloom 2002), we showed adults a series of word learning contexts that varied in ambiguity depending on whether there was a useful social cue to reference available (a speaker's gaze). We then measured learners' memory for alternative word-object links. People flexibly responded to the amount of ambiguity in the input, and as uncertainty increased, they tended to store more word-object hypotheses. Moreover, we found that learners stored representations with different levels of fidelity as a function of the reliability of the social cue. When the speaker was a less reliable source of information, learners distributed attention and memory broadly, storing more hypotheses.

These results provide evidence that the content of learners' hypothesis spaces changed as a function of social information. Further suppport for this idea comes from experimental work showing that even children as young as 16 months prefer to map novel words to objects that are the target of a speaker's gaze and not their own (Baldwin 1993), and analyses of naturalistic parent-child labeling events shows that young learners tended to retain labels accompanied by clear referential cues, which served to make a single object dominant in the visual field (Yu and Smith 2012). One important direction for future research is to measure the full causal pathway from variation in social information through children's hypothesis spaces to their information seeking behaviors. For example, it would be interesting to know whether learners' subsequent questions or decisions about where to allocate attention would be affected by the social context in which they were first exposed to a new word.



Proposed work

The goal of the proposed work is to understand the factors that influence eye movements for information gathering during novel word learning.

test predictions of our information seeking account generalizes to contexts where there is uncertainty over word-object links.

Here are the factors that we could manipulate:

- noise in the auditory signal (quality of the linguistic information)
- number of novel objects (attention demands)
- interval between exposure and test (memory demands)
- presence of gaze cue (referential ambiguity)
- proportion of familiar vs. novel objects in the learning
- number of exposures (or pre-exposures) to word-object pairing

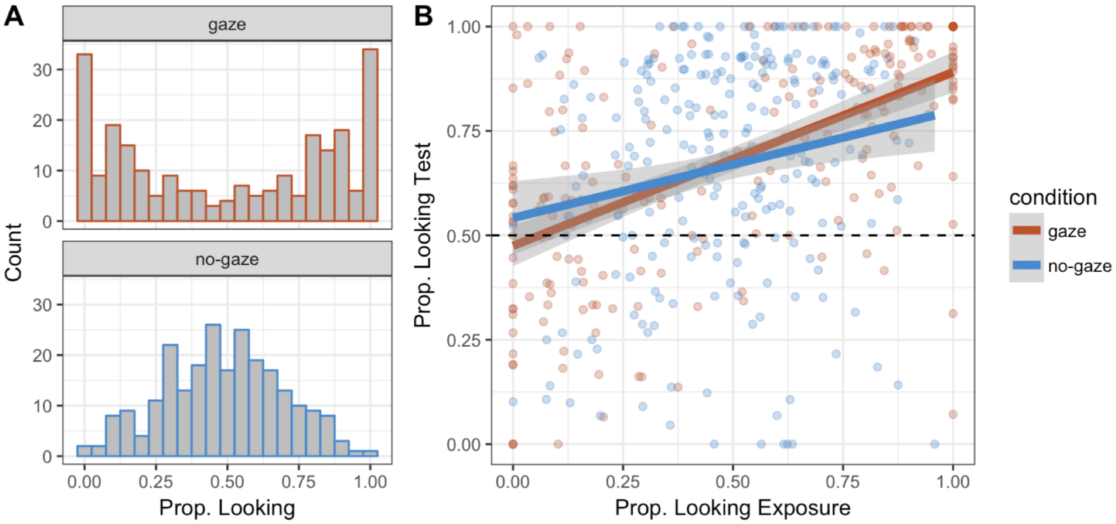
Eye movements for information seeking during novel word learning

The goal is to test how our information seeking account generalizes to contexts where there is uncertainty over word-object links. The word learning context is interesting because people are trying to achieve towards multiple goals: comprehending speech in the moment (a function of listening and looking to the speaker), mapping the new word to an object, and learning that mapping over time. Eye movements during concept formation can gather information about the speaker or about the nonlinguistic visual world. How do we explain where children look as they acquire more information in-the-moment of language comprehension and as they build a learning history about the correct word-object mapping? This question can be formalized as a sequential decision making problem where children make fixation choice based on (1) their knowledge of the target concept, (2) the value of fixating a speaker for linguistic processing, and (3) the cost of each eye movement.

The intuitive idea is that people balance fixating a speaker and fixating objects to support concept learning. The question is whether models of Bayesian concept learning and Optimal Experiment Design (Neslon & Cottrell, 2007) provide a good explanation of children's eye movements. How far can we get using a purely computational information seeking decision model?

Pilot

When gaze cued adults' visual attention, they showed stronger memory for the word-object link compared to when a gaze cue was absent (Figure 2). social information does more than modulate how people allocate their visual attention; instead, social contexts change strength of inferences



Design

Predictions

The prediction is that the dynamics of eye movement will shift over the course of learning. In the beginning of the task, learners will distribute fixations to prioritize gathering information about the objects or about disambiguating reference (e.g., gathering a gaze cue). After learning the word-object links, people will shift and start to distribute more fixations to the speaker to gather visual information that supports comprehension of the speech, showing the behavioral signatures measured in the familiar language comprehension task.

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