

Adults and preschoolers seek visual information to support language comprehension in noisy environments

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Abstract

Language comprehension is a multisensory and interactive process. When interpreting an utterance, listeners rapidly integrate information from both the visual and the linguistic signals. But the quality of each information source varies depending on the processing context, e.g., understanding speech in noise. Here, we present a strong test of the hypothesis that listeners will adapt the dynamics of gaze during lexical access to seek higher value visual information that supports comprehension. We measured the timing and accuracy of adults ($n=31$) and children's ($n=40$, 3-5 y.o.) eye movements during a real-time language comprehension task and found that both age groups delayed the timing of gaze shifts away from a speaker's face when processing speech in noise. Interestingly, this delay resulted in higher information accumulation from the visual signal, more accurate shifts, and fewer random eye movements to the rest of the visual world. This results suggest that the dynamics of gaze adapt to the processing demands of different contexts and even young listeners will seek visual information that supports real-time language comprehension.

Keywords: eye movements; language processing; information-seeking; speech in noise;

Introduction

Real-time language comprehension is an interactive and multimodal phenomenon. As skilled listeners, we continually integrate information from both the visual and the linguistic signal in order to understand what others are saying. A classic demonstration of this integration process is the “McGurk effect” where a speaker's mouth movements suggest one sound while their acoustic output suggests another. This conflict results in the listener perceiving a third, intermediate sound (J. MacDonald & McGurk, 1978). Findings such as these have inspired prominent theories of speech perception (McClelland, Mirman, & Holt, 2006) and lexical processing (M. C. MacDonald & Seidenberg, 2006; Smith, Monaghan, & Huetig, 2017) that argue for the fundamental role of *interactive* processes – where listeners process information from multiple sources in parallel. Moreover, empirical work on speech perception shows that adults are better able to “recover” linguistic information in noisy contexts when they have visual access to a speaker's face (Erber, 1969)

However, the usefulness of integrating visual information varies depending on features of the listener and features of the processing context. Consider the case of processing a visual-manual language like American Sign Language (ASL). Here, the value of allocating visual fixations to the language source (i.e., the signer) is incredibly high since all of the language-relevant information is available in that location. In our prior work, we showed that, compared to spoken language learners, ASL-learners were more sensitive to the

higher value of eye movements in a visual language, choosing to prioritize information accumulation and accuracy over and above speed when deciding to shift gaze away from another signer (K. MacDonald, Blonder, Marchman, Fernald, & Frank, 2017). To explain this difference, we proposed an information-seeking account inspired by goal-based theories of vision (Hayhoe & Ballard, 2005): that signers adapted the dynamics of gaze during lexical access to seek information that supported accurate language comprehension.

In the work reported here, we test a specific prediction of this information-seeking account and ask whether listeners would adapt patterns of fixation when looks to a speaker become more valuable – as is the case of processing speech in noise. Consider the familiar example of a speaker who asks you to “Pass the salt” in a noisy restaurant where it is difficult to understand the request. The intuition is that comprehension can be facilitated by gathering information via fixations to the speaker by reading lips or perhaps the direction of gaze.

There has been recent interest in understanding how gaze patterns during lexical access might adapt to different contexts that deviate from the well-controlled lab settings that are typically used in psycholinguistic tasks. For example, recent work by McMurray, Farris-Trimble, & Rigler (2017) shows that individuals with Cochlear Implants, who are consistently processing degraded auditory input, are more likely to delay the process of lexical access as compared to listeners with typical hearing. Our work asks a related question about whether the interaction between language and visual attention interaction flexibly adapts to the features of the processing context.

Specifically, we hypothesized that a noisy auditory environment would make the auditory signal less reliable, and in turn increase the value of fixating on a speaker for the task of language understanding. Our key behavioral prediction is that listeners who process speech in noise will delay generating an eye movement away from a speaker until they have accumulated additional information about the named referent. In other words, we predict that noisy contexts will lead to more fixations allocated to a language-relevant aspect of the visual world. The next section outlines the specific measurements and models that we use to quantify the evidence for this hypothesis.

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Experiment

In this experiment we test whether our information-seeking account of eye movements would generalize to a novel and

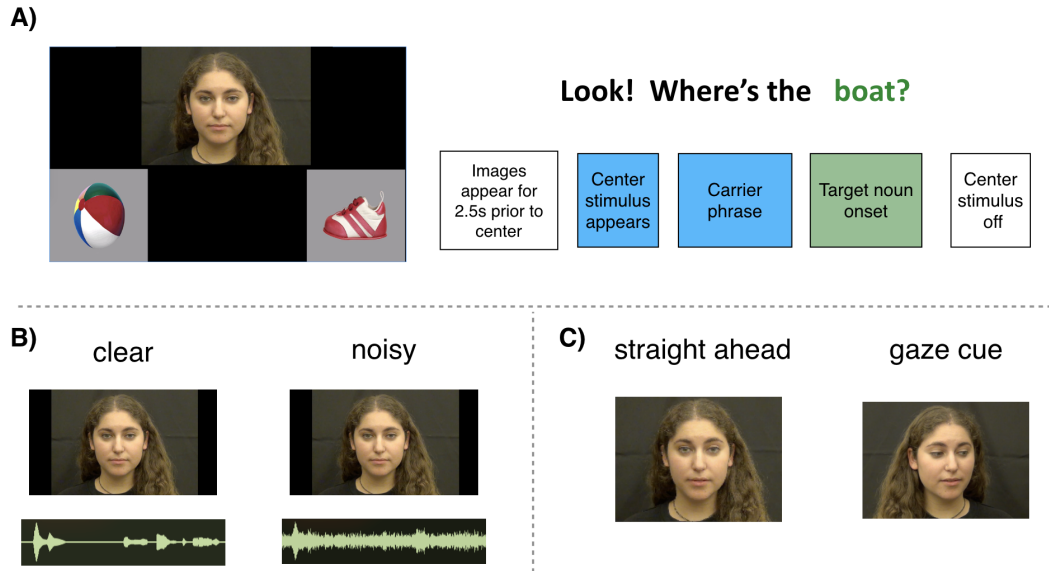


Figure 1: Stimuli for E1 and E2. Panel A shows the layout of the three fixation locations (speaker, target, and distracter), and the timecourse of a single trial. Panel B shows a visual representation of the clear and noisy waveforms used in E1. Panel C shows the gaze manipulation used in E2.

ecologically valid processing context – speech in noise. We recorded eye movements during a real-time language comprehension task where children and adults processed familiar sentences (e.g., “Where’s the ball?”) while looking at a simplified visual world with three fixation targets (see Fig 1). Using a within-participants design, we manipulated the signal-to-noise ratio of the auditory signal by convolving the language with brown noise. We predicted that processing speech in noise would increase the value of fixating on the speaker, causing listeners to gather additional information before generating a shift to the named referent even after the target word began unfolding in time.

To quantify evidence for our prediction, we compare the Accuracy and Reaction Times (RTs) of participants’ first shifts after target noun onset between the noisy and clear contexts. We take a “micro-level” approach and use first shifts as window onto changes in the underlying decision processes that generate eye movements. However, it is important to point out that when we analyze differences in Accuracy, we are not making claims about overall amount of time spent looking at the target vs. the distractor image – a measure that is typically used in analyses of the Visual World Paradigm.

We also present two model-based analyses that link the observable behavior to underlying psychological constructs of interest. First, we use an exponentially weighted moving average (EWMA) method (Vandekerckhove & Tuerlinckx, 2007) to classify participants’ gaze shifts as language-driven or random. In contrast to the standard RT/Accuracy analysis, the EMWA approach allows us to quantify participants’ willingness to generate gaze shifts after noun onset but before collecting sufficient information to seek the named referent.

Higher values indicate that participants were shifting early and equally likely to land on the target or distractor image.

Next, we use drift-diffusion models (DDMs) (Ratcliff & Childers, 2015) to ask whether behavioral differences in Accuracy and RT are driven by a more cautious responding strategy or by more efficient information processing – an important distinction for our theoretical account. We predicted that processing speech in noise would make participants less likely to shift before collecting sufficient information, leading to a lower proportion of shifts flagged as random in the EWMA, and a higher boundary separation estimate in the DDM, indicating a prioritization of accuracy over and above speed.

Method

Participants Participants were native, monolingual English-learning children ($n = 39$; 22 F, 17 M) and adults ($n = 31$; 22 F, 9 M). All participants had no reported history of developmental or language delay and normal vision. 14 participants (11 children, 3 adults) were run but not included in the analysis because either the eye tracker failed to calibrate or the participant did not complete the task.

Stimuli *Linguistic stimuli.* The video/audio stimuli were recorded in a sound-proof room and featured two female speakers who used natural child-directed speech and said one of two phrases: “Hey! Can you find the (target word)” or “Look! Where’s the (target word)” – see panel A of Fig 1. The target words were: ball, bunny, boat, bottle, cookie, juice, chicken, and shoe. The target words varied in length (shortest = 411.68 ms, longest = 779.62 ms) with an average length of 586.71 ms.

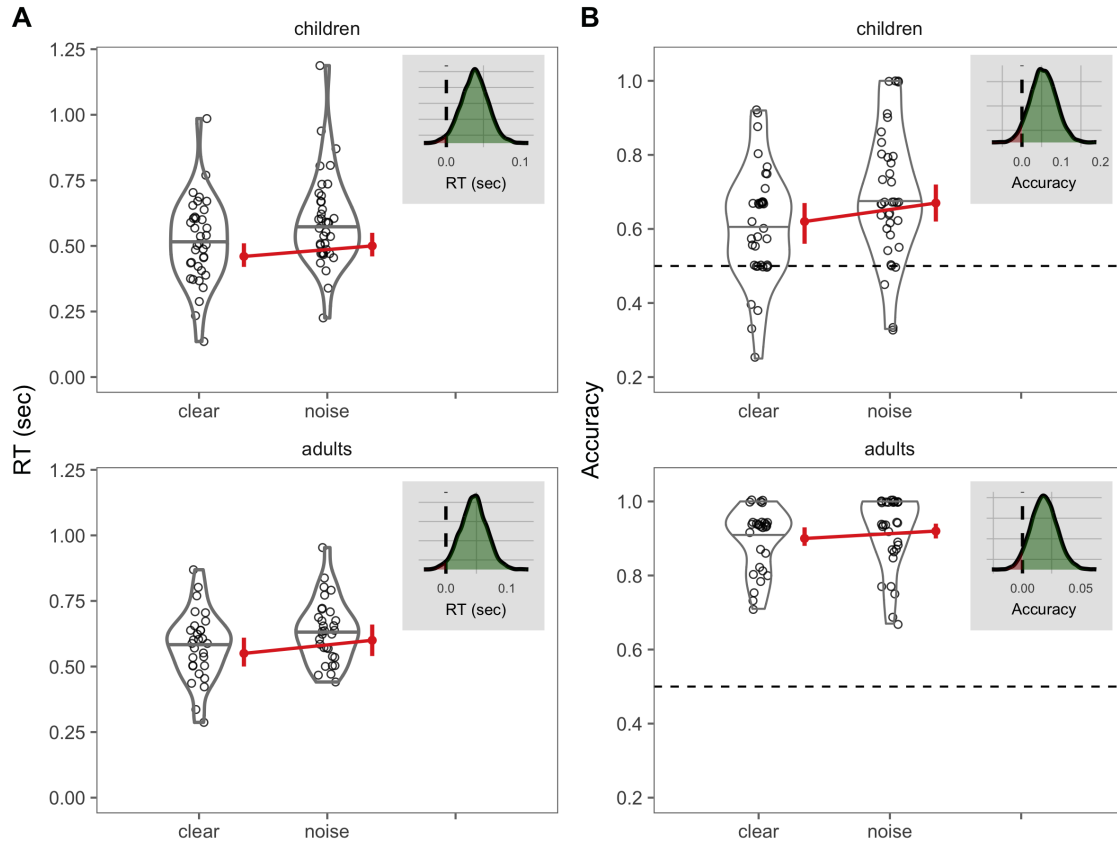


Figure 2: Behavioral results for first shift Reaction Time (RT) and Accuracy. Panel A shows violin plots representing the distribution of RTs for each participant in each condition. Each black point represents a participant. The dark red points represent the model estimate for the group mean with the error bars showing the 95% Highest Density Interval around that point estimate. The grey inset shows the full posterior distribution of the plausible RT differences across conditions with the vertical dashed line representing the null value of zero condition difference. The green shading represents estimates in the predicted direction and above the null value while the red shading represents estimates below the null. Panel B shows the same information but for Accuracy.

Noise manipulation. To create the stimuli in the noise condition, we convolved each recording with Brown noise using the Audacity audio editor. The average signal-to-noise ratio¹ in the noise condition was 2.87 dB compared to the clear condition, which was 35.05 dB.

Visual stimuli. The image set consisted of colorful digitized pictures of objects presented in fixed pairs with no phonological overlap between the target and the distractor image (cookie-bottle, boat-juice, bunny-chicken, shoe-ball). The side of the target picture was counterbalanced across trials.

Design and procedure Participants viewed the task on a screen while their gaze was tracked using an SMI RED corneal-reflection eye-tracker mounted on an LCD monitor, sampling at 60 Hz. The eye-tracker was first calibrated for each participant using a 6-point calibration. On each trial,

participants saw two images of familiar objects on the screen for two seconds before the center stimulus appeared (see Fig 1). Next, they processed the target sentence – which consisted of a carrier phrase, a target noun, and a question – followed by two seconds without language to allow for a response. Child participants saw 32 trials (16 noise trials; 16 clear trials) with several filler trials interspersed to maintain interest. Adult participants saw 64 trials (32 noise; 32 clear). The noise manipulation was presented in a blocked design with the order of block counterbalanced across participants.

Results and Discussion

Analysis plan First, we present behavioral analyses of First Shift Accuracy and Reaction Time (RT).² RT corresponds to the latency to shift away from the central stimulus to either picture measured from the onset of the target noun. (all RTs were analyzed in log space). Accuracy corresponds to

¹The ratio of signal power to the noise power, with values greater than 0 dB indicating more signal than noise.

²See <https://osf.io/g8h9r/> for a pre-registration of the analysis plan.

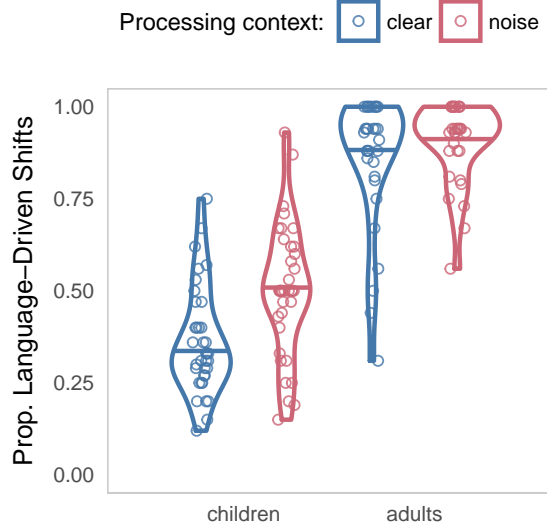


Figure 3: EWMA results for children and adults. Each point represents the proportion of shifts categorized as guessing for a single participant. The color of the violin plot represents the processing context: noise vs. clear.

whether participants' first gaze shift landed on the target or the distracter picture. We used the `rstanarm` (Gabry & Goodrich, 2016) package to fit Bayesian mixed-effects regression models. The mixed-effects approach allowed us to model the nested structure of our data – multiple trials for each participant and item, and a within-participants manipulation – by including random intercepts for each participant and item, and a random slope for each item and noise condition. We used Bayesian estimation to quantify uncertainty in our point estimates, which we communicate using a 95% Highest Density Interval (HDI). The HDI provides a range of credible values given the data and model. All analysis code can be found in the online repository for this project: <https://github.com/kemacdonald/speed-acc/R/analysis>.

Next, we present the two model-based analyses – the EWMA and DDM. The goal of these models is to move beyond a description of the data and map behavioral differences in eye movements to underlying psychological variables. The EWMA method models changes in random shifting behavior as a function of RT. For each participant, the model classifies the proportion of shifts that were likely to be language-driven as opposed to random responding, which we call the *guessing* parameter.

After fitting the EWMA, we took the shifts that were categorized as language-driven and fit a hierarchical Bayesian drift-diffusion model (HDDM). This model quantifies differences in separable parameters of the underlying decision process that lead to different patterns of behavior. The model assumes that people accumulate noisy evidence in favor of one alternative with a response generated when the evidence crosses a pre-defined decision threshold. Here, we focus on two parameters of interest: **boundary separation**, which in-

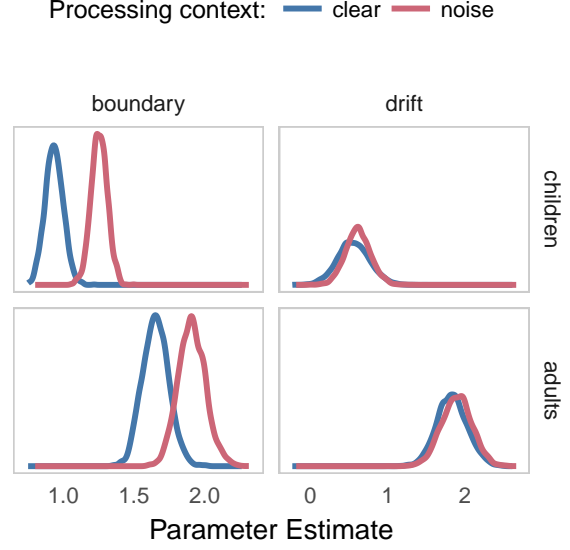


Figure 4: HDDM results. Each panel shows the posterior distribution for either the boundary separation or drift rate parameters for children (top panels) and adults (bottom panels).

dexes the amount of evidence gathered before generating a response (higher values suggest more cautious responding) and **drift rate**, which indexes the amount of evidence accumulated per unit time (higher values suggest more efficient processing).

Behavioral analyses RT. To make RTs more suitable for modeling on a linear scale, we analyzed responses in log space with the final model specified as: $\log(RT) \sim \text{noise_condition} + \text{age_group} + (\text{sub_id} + \text{noise_condition} | \text{item})$. Panel A of Figure 2 shows the full RT data distribution, the estimates of condition means, and the full posterior distribution of the estimated difference between the noise and clear conditions. Both children and adults were slower to identify the target in the noise condition (Children $M_{\text{noise}} = 0.5$ ms; Adult $M_{\text{noise}} = 0.6$ ms), as compared to the clear condition (Children $M_{\text{clear}} = 0.46$ ms; Adult $M_{\text{clear}} = 0.55$ ms). RTs in the noise condition were 41.73 ms slower on average, with a 95% HDI from 1.19 ms to 82.26 ms that did not include the null value of zero condition difference.

Accuracy. Next, we modeled adults' and children's first shift accuracy using a mixed-effects logistic regression with the same specifications (see Panel B of Fig 2). Both groups were more accurate than a model of random responding (null value of 0.5 falling well outside the lower bound of the 95% HDI for all group means). Adults were more accurate ($M_{\text{adults}} = 90\%$) than children ($M_{\text{children}} = 62\%$). The key result is that both groups showed evidence of higher accuracy in the noise condition (Children $M_{\text{noise}} = 67\%$; Adult $M_{\text{noise}} = 92\%$) as compared to the clear condition (Children $M_{\text{clear}} = 62\%$; Adult $M_{\text{clear}} = 90\%$). Accuracy in the noise condition was 4% higher on average, with a 95% HDI from 0% to 11%. Note that the null value of zero difference falls at the very

edge of the 95% HDI such that 95% of the credible values fall below the null, providing evidence for higher accuracy in the noise condition.

Model-based analyses EWMA. Figure 3 shows the proportion of shifts that the model classified as random vs. language-driven for each age group and processing context. Critically, processing speech in noise caused both adults and children to produce a higher proportion of language-driven shifts with the 95% HDI excluding the null value (see Table 1). This pattern suggests that the noise condition led participants to increase visual fixations to the language source, leading them to generate fewer exploratory, random shifts before accumulating sufficient information to respond accurately.

HDDM. Figure 4 shows the full posterior distributions for the HDDM output. Children had lower drift rates and boundary separation estimates as compared to adults, suggesting that children were less efficient and less cautious in their responding (see also Table 2). Interestingly, the noise manipulation only affected the boundary separation parameter, with higher estimates in the noise condition for both age groups. This result suggests that participants’ in the noise condition prioritized information accumulation over speed when generating an eye movement in response to the incoming language. This increased decision threshold led to higher accuracy. Moreover, the high overlap in estimates of drift rate suggests that participants were able to integrate the visual and auditory signals such that they could achieve a level of processing efficiency comparable to the clear processing context.

Together, the behavioral and EWMA/HDDM results provide converging support for the predictions of our information-seeking account. In summary, processing speech in noise caused listeners to seek additional visual information to support language comprehension. Moreover, we observed a strikingly similar pattern of behavior in children and adults, with both groups producing more language-driven shifts and prioritizing accuracy over speed in the more challenging, noisy context. These data have interesting parallels to recent work from McMurray et al. (2017), showing that adults with Cochlear Implants, who consistently process degraded auditory input, will delay lexical access and wait until substantial information has accumulated. This process is in contrast to the “immediate competition” model of word recognition where listeners activate candidate meanings from word onset.

General Discussion

Language comprehension in grounded contexts involves integrating the visual and linguistic signals. But the value of gathering visual information can vary depending on features of the processing context. Here, we presented a strong test of an information-seeking account of eye movements during language processing – an account that we first proposed in K. MacDonald et al. (2017) to explain population-level differences in the dynamics of gaze between children learning ASL and children learning spoken English. Here, we showed that

Parameter	Contrast	Estimate (95% HDI)
Cut point	age group	0.21 [0.18, 0.24]
Cut point	noise	0.04 [0.01, 0.06]
Guessing	adults-children	0.46 [0.43, 0.49]
Guessing	noise-clear	0.12 [0.07, 0.17]

Table 1: EWMA results for E1 and E2. The guessing parameter refers to the proportion of gaze shifts classified as random vs. language-driven with higher values indicating more random responding. Estimate refers to the difference between condition or age group.

Parameter	Condition	Age Group	Estimate [95% HDI]
boundary	clear	adults	1.68 [1.5, 1.87]
boundary	clear	children	0.96 [0.84, 1.09]
boundary	noise	adults	1.65 [1.48, 1.83]
boundary	noise	children	1.23 [1.12, 1.34]
drift	clear	adults	1.86 [1.48, 2.25]
drift	clear	children	0.58 [0.17, 0.99]
drift	noise	adults	1.94 [1.56, 2.33]
drift	noise	children	0.59 [0.27, 0.93]

Table 2: HDDM parameter estimates for each age group and noise condition. The drift rate parameter indexes processing efficiency and the boundary separation parameter indexes participants’ information accumulation threshold.

children and adults adapt to processing speech in noise by producing slower but more accurate gaze shifts away from a speaker. Both groups also showed evidence of prioritizing information accumulation over speed (HDDM) while producing more language driven shifts (EWMA). It is interesting that listeners were able to achieve higher accuracy in the more challenging, noisy context. Together, the behavioral and modeling results suggest that when the linguistic signal is degraded, listeners adapt their eye movements to seek language-relevant information in the visual world.

These results bring together ideas from several research programs. First, work on language-mediated visual attention shows that adults and children rapidly shift gaze upon hearing the name of an object in the visual scene (Allopenna, Magnuson, & Tanenhaus, 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). The speed and consistency of this response has led to debates about whether language-mediated gaze shifts are automatic as opposed to under the control of the listener. While we do claim that listeners in our task have explicit access to the underlying decision process, our findings show that the dynamics of gaze during lexical access adapt to the information features of the context. This finding parallels recent work by McMurray et al. (2017), showing that adults with Cochlear Implants, who consistently process degraded auditory input, will delay the process of lexical access, waiting to begin until substantial information has accumulated.

Second, empirical work on vision during natural tasks

shows that people overwhelmingly prefer to look at *goal-relevant* locations – e.g., an upcoming obstacle while walking (Hayhoe & Ballard, 2005). These accounts inspired our prediction that gaze dynamics during language comprehension should adapt to the value of different fixation behaviors with respect to the listener’s goal of rapid language processing. And third, work on effortful listening shows that listeners generate compensatory responses (e.g., increases in attention and working memory) within “challenging” comprehension contexts such as processing noisy or accented speech (Van Engen & Peelle, 2014). These accounts predict that our young listeners might compensate for the reduced quality of the auditory signal by allocating gathering additional visual information.

This work has several important limitations that we hope will pave the way for future work. Here, we chose to focus on a single decision about visual fixation to provide a window onto the underlying dynamics of decision-making across different processing contexts. However, the decision to shift away from a language is just one of the many decisions that listeners make while processing language in real-time. Moreover, our micro-level analysis does not consider the rich gaze patterns that occur before this decision. In our future work, we aim to quantify changes in the dynamics of gaze across the full sentence processing context. Finally, we used a simple visual world, with only three places to look, and very simple linguistic stimuli, especially for the adults. Thus it remains an open question how these results might scale up to more complex language information and visual environments.

We designed this experiment as a strong test our information-maximization proposal in the domain of familiar language comprehension. However, we think that the account is more general. And we are interested in applying this framework – the in-depth analysis of decisions about visual fixation – to the language acquisition context. Consider that early in language learning children are acquiring novel word-object links while also learning about visual object categories. Both of these tasks produce goals that should in turn modulate children’s decisions about where to allocate visual attention, e.g., seeking nonlinguistic cues to reference such as eye gaze and pointing become critical when you are unfamiliar with the information in the linguistic signal. More generally, we think that these results contribute to a recent theoretical emphasis on including goal-based accounts of eye movements during language comprehension (Salverda, Brown, & Tanenhaus, 2011). We hope that our approach presents a way forward for explaining fixation behaviors across a wider variety of populations, processing contexts, and during different stages of language learning.

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