Linear (not logarithmic) effects of lexical predictability:

A challenge to surprisal theory

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Introduction

While it is clear that unpredictable linguistic content incurs processing costs, different models of sentence comprehension predict different *linking functions* relating context-based word probabilities and processing difficulty.

Surprisal Theory (Levy, 2008) and **Bayesian Reader** (Norris, 2009) predict a *logarithmic* relationship, with low probability words incurring additional processing costs

Proportional pre-activation accounts predict a *linear* relationship between probability and RTs, assuming 1) finite pre-activation and 2) behavioral facilitation proportional to the strength/degree of activation across features

To test these models we developed 216 sentence triplets which manipulated the semantic predictability of a single critical word

High cloze: 90% ± 0.4%, range: 100% - 60%
Mod. cloze: 20% ± 0.6%, range: 50% - 7%
Low cloze: 1% ± 0.1%, range: 0% - 5%

H: *For Halloween, they were carving a large **pumpkin** at the farmer's market.*

M: *For the pie, they bought a large **pumpkin** at the farmer's market.*

L: *Before the party, they bought a large **pumpkin** at the farmer's market.*

Methods

Sentence Norming: Word probabilities were calculated using an offline sentence completion task (Mechanical Turk, 58,000 observations)

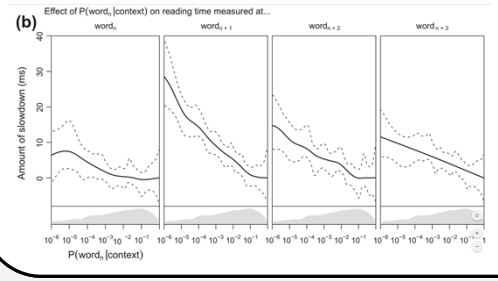
Experiment 1: Self-paced Reading (N = 216) Participants read sentences (self-paced moving window) and answered comprehension questions. RTs were analyzed for a three-word critical region.

Exp 2: Cross-modal picture naming (N = 36) Participants heard sentence contexts and named pictures corresponding to the CW, appearing 250ms after sentence offset.

Exp 3. ERP Study (N = 19) – Participants read sentences (self-paced RSVP) as EEG was recorded from the scalp. The amplitude of the N400 was measured, 300-500ms after CW onset

Eye-tracking meta-analysis: A meta-analysis of prior ET studies with factorial cloze manipulations with 3+ levels (8 studies, N = 223)

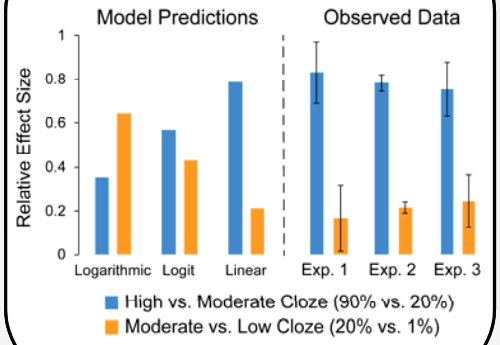
Smith & Levy, 2013



Limitations

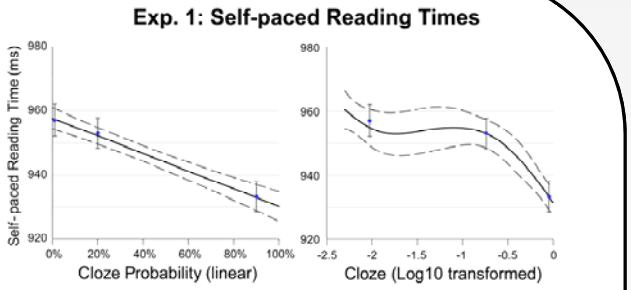
1) Relative to cloze probability, corpus-based probabilities like trigram are poor predictors of human reading times (Smith & Levy, 2011)
2) Trigram probabilities are highly correlated with unigram frequency (r = 0.75)
3) The relationship between trigram and subjective probabilities may *itself* be non-linear
4) Probability is not experimentally manipulated in corpus studies, leaving the possibility of bias or confounds due to uncontrolled lexical variables

Summary of Results



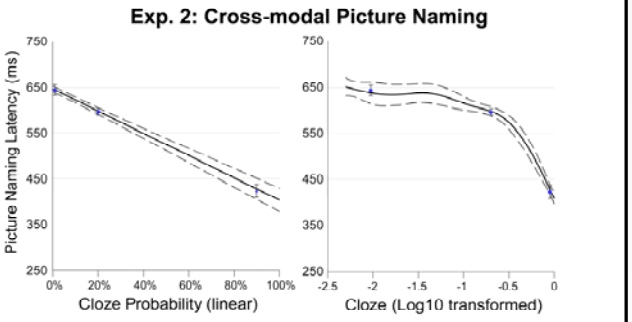
Experiment 1

a _____ _____
_ large _____
_ _____ pumpkin

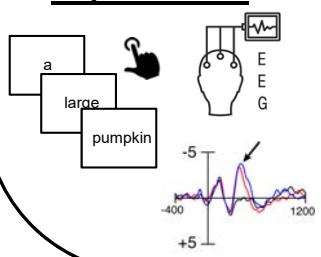


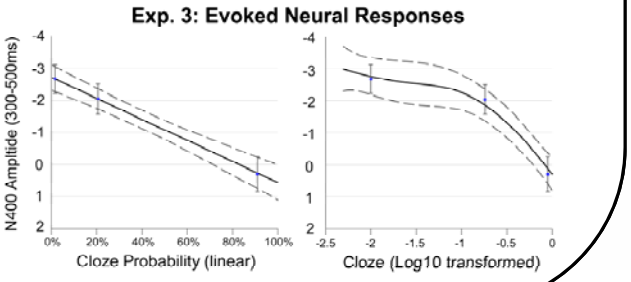
Experiment 2

carving a large…



Experiment 3





Behavioral and ERP Results

- Across all three experiments, we saw a robust linear relationship between word probability and processing difficulty.
- Log-transformed cloze resulted in significant reductions in model fit, and produced non-linear GAM fits (mgcv)
- The pattern of effects (90% vs. 20% > 20% vs. 1%) was exactly opposite the predictions of surprisal/Bayesian Reader
- In Experiment 2, at the single-trial level, behavioral responses for *all* 36 participants were better fit by a linear function (mean r = -.435) than a logarithmic function (mean r = -.399, $p < .001$).
- These findings are incompatible with the two main claims of surprisal theory: 1) that RTs covary with -log(prob|context), and 2) lexical probabilities can provide a unitary "causal bottleneck" for explaining all forms of comprehension difficulty

Frequently Asked Questions

Q: *Isn't cloze bad at estimating probabilities below 1%?*
A: We may have overestimated the probability of some very low-cloze items (by replacing values of 0% with 0.5%). But if so, a log function would provide even worse empirical fit to the data

Q: *Can corpus-based probabilities account for additional variance in the very low end of the probability scale?*
A: No, BNC trigram/LSTM probabilities (log or linear) accounted for no additional variance above and beyond the effects of cloze

Q: *Is natural language actually this predictable?*
A: Yes. The mean cloze of words in connected texts is ~18% with the vast majority of words falling within the 1%-100% cloze range (Luke & Christianson, 2015).

Q: *Should I log-transform my probability measures?*
A: No. There is no compelling experimental data supporting a logarithmic linking function between word probability and RTs