Dual-Route Model in Auditory Word Recognition

by Hanno Müller, Louis ten Bosch, Mirjam Ernestus

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Models of Word Recognition

/aʊls/

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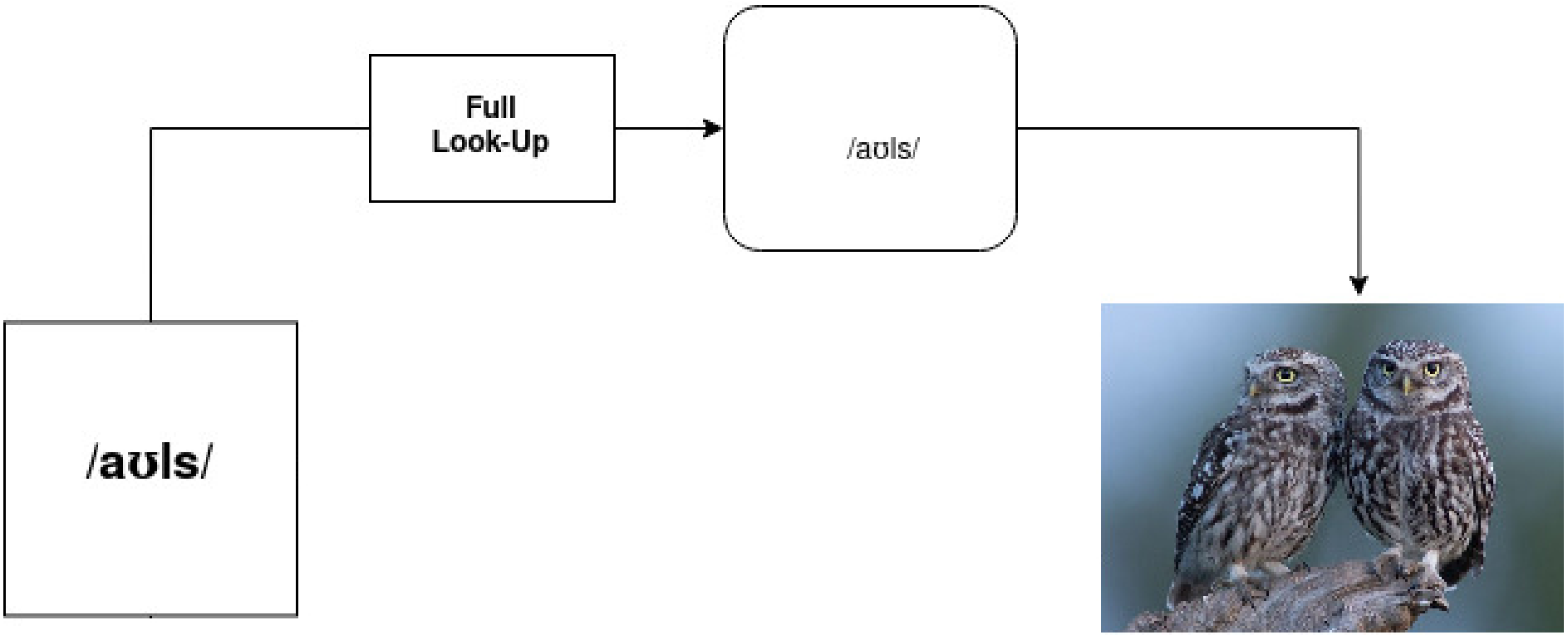

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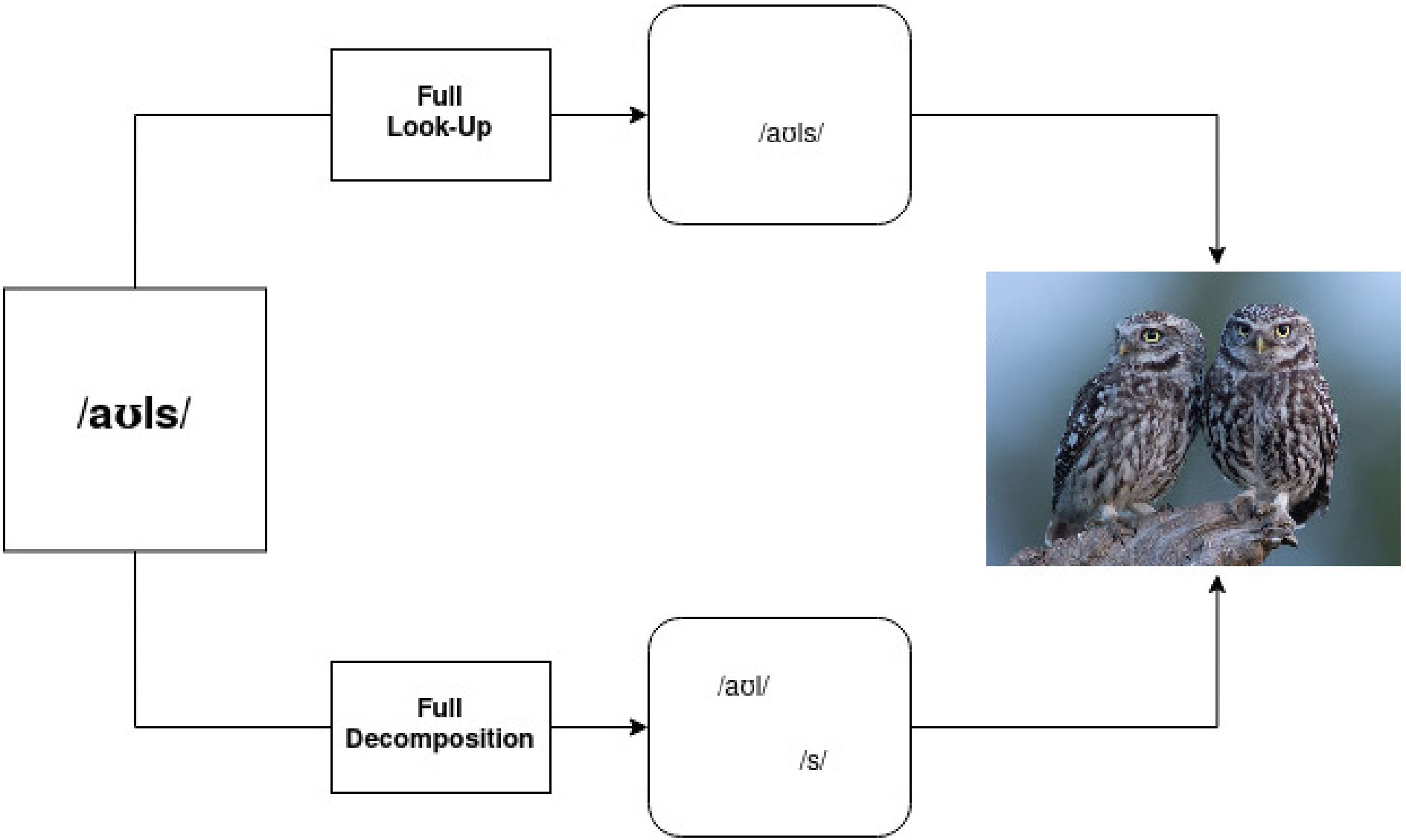

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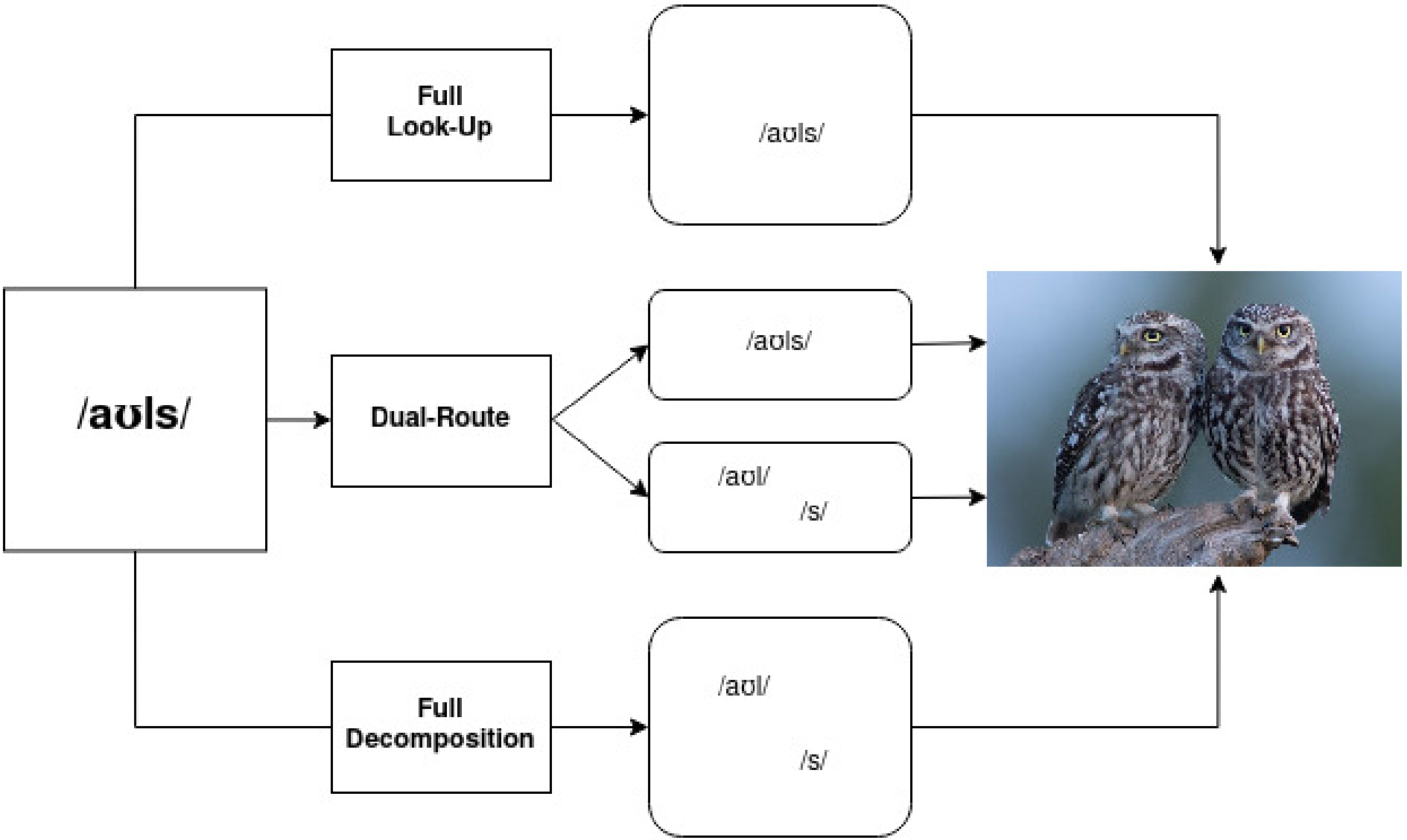

Related Work - Written Language

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  - ➔ Especially good in explaining word frequency effect
- But there is also evidence for morphological decomposition, e.g. in Dutch (Baayen et al., 2003, 2007) and Italian (Baayen, Burani, & Schreuder, 1997)
- Decomposition successfully account for by dual-route models (Schreuder & Baayen, 1995; Baayen, Dijkstra, & Schreuder, 1997)

Related Work - Speech

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- Models are mostly full look-up throughout decades: Cohort-model (Marslen-Wilson & Welsh, 1978), Trace (Elman & McClelland, 1985), Shortlist (Norris, 1994), SpeM (Scharenborg et al., 2003), Shortlist B (Norris & McQueen, 2008), DIANA (ten Bosch et al., 2015, 2017)

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➔ Should models of auditory word recognition incorporate a decomposition route?

Visual vs. Auditory

Visual	Auditory

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Research Questions

- Is it possible to transfer the visual domain dual-route model (henceforth 1997-model) (Schreuder & Baayen, 1995; Baayen, Dijkstra, & Schreuder, 1997) to the auditory domain?

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- Which adaptations are necessary to improve the models performance for more natural stimuli?
- Is the assumption tenable that whichever route - look-up or decomposition - is fastest, determines the response time?

Methods

- Prediction of response times in BALDEY (Ernestus & Cutler, 2015)

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- BALDEY is an auditory lexical decision database entailing Dutch simplex and morphologically complex words
- Subset: 172 nouns (either singular or plural) forming their plural using the scheme *stem* + *-en*
  ➔ 2663 observations

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   decomposition: stem frequency e.g., $freq_{owl}$ + parsing penalty Δp
3. Whichever route first leads to recognition of word, determines the RT

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- 1997-model dual-route mixed effects model:
  - ➔ Taking into account random effects
    - without assumption that fastest route determines the response time

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$$RTprev + wordDuration + trialNumber +$$
$$(1|subject) + (1|word)$$

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owls	1	0
humans	1	0
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➔ **Which nouns are decomposed and which not?**

- There are 2^n configurations, where n = number of plurals
  - For 1684 plurals, there are $8.6 * 10^{506}$ distinct configurations
- Not feasible ➔ Search algorithm

Search Algorithm - Concept

- Aim: Find the optimal configuration

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- Aim: Find the optimal configuration
- Solution:
  - Ascribe plurals to decomposition route systematically
  - Fit dual-route mixed effects model to every configuration
  - The better the fit (AIC), the greater the likelihood of the model
  - Return the configuration that results in the best fit

Search Algorithm I

1. Fit full look-up model

word	DCMP	LKP
cats	0	1
cakes	0	1
owls	0	1
humans	0	1
ideas	0	1

Search Algorithm I

1. Fit full look-up model
2. Calculate and store average squared residuals for each word

word	DCMP	LKP	$(\overline{resid})^2$
cats	0	1	0.4
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Search Algorithm I

1. Fit full look-up model
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3. Calculate and store AIC

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→ AIC = -952

Search Algorithm II

For $plural_i$ in $1 : N_{plurals}$

1. Ascribe plurals with average $(\overline{resid})^2$ greater than or equal average $(\overline{resid})^2$ of $plural_i$ to decomposition route

i	word	DCMP	LKP	$(\overline{resid})^2$
cats	0	1	0.4	
cakes	0	1	0.1	
owls	0	1	0.2	
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For $plural_i$ in $1 : N_{plurals}$

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i	word	DCMP	LKP	$(\overline{resid})^2$
→	cats	**1**	**0**	0.4
	cakes	0	1	0.1
	owls	0	1	0.2
	humans	0	1	0.3
	ideas	**1**	**0**	0.4

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	ideas	**1**	**0**	0.4

→ AIC = -948

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	humans	**1**	**0**	0.3
	ideas	**1**	**0**	0.4

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i	word	DCMP	LKP	$(\overline{resid})^2$
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	cakes	0	1	0.1
	owls	0	1	0.2
→	humans	**1**	**0**	0.3
	ideas	**1**	**0**	0.4

→ AIC = -962

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	cakes	0	1	0.1
	owls	0	1	0.2
	human	0	1	0.3
→	ideas	**1**	**0**	0.4

→ AIC = -950

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➔ AIC = -962

Search Algorithm III

- The model with the lowest AIC score is returned
- (if the predicted RTs of plurals are shorter than in a full look-up model)
  - ➔ assumption that the fastest route wins

word	DCMP	LKP	$(\overline{resid})^2$
cats	1	0	0.4
cakes	0	1	0.1
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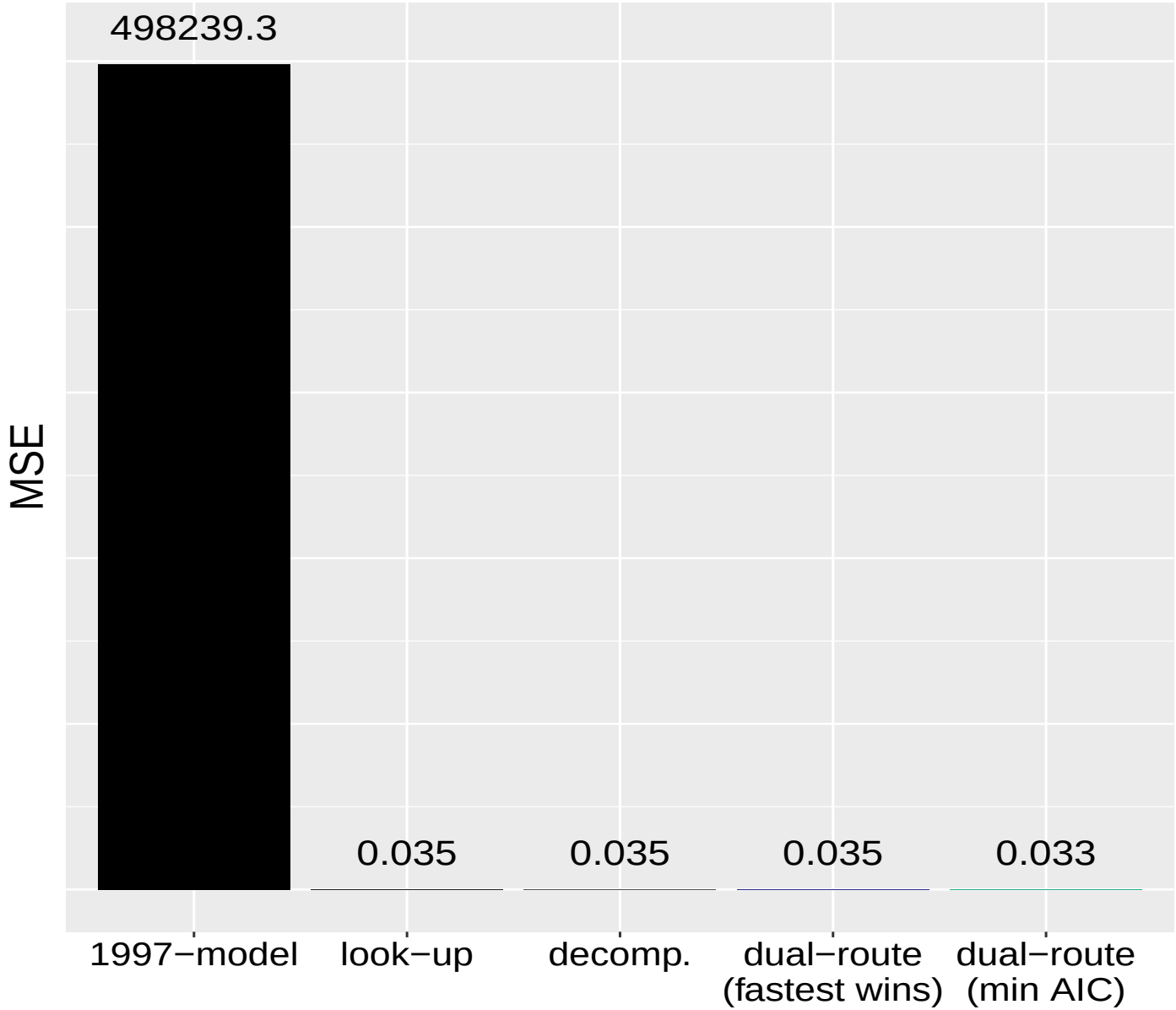
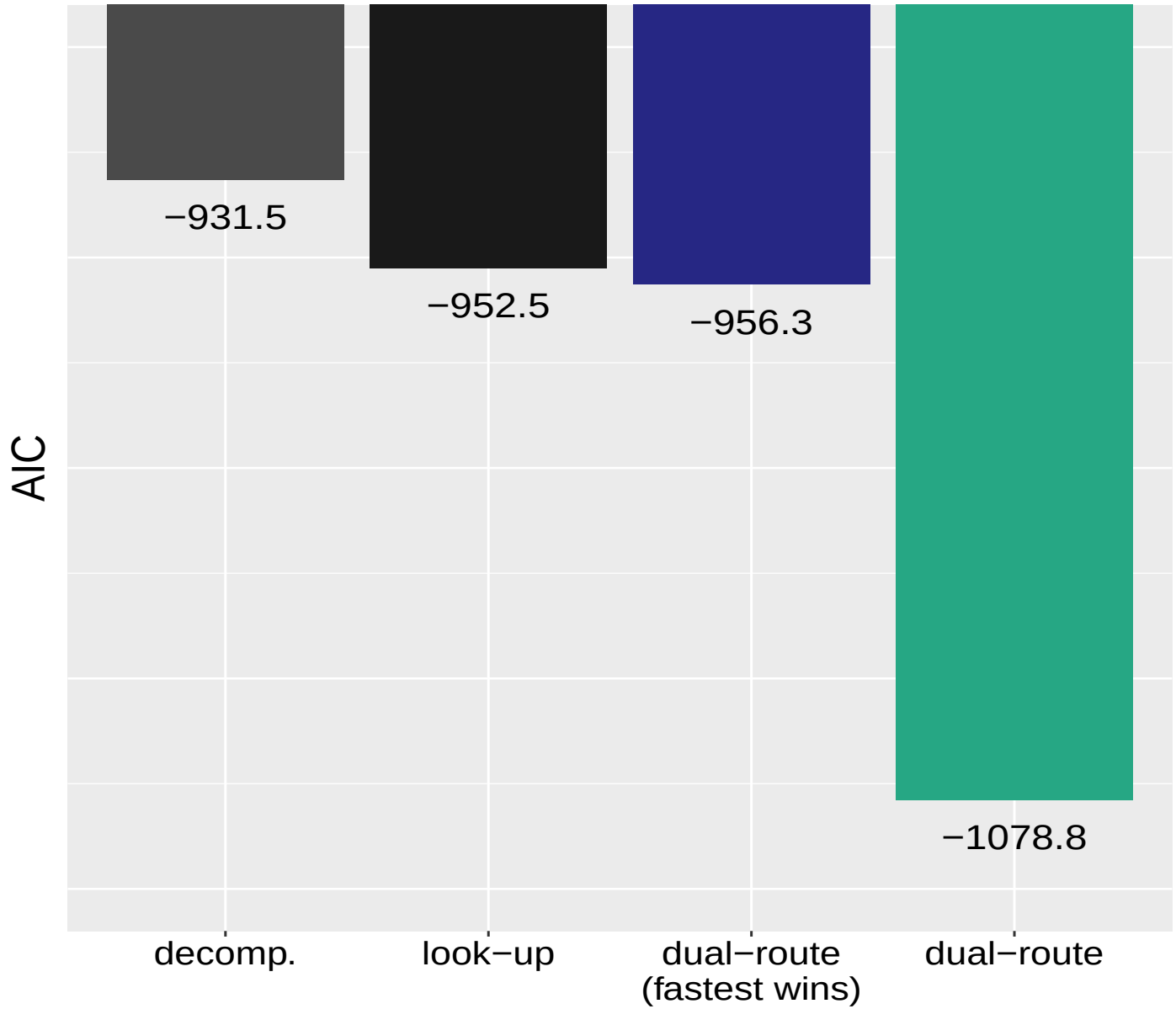
Model - MSE


498239.3
0.035
0.035
0.035
0.033
MSE
1997−model
look−up
decomp.
dual−route (fastest wins)
dual−route (min AIC)

Model - AIC


AIC
−931.5
−952.5
−956.3
−1078.8
decomp.
look−up
dual−route
(fastest wins)
dual−route

Results Visual vs. Audio

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    ➔ conflict between stem and suffix preferences

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- stem recognition achieved before suffix onset
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  auditory:

  - stem recognition achieved before suffix onset
  - stem's vowel duration points to presence of following syllable (Kemps et al., 2005) which might facilitate parsing
    ➔ no conflict and more information available

- Percentage decomposed words: 6% (audio) vs. 7% (visual)

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➔ Models of human word recognition should integrate a decomposition mechanism

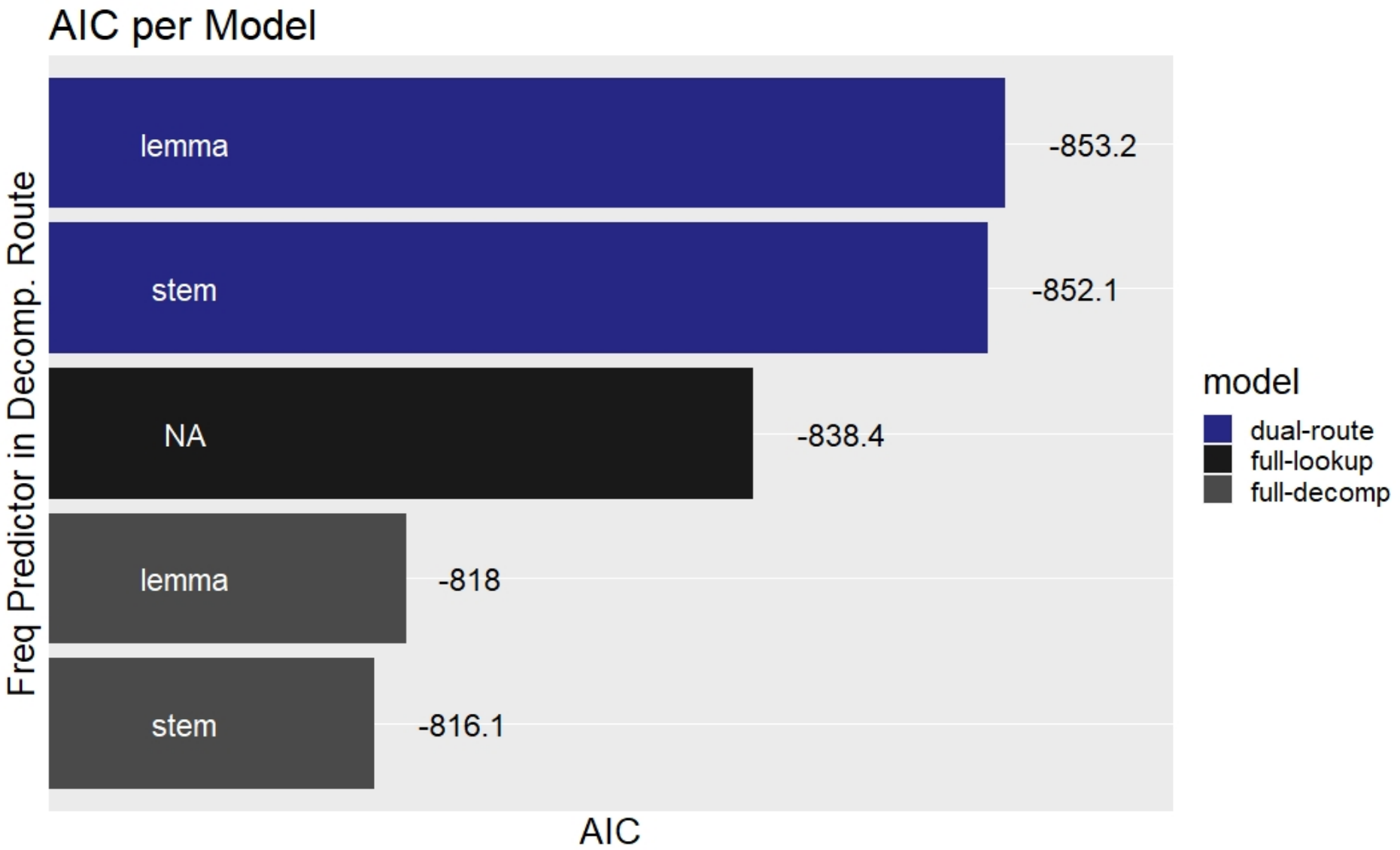
Appendix

Model - Summary

Fixed Effects	Estimate	Estimate ms	Std. Error	t-value
Intercept	6.9835346	1079	0.0289374	241.333
duration	0.1871347	222	0.0277632	6.740
RTprev	0.2712476	336	0.0183252	14.802
freqFORM:LKP	-0.0006865	-1	0.0013885	-0.494
freqLEM:DCMP	0.0061901	7	0.0165784	0.373
penalty:DCMP	0.1959866	236	0.0704964	2.780

Table: Fixed effects of final model.

Model - AIC


AIC per Model
Freq Predictor in Decomp. Route
lemma
stem
NA
lemma
stem
-853.2
-852.1
-838.4
-818
-816.1
AIC
model
dual-route
full-lookup
full-decomp

Model - Interpretation

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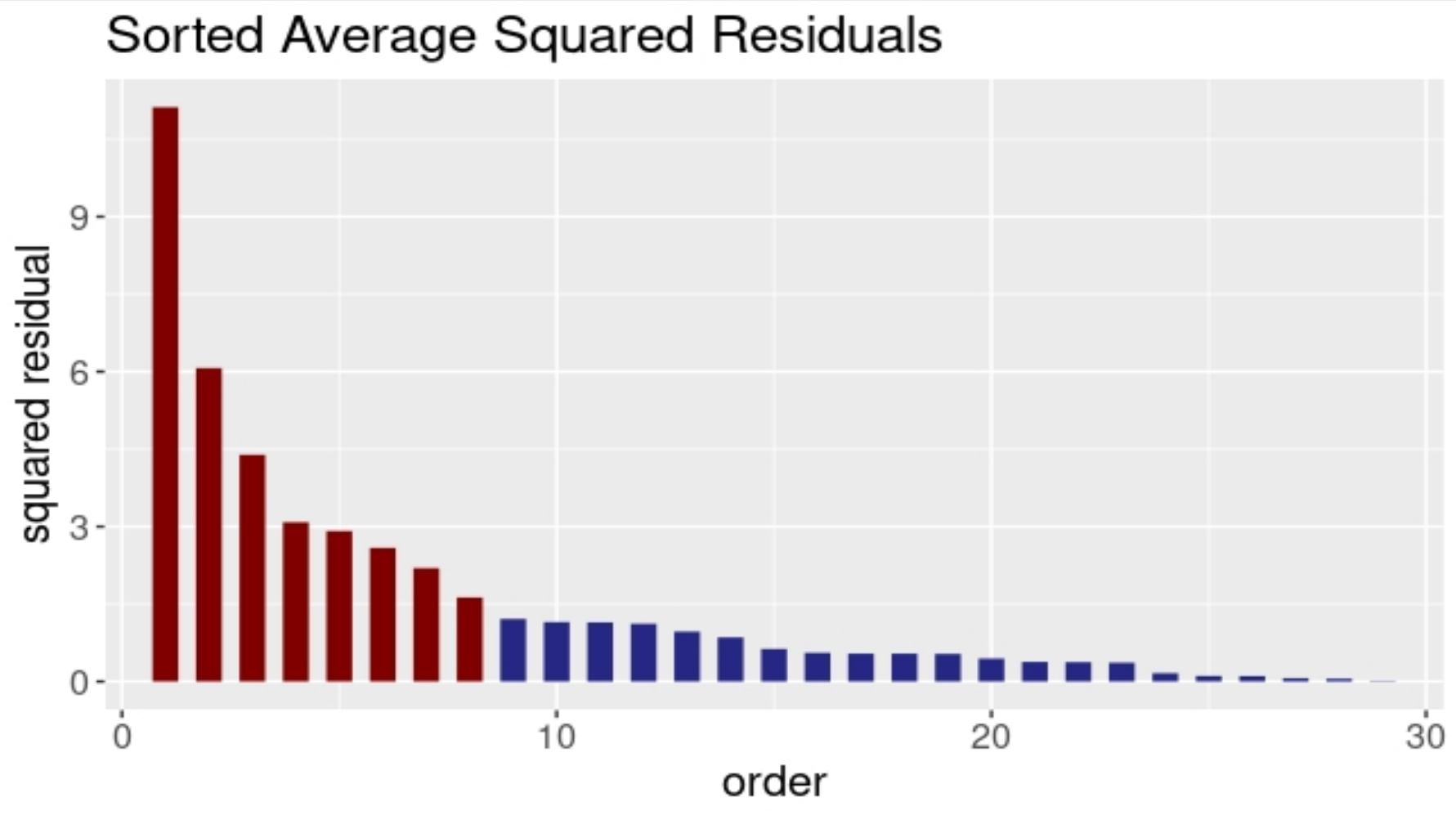
Search algorithm based on erroneous assumption



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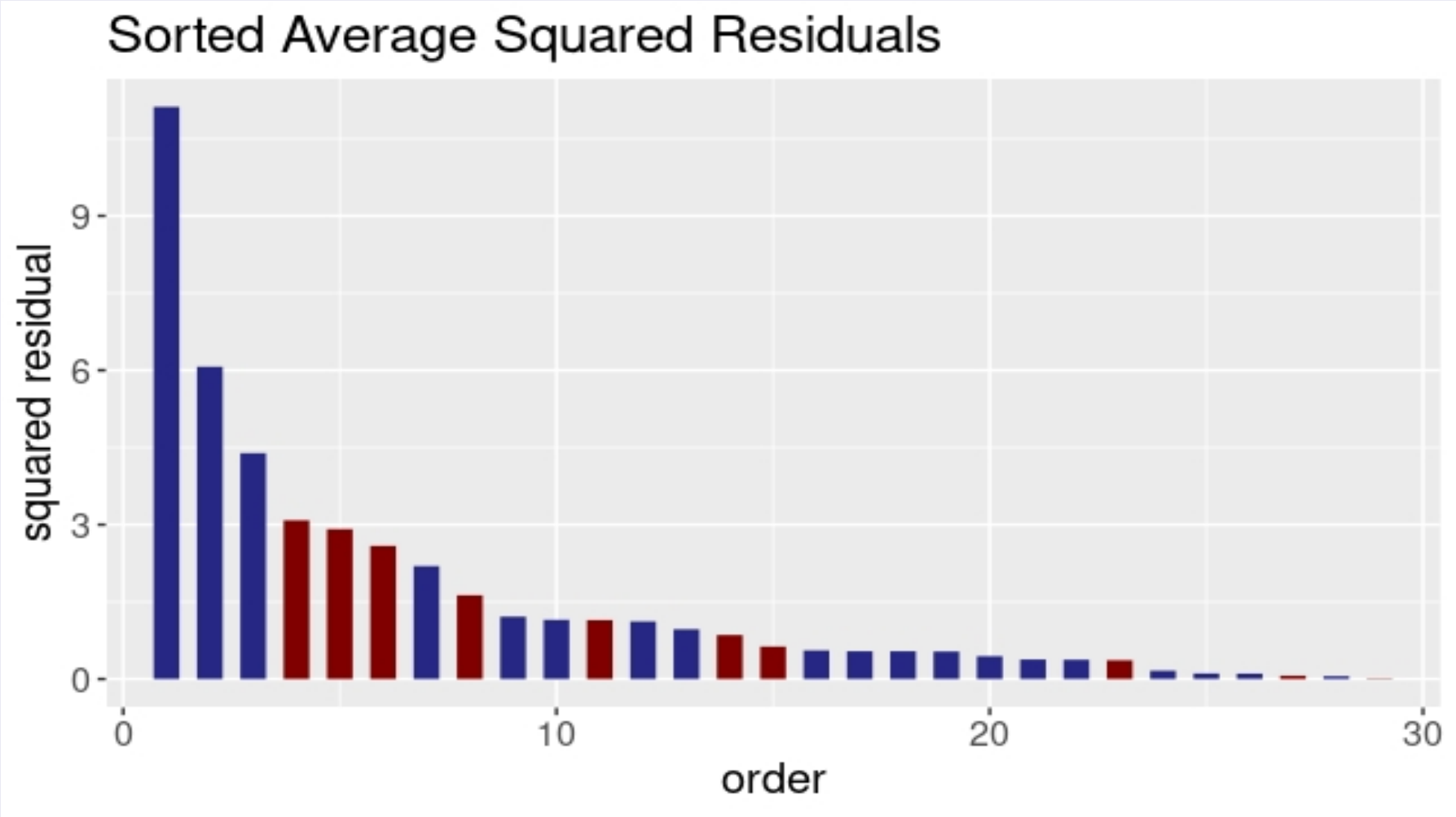

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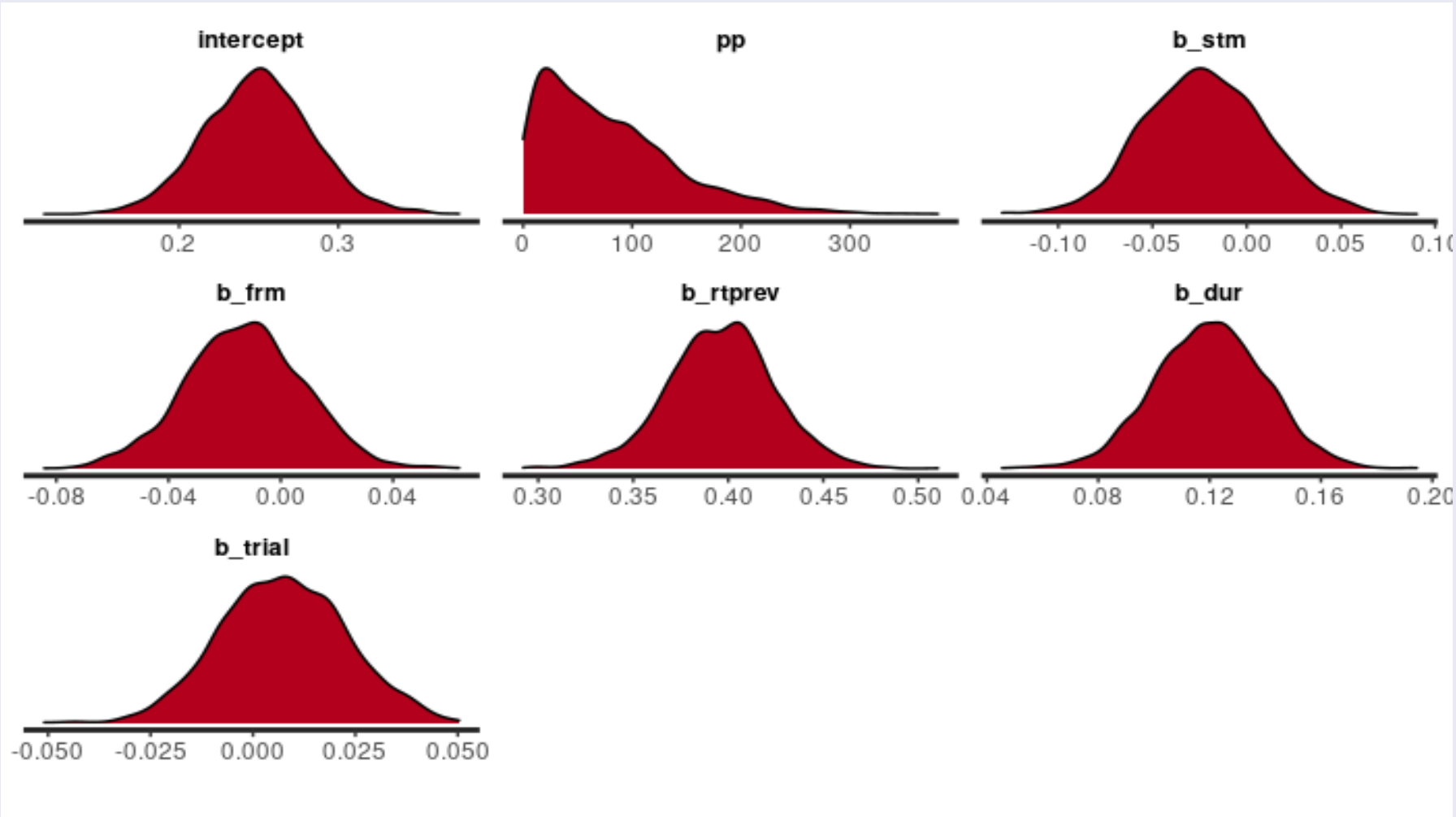
Search algorithm based on erroneous assumption



Model - Interpretation

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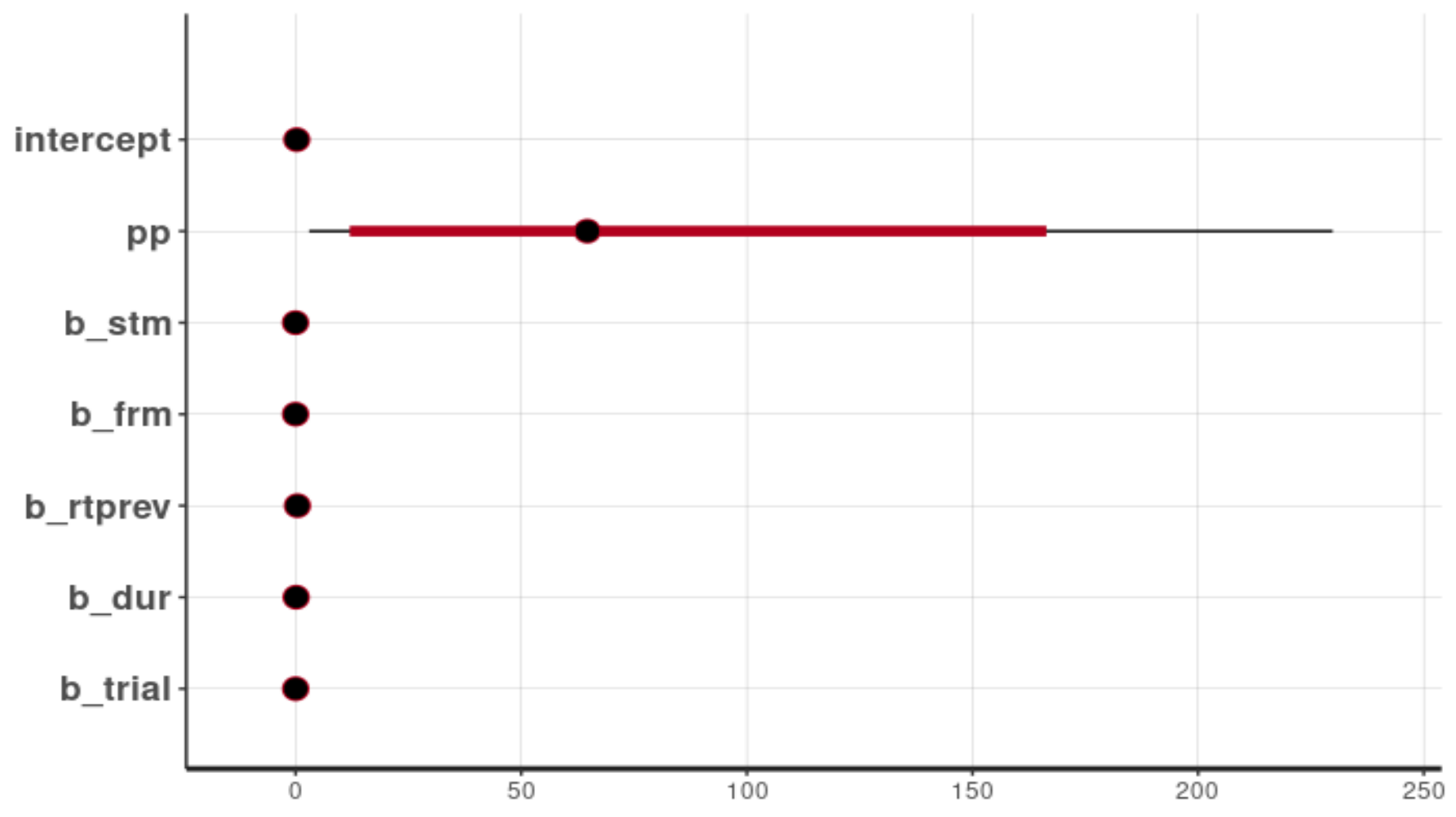

Model - Interpretation

Why does assumption that fastest route determines RT not hold?

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- Decomposed words probably not ordered along residuals
- Solutions are technical challenging

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Effect of not included variables

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- Words processed via decomposition route may share certain properties

Model - Interpretation

Why does assumption that fastest route determines RT not hold?

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- Decomposed words probably not ordered along residuals
- Solutions are technical challenging

Effect of not included variables

- Words processed via decomposition route may share certain properties
- e.g. high lexical neighborhood density might lead to higher RT

Baayen, R. H., Burani, C., & Schreuder, R. (1997). Effects of semantic markedness in the processing of regular nominal singulars and plurals in Italian. In *Yearbook of morphology 1996* (pp. 13–33). Springer.

Baayen, R. H., Dijkstra, T., & Schreuder, R. (1997). Singulars and plurals in Dutch: Evidence for a parallel dual-route model. *Journal of Memory and Language*, *37*(1), 94–117.

Baayen, R. H., McQueen, J. M., Dijkstra, T., & Schreuder, R. (2003). Dutch inflectional morphology. frequency effects in regular inflectional morphology> revisiting dutch plurals. *Morphological structure in language processing*, *151*, 355.

Baayen, R. H., Wurm, L. H., & Aycock, J. (2007). Lexical dynamics for low-frequency complex words: A regression study across tasks and modalities. *The mental lexicon*, *2*(3), 419–463.

Elman, J. L., & McClelland, J. L. (1985). An architecture for parallel processing in speech recognition: The trace model. *Speech recognition*, 6–35.

Ernestus, M., & Cutler, A. (2015). Baldey: A database of auditory lexical decisions. *Quarterly Journal of Experimental Psychology*, *68*(8), 1469–1488.

Kemps, R. J., Ernestus, M., Schreuder, R., & Baayen, R. H. (2005). Prosodic cues for morphological complexity: The case of dutch plural nouns. *Memory & cognition*, *33*(3), 430–446.

Marslen-Wilson, W. D., & Welsh, A. (1978). Processing interactions and lexical access during word recognition in continuous speech. *Cognitive psychology*, *10*(1), 29–63.

Morton, J. (1969). Interaction of information in word recognition. *Psychological review*, *76*(2), 165.

Norris, D. (1994). Shortlist: A connectionist model of continuous speech recognition. *Cognition*, *52*(3), 189–234.

Norris, D. (2006). The bayesian reader: explaining word recognition as an optimal bayesian decision process. *Psychological review*, *113*(2), 327.

Norris, D., & McQueen, J. M. (2008). Shortlist b: a bayesian model of continuous speech recognition. *Psychological review*, *115*(2), 357.

Scharenborg, O., McQueen, J. M., Bosch, L. t., & Norris, D. (2003). Modelling human speech recognition using automatic speech recognition paradigms in spem. In *Eighth european conference on speech communication and technology.*

Schreuder, R., & Baayen, R. H. (1995). Modeling morphological processing. *Morphological aspects of language processing*, *2*, 257–294.

Sibley, D. E., Kello, C. T., Plaut, D. C., & Elman, J. L. (2008). Large-scale modeling of wordform learning and representation. *Cognitive Science*, *32*(4), 741–754.

ten Bosch, L., Boves, L., & Ernestus, M. (2015). Diana, an end-to-end computational model of human word comprehension. In *Interspeech 2015.* Glasgow: University of Glasgow.

ten Bosch, L., Boves, L., & Ernestus, M. (2017). Diana, a computational model of human word comprehension. In *the workshop conversational speech and lexical representations.*

Wurm, L. H. (1997). Auditory processing of prefixed english words is both continuous and decompositional. *Journal of memory and language*, *37*(3), 438–461.

Wurm, L. H., & Aycock, J. (2003). Recognition of spoken prefixed words: The role of. *Morphological structure in language processing*, *151*, 259.

Wurm, L. H., Ernestus, M. T., Schreuder, R., & Baayen, R. H. (2006). Dynamics of the auditory comprehension of prefixed words: Cohort entropies and conditional root uniqueness points. *The Mental Lexicon*, *1*(1), 125–146.

Wurm, L. H., & Ross, S. E. (2001). Conditional root uniqueness points: Psychological validity and perceptual consequences. *Journal of Memory and Language*, *45*(1), 39–57.