Toward an Integrated Model of Sentence Processing in Reading

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Introduction

Time Out
- Exercise

Reanalysis
- Exercise

Underspecification

Extension

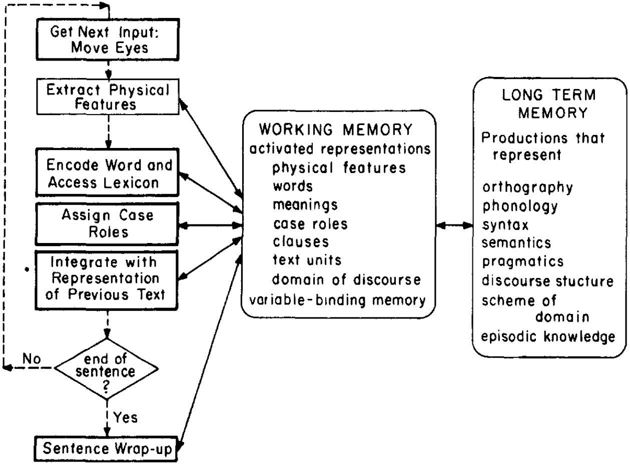
Conclusion

The eye-mind assumption

"The eye-mind assumption posits that there is no appreciable lag between what is being fixated and what is being processed."

(Just & Carpenter, 1980, p. 331)

The eye-mind assumption

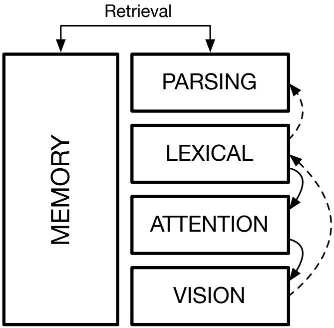


(Just & Carpenter, 1980, Fig. 1)

What is the link between processing and eye movement behaviour?

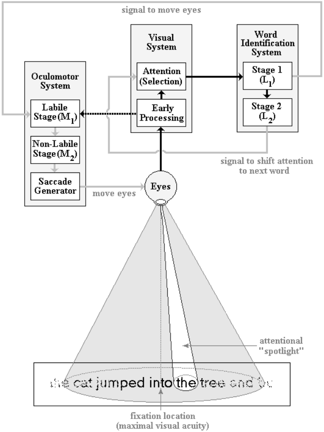
PROCESS $\times$ **?** $\rightarrow$ **FIXATIONS**

task demands
individual differences
adaptive processing



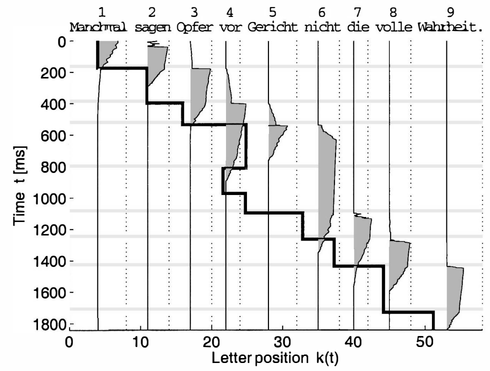
Eye movement control

E-Z Reader



(Reichle et al., 2003, Fig. 3)

SWIFT



(Engbert et al., 2005, Fig. 7)

PROCESS × **?** → **FIXATIONS**

task demands
individual differences
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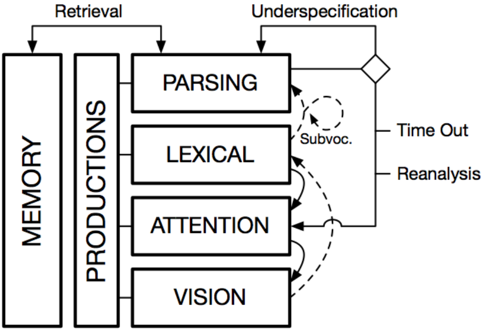


ACT-R
An Integrated Theory of the Mind (Anderson et al., 2004)

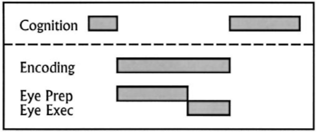
LV05
An activation-based model of sentence processing as skilled memory retrieval (Lewis & Vasishth, 2005)

EMMA
An integrated model of eye movements and visual encoding (Salvucci, 2001)

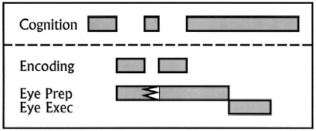
EMMA

Salvucci (2001)

Normal progression:



Skipping:



Encoding time:

$$T_i = K(-\log f_i)e^{k\varepsilon_i}$$

Encoding factor | Word frequency | Encoding exponent | Word eccentricity

Saccades:

- 135 ms preparation (Salvucci default)
- 50 ms motor programming
- Execution: 20 ms execution + 2 ms per degree of visual angle

Parameters:

```
:VISUAL-ENCODING-FACTOR    0.002
:VISUAL-ENCODING-EXPONENT  0.4
:SACCADE-PREPARATION-TIME  0.110
```

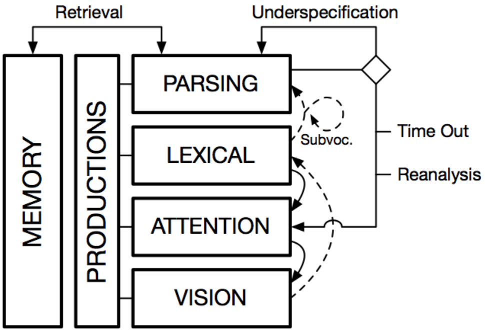
The Time Out proposal

Mitchell, Shen, Green, and Hodgson (2008):
"Regressions are programmed not to facilitate repair, but merely to buy time for the linguistic processor to catch up with its existing backlog of processing."

Reichle, Warren, and McConnell (2009):
"The average length of readers' initial regressive eye movements are often quite short, moving the eyes back only a word or two."

Interface I: Time Out

When word integration is too slow, a short regression interrupts the autonomous eye movement programme.



Interface I: Time Out

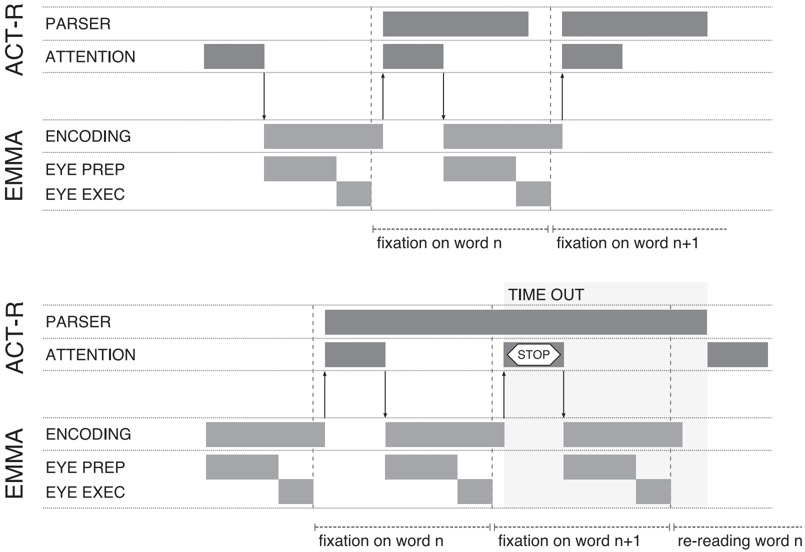
Implementation of a Time Out mechanism in Reichle et al. (2009)'s E-Z Reader 10 in terms of a linear-order requirement:

"... word n+1 is identified ... before word n has been integrated, which ... halts both the post-lexical processing ... of word n and the forward movement of the eyes ... so that both attention and the eyes can be directed back ..."

But what about fixation durations?

Slowed reading as a by-product of Time Out: When the delayed integration finishes before the regression is executed, the extra processing time of the then cancelled saccade leads to an inflated reading time.

Interface I: Time Out



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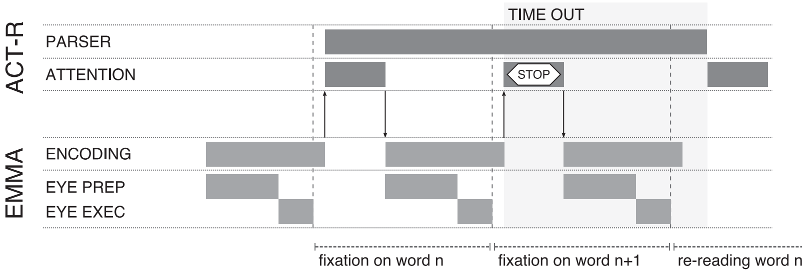
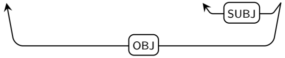


The employees that the fireman **noticed** hurried across the field.



Engelmann, Vasishth, Engbert, and Kliegl (2013); Vasishth, von der Malsburg, and Engelmann (2013)

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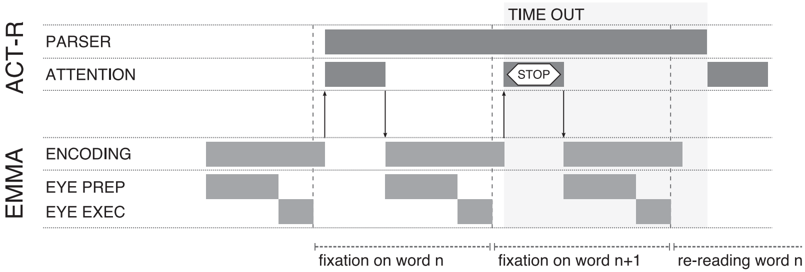

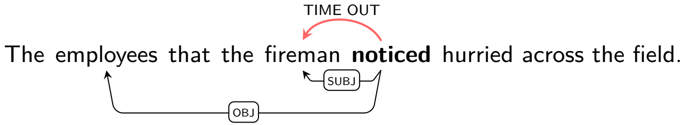

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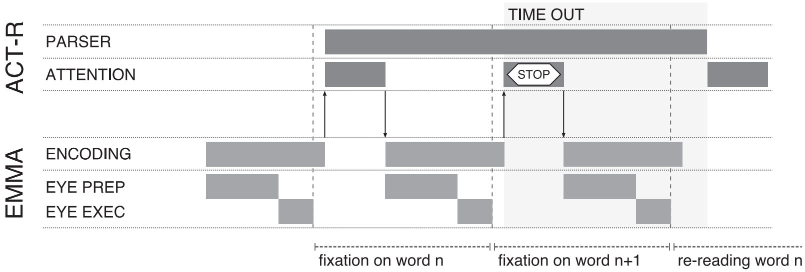
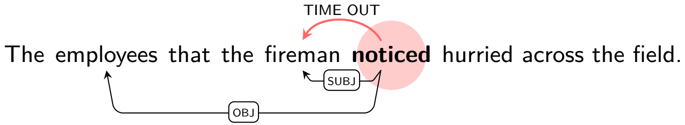


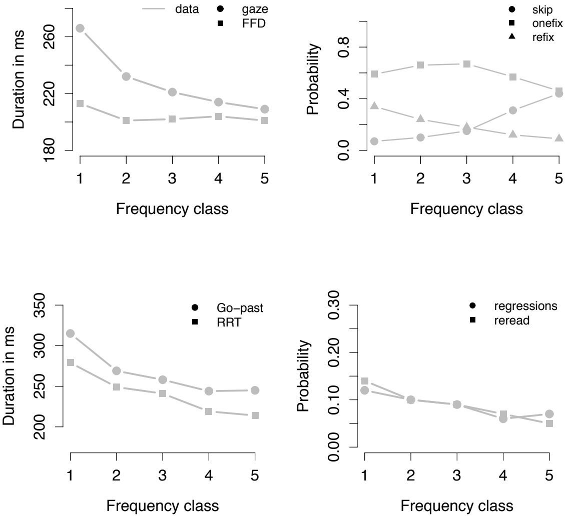


Engelmann, Vasishth, Engbert, and Kliegl (2013); Vasishth, von der Malsburg, and Engelmann (2013)

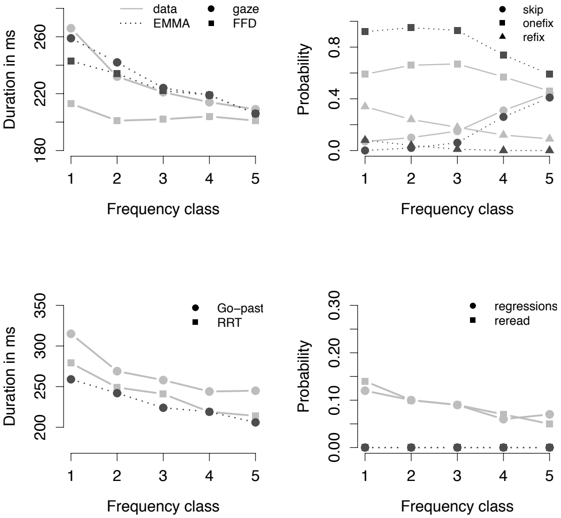
```
(p start-time-out
    =goal>
       ISA              comprehend-sentence
       state            "wm-retrieval"
       em-state         "attending"
       attend-to        "next-word"
       time-out         nil
    ?visual>
       processor        free                 ;; no current encoding
       execution        free                 ;; no current saccade execution
    =visual>
       ISA              text
       screen-pos       =visual-location
==>
    !bind! =eye-loc (first (current-eye-loc))
    !bind! =parse-loc (parsing-get-loc)
    =goal>
       em-state         "looking"
       last-loc         =visual-location
       time-out         t
   +visual-location>
        ISA             visual-location
      < screen-x        =eye-loc             ;; target before current fixation
        screen-x        highest              ;; target nearest to the left

   !eval! (start-time-out =parse-loc)
   !eval! (trialmessage "timeout" =eye-loc)
)
```

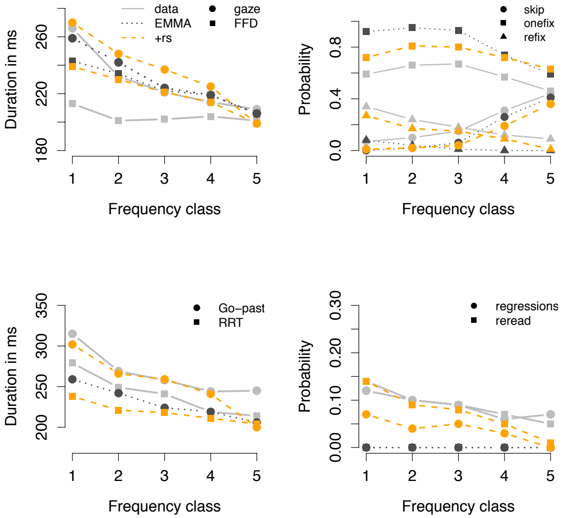
Time Out evaluation on Potsdam Sentence Corpus



Time Out evaluation on Potsdam Sentence Corpus



Time Out evaluation on Potsdam Sentence Corpus



Time Out evaluation on Potsdam Sentence Corpus

	$RMSD$	$\%regr$
EMMA	0.638	0
EMMA+parsing	0.206	23

Early measures: Gaze, FFD, SFD, skipping, single fixation prob., refixation prob.
Late measures: RPD, TFT, RRT, FPREG, rereading prob.

Table 1: Goodness of fit

lf	0.2
VISUAL-ENCODING-FACTOR	0.002
VISUAL-ENCODING-EXPONENT	0.4
SACCADE-PREPARATION-TIME	0.110

Table 2: Parameters

1. Predicted regressive eye movements.
2. Improved prediction of late and early fixation measures.

Engelmann, Vasishth, Engbert, and Kliegl (2013)

Exercise – Time Out

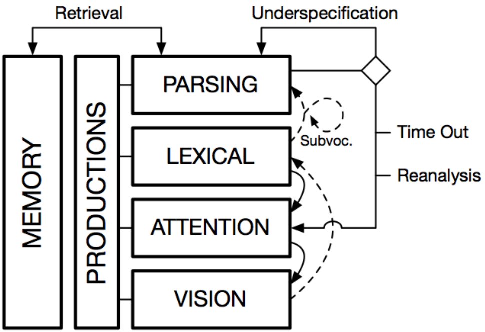
- Run Grodner and Gibson (2005) experiment:

  ```
  (re 'gg-exp1 100)
  ```

- Go to output directory: `LewisVasishth2005/output/`
- Run R script: `2_analyse_experiment.R`

Interface II: Reanalysis

Any rule that revises the attachment of a previously created constituent in memory triggers an immediate attention shift to the left.



```
(P attach-DP-as-subject-of-predicted-IP-gapped
   =goal>
      ISA                comprehend-sentence
      state              "wm-retrieval"
      goal-cat           VP-gapped-goal
  =retrieval>
      isa                syn-obj
      cat                IP
      head               nil
      subj-word          =subj-word
      waiting-for-cat    wait-for-VP
      spec               =empty-op
      gap                spec
   =lex>
      isa                lexical-entry
      cat                DET
      word               =word
==>
   !bind! =ID-DP (new-name DP)
   =goal>
      state              "wm-retrieval"
      cue1               =empty-op
      attend-to          "left"
  +DPb>
      isa                syn-obj
      cat                DP
      ID                 =ID-DP
      case               nom
      head               =word
      spec-of            =retrieval
      waiting-for-case   wait-for-nom
      waiting-for-cat    wait-for-NP
      next-goal          next-VP-gapped-goal
   =retrieval>
      number             sing-plural
      spec               =ID-DP
      gap                open
  +retrieval>
      ISA                syn-obj
      CAT                DP
      ID                 =empty-op
      filler             DONE
)
```

```
(P revise-subject-relative
   =goal>
      ISA                comprehend-sentence
      state              "wm-retrieval"
      goal-cat           VP-gapped-goal
   =retrieval>
      isa                syn-obj
      filler             done
==>
   =goal>
      state              "read"
      goal-cat           NP-goal
      attend-to          "next-word"
   =retrieval>
      ;; reinstate filler as active
      filler             yes-filler
  !eval! (set-end-time)
)
```

Reanalysis regression (fast)

Expectation

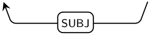
The **employees** that the fireman

Simulation: Time Out + Reanalysis

Staub (2010)

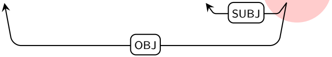
SUBJECT RELATIVE CLAUSE

a. The employees that **noticed the fireman** hurried across the field.



OBJECT RELATIVE CLAUSE

b. The employees that **the fireman noticed** hurried across the field.



No parameters were fitted.

Simulation: Time Out + Reanalysis

Staub (2010)

SUBJECT RELATIVE CLAUSE

a. The employees that **noticed the fireman** hurried across the field.

SUBJ

OBJECT RELATIVE CLAUSE

TIME OUT

b. The employees that **the fireman noticed** hurried across the field.

SUBJ

OBJ

No parameters were fitted.

Simulation: Time Out + Reanalysis

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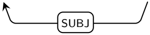

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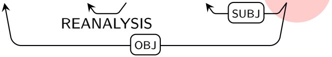
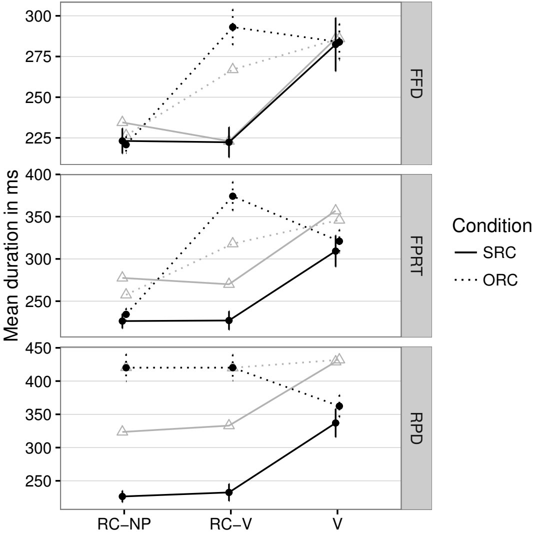


No parameters were fitted.

Simulation: Time Out + Reanalysis



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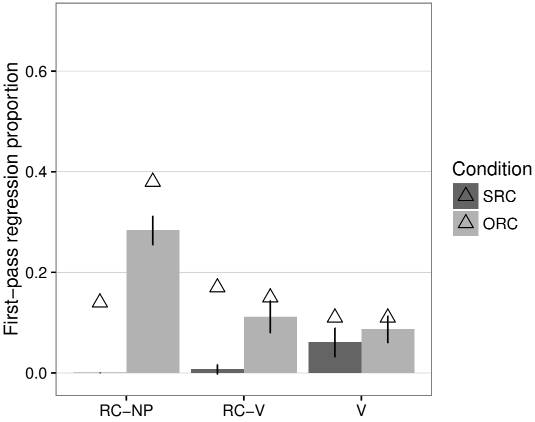


Simulation: Time Out + Reanalysis

Staub (2010)

SUBJECT RELATIVE CLAUSE

a. The employees that **noticed the fireman** hurried across the field.

SUBJ

OBJECT RELATIVE CLAUSE

REANALYSIS

TIME OUT

b. The employees that **the fireman noticed** hurried across the field.

SUBJ

REANALYSIS

OBJ

Exercise – Reanalysis

- Run Staub (2010) experiment:

```
(re 'staub10 100)
```

- Go to output directory: `LewisVasishth2005/output/`
- Run R script: `staub10-analysis.R`

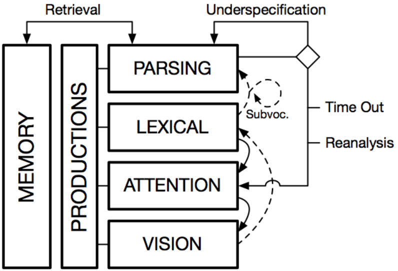
Underspecification

Swets et al. (2008): "According to construal [Frazier & Clifton, 1996], syntactic relations can be divided into primary and secondary types. Whereas **primary relations (roughly, arguments)** are immediately attached [...], **secondary relations (roughly, adjuncts)**, including relative clauses and other modifiers initially are indeterminately 'associated' with the current thematic domain, at which point other information can be called upon to resolve the association into a determinate attachment."

The rate of underspecification is affected by task demands like the type of comprehension questions (Swets et al., 2008) and by working memory capacity (von der Malsburg & Vasishth, 2012).

Interface III: Underspecification

For relations of low priority, an attachment attempt is aborted as soon as the next word is ready for integration, so that reading proceeds uninterrupted.



Modelling working memory capacity

Latency factor F (:lf) **—> Speed**	$RT = Fe^{-(f*A_i)}$
Decay parameter d (:bll) **—> Speed, forgetting**	$B_i = \ln(\sum_{j=1}^{n} t_j^{-d}) + \beta_i$
Source activation W_k of buffer k (e.g., goalbuffer :ga) This activation is distributed among goal-related chunks. **—> Accuracy (goal-relevant), speed**	$A_i = B_i + S_i + P_i + \varepsilon_i$ $S_i = \sum_k \sum_j W_{kj} S_{ji}$
Mismatch penalty P (:mp) **—> Error sensitivity**	$P_i = \sum_k PM_{ki}$
Similarity M_{ki} between the value k in the retrieval specification and the value in the corresponding slot of chunk i **—> Association between cue and target**	

Modelling working memory capacity

Goal buffer source activation W:
The amount of activation from source j in the goal buffer is the source activation W divided by the number of sources j in that buffer.

$$A_i = B_i + \sum_{j=1}^{n} \frac{W}{n} S_{ji} \qquad (1)$$

!!! This means that activation spread is less when there are more slots in the goal buffer (filled slots, those with nil do not count) !!!

An ACT-R model of WM (Digit span task, Lovett et al., 1999): Daily, L. Z., Lovett, M. C., & Reder, L. M. (2001). Modeling individual differences in working memory performance: A source activation account. Cognitive Science, 25(3), 315-353.

WM modeled in language processing: van Rij, J., van Rijn, H., & Hendriks, P. (2013). How WM load influences linguistic processing in adults: A computational model of pronoun interpretation in discourse. Topics in Cognitive Science.

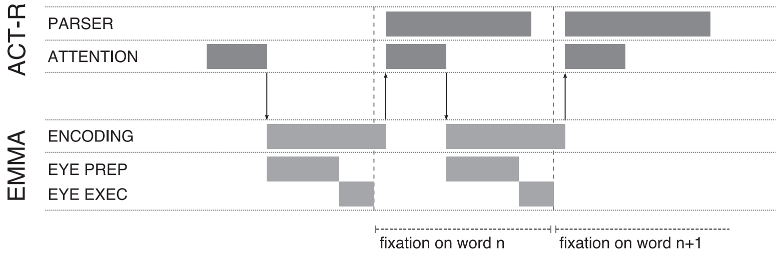
Running individual subjects

E.g., 100 iterations, 60 subjects: `(res 'gg-exp1 100 60)` For

each subject, goal activation W is drawn from a normal distribution with mean $= 1$ and standard deviation $= 0.25$.

Interface III: Underspecification

The mechanism is similar to Time Out, but here the eye movement is not interrupted:



Von der Malsburg & Vasishth (2012)

reanalysis for high-capacity readers

El profesor dijo que los alumnos se levantaran del asiento...
The teacher said that the students had to stand up from their seats...

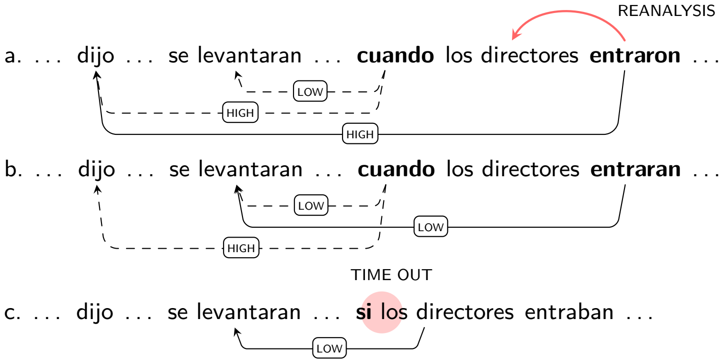
ambiguity advantage for low-capacity readers

a. ***cuando*** *los directores* ***entraron*** *en la clase de musica.* — HIGH attachment
when the directors **came** into the class.

b. ***cuando*** *los directores* ***entraran*** *en la clase de musica.* — LOW attachment
when the directors **come** into the class.

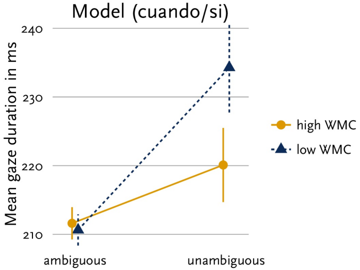
c. ***si*** *los directores* ***entraban*** *en la clase de musica.* — UNAMB (low)
if the directors **come** into the class.

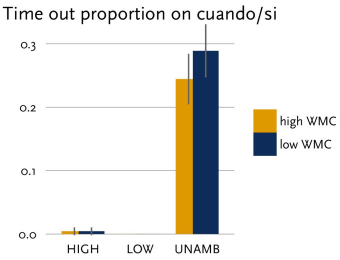
von der Malsburg and Vasishth (2013)



1. Ambiguity advantage
2. More rereading in ambiguous conditions
3. Greater amb. advantage less rereading for low-capacity readers

→ **Different underspecification strategies for low/high WM?**





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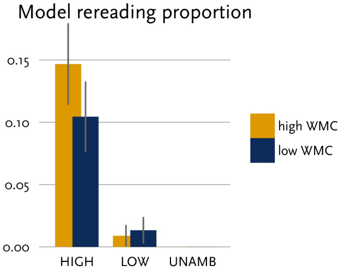

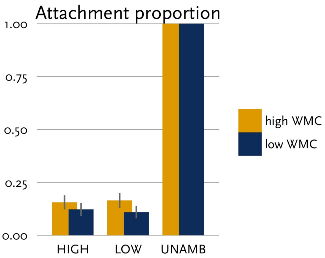

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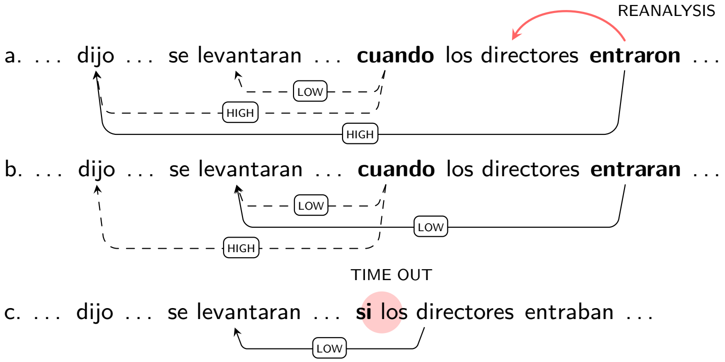
Simulation: Time Out + Reanalysis + Underspecification



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3. Greater amb. advantage less rereading for low-capacity readers

→ **Different strategies are phenomena of one common underlying mechanism!**

Possible extension: Speed-accuracy trade-off

- Utility value decides between time-out (completing the attachment) and cut-off (underspecification).
- Value is adjusted after every sentence by a reward according to task success (comprehension questions)
- **Accuracy:** Incorrect responses shift the utility towards time-outs.
- **Speed:** Many time-outs that slow down reading shift utility towards underspecification.

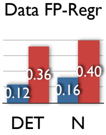
$$U_i(n) = U_i(n-1) + \alpha[R_i(n) - U_i(n-1)] \quad (2)$$

where α is the learning rate, $R_i(n)$ is the reward value given to production i at time n.

Possible extension: Articulatory loop

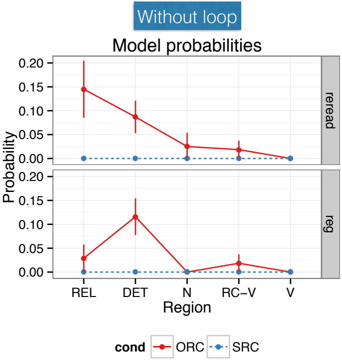
There is evidence that subvocalization could play the role of short-term storage in reading (Baddeley, 1979; Baddeley, Eldridge, & Lewis, 1981; Daneman & Newson, 1992; Eiter & Inhoff, 2010; Kleiman, 1975; Slowiaczek & Clifton Jr., 1980).

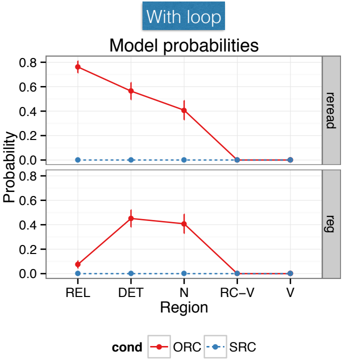
Possible extension: Articulatory loop



Articulatory Loop

Staub (2010) revisited





Possible extension: Articulatory loop

Articulatory Loop

Predictions:

- Delayed effects of parsing depend on articulatory loop
- In some cases retrieval not necessary because two words can be integrated in one step
- „Wrap-up effects“ at phrasal boundaries due to clearing the loop (especially when storing more than one word)

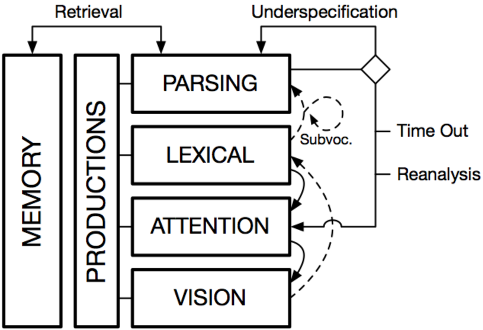
Questions:

- How to decide between Time Out and Loop?
- How many words to store? (Decide based on structural expectations?)

➡ **Run experiments with blocking subvocalization**

Summary

1. At processing difficulties, the parser chooses between interruption and underspecification.
2. Interruptions trigger late untargeted (Time Out) or early targeted (Reanalysis) regressions.
3. The ratio between interruptions and underspecification is adjusted according to task demands and individual capacity.



ACT-R
An Integrated Theory of the Mind (Anderson et al., 2004)

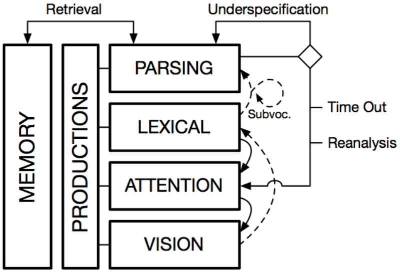
LV05
An activation-based model of sentence processing as skilled memory retrieval (Lewis & Vasishth, 2005)

EMMA
An integrated model of eye movements and visual encoding (Salvucci, 2001)

Summary

The essential eye-parser interactions are Time Out, Reanalysis, and Underspecification (and Subvocalization).
In interaction with individual differences and task demands, the same mechanism can produce qualitatively different results:

1. Interruptions × timing → regressions / inflated fixation durations
2. Timed cut-off × working memory → (under)specification.



Open issues

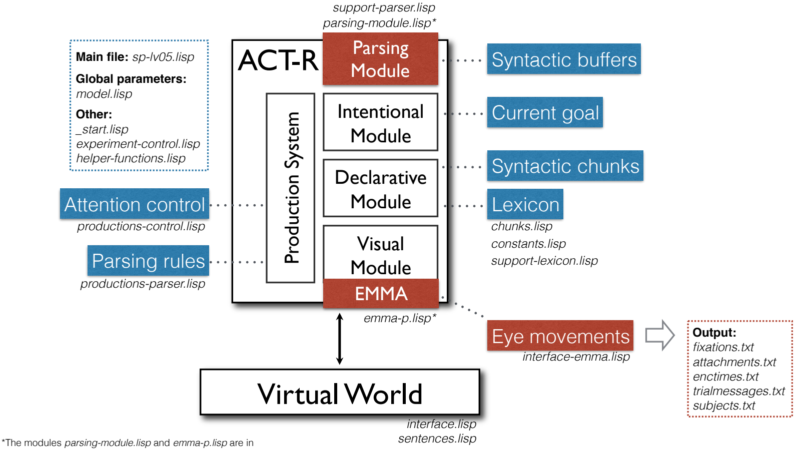
1. Regression targeting and storage of spatial information.
2. Expectation-based processing.
3. Tuning of time-accuracy trade-off between interruption and underspecification.

Software

- A parsing module for ACT-R:
  https://github.com/felixengelmann/ACT-R-Parsing-Module
- The ACT-R model with implemented eye-parser Interfaces I, II, and III:
  https://github.com/felixengelmann/act-r-sentence-parser-em

Model Structure

File Structure



*The modules *parsing-module.lisp* and *emma-p.lisp* are in *actr6/other-files/*. All the others are either in the core directory *sp/* or in the specific model folder (e.g. *LewisVasishth2005/*).

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