Attachment Without Competition:
A Computational Model of Race-based Parsing in a Limited Working Memory

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18 March 1999

Revisiting Minimal Attachment

"This … observation about Minimal Attachment is what permits it to be dispensed with as an independent strategy. We need only suppose that the structural hypothesis which the parser pursues is the **first one that it recognizes.** *….It is particularly interesting that for this explanation to go through, it is* **not even necessary to suppose that the human parsing mechanism considers alternative hypotheses in serial rather than in parallel.** *But because the alternatives are recognized at different speeds, its* **parallel processing of them would be staggered.**"

— Frazier & Fodor (1978)

Why race-based parsing?

- Theoretical motivation
  - Will generally be asymmetries in processing different alternatives (e.g., due to *frequency*)
  - In a rapid task like on-line comprehension, makes sense to go with first available computation
  - Effectively treats parsing as *automatic* vs. *controlled* process
- Empirical motivation
  - Race-based models correctly predict no increase in reading time for (equi-biased) structural ambiguities (e.g., Frazier, 1995 ,1998; Clifton et al 1998; Mitchell 1994; Van Gompel et al 1998)

Theoretical approach: Properties of memory determine the winner

- What determines the winner of the race?
- Proposed answer: *Independently motivated principles of working memory & LTM, interacting with linguistic structure*
  - In particular: <u>Interference, decay, and focus of attention</u>
  - These factors combine to determine activation levels of to-be-retrieved items in WM or LTM

  👉 *Higher activation maps on to decreased retrieval time; hence, in Race-based Parsing, determines how ambiguities are resolved on-line*

Overview

(1) The activation-based model

- Syntactic attachment as cue-driven STM retrieval

(2) Complexity of unambiguous structures

- Contrasts in center-embedding
- Locality vs. interference

(3) Some implications for ambiguity resolution

- Lexical frequency: major category, subcategory
- Recency & discourse salience: 2-site, 3-site NP modifier attachment
- Ambiguous can be easier: Van Gompel et al. (1998)

(5) Conclusion

Decay, focus, & interference

Base level activation is function of usage history; yields both power law decay & power law learning (e.g., Anderson, 1993)

Time →

Decay, <u>focus</u>, & interference

Current and most recent item are in focus of attention and have high activations (e.g., Cowan, 1993; McElree, 1998; also Wickens et al 1963). There is a limit on focus activation.
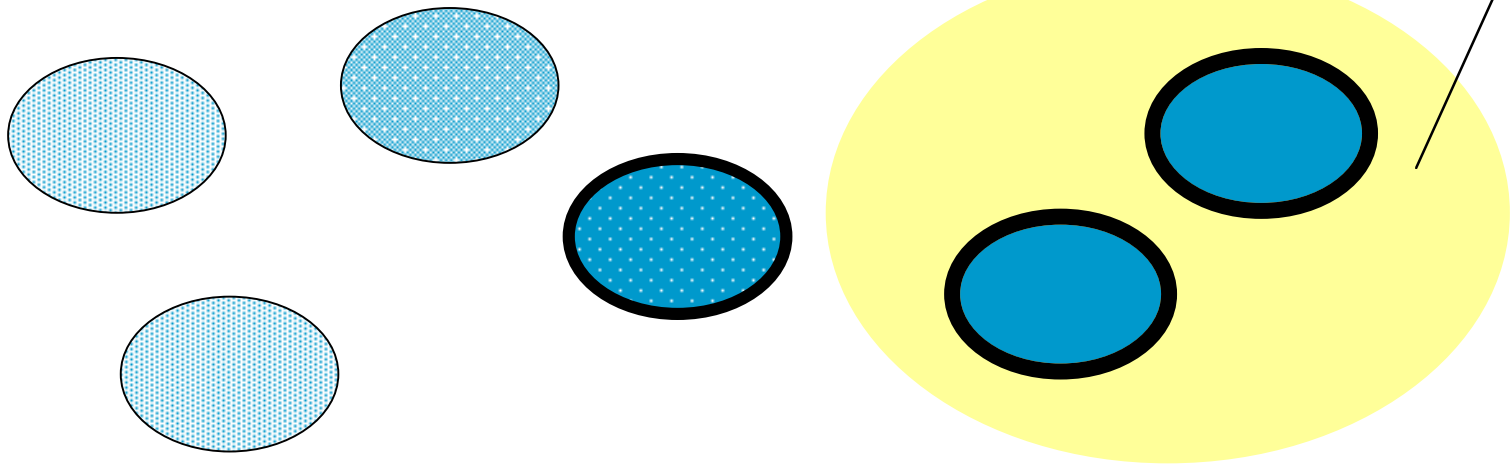
Decay, focus, & <u>interference</u>

Memory elements receive additional activation from associated focus elements; these focus elements serve as retrieval *cues*. Effectiveness of cue decreases as number of associates increases, giving rise to *interference* effects (Anderson, 1993)
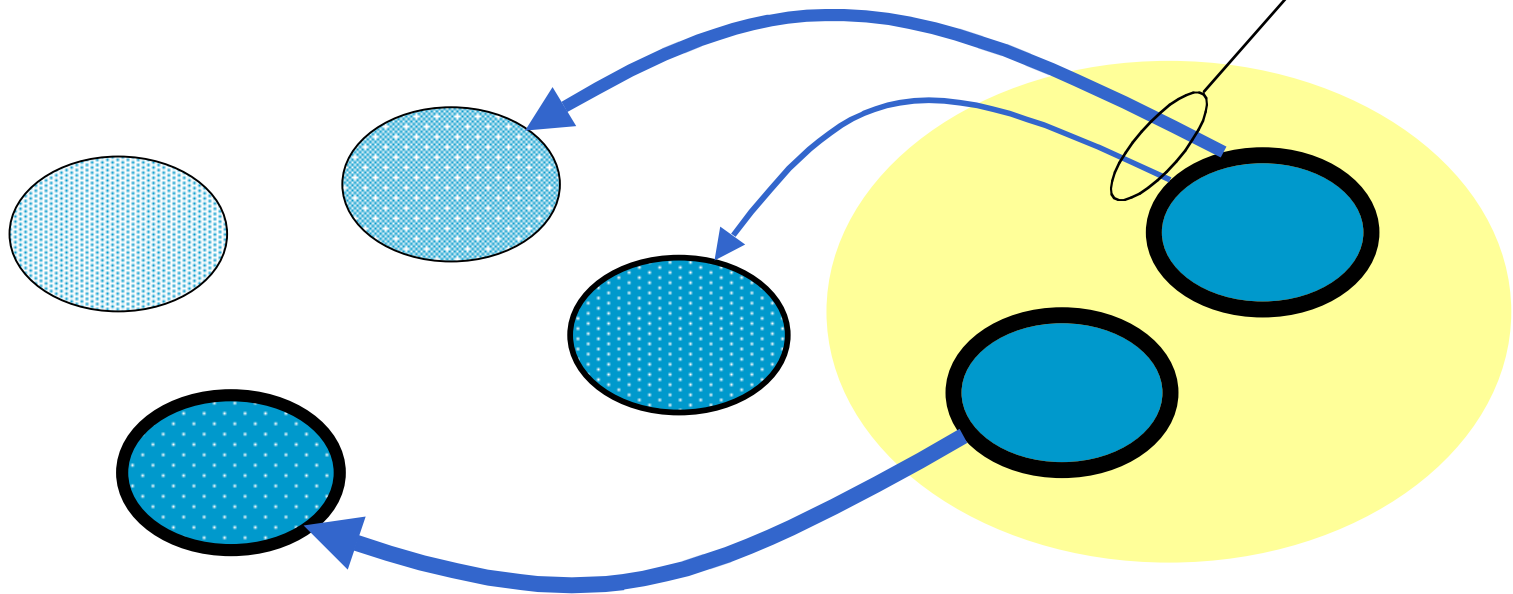
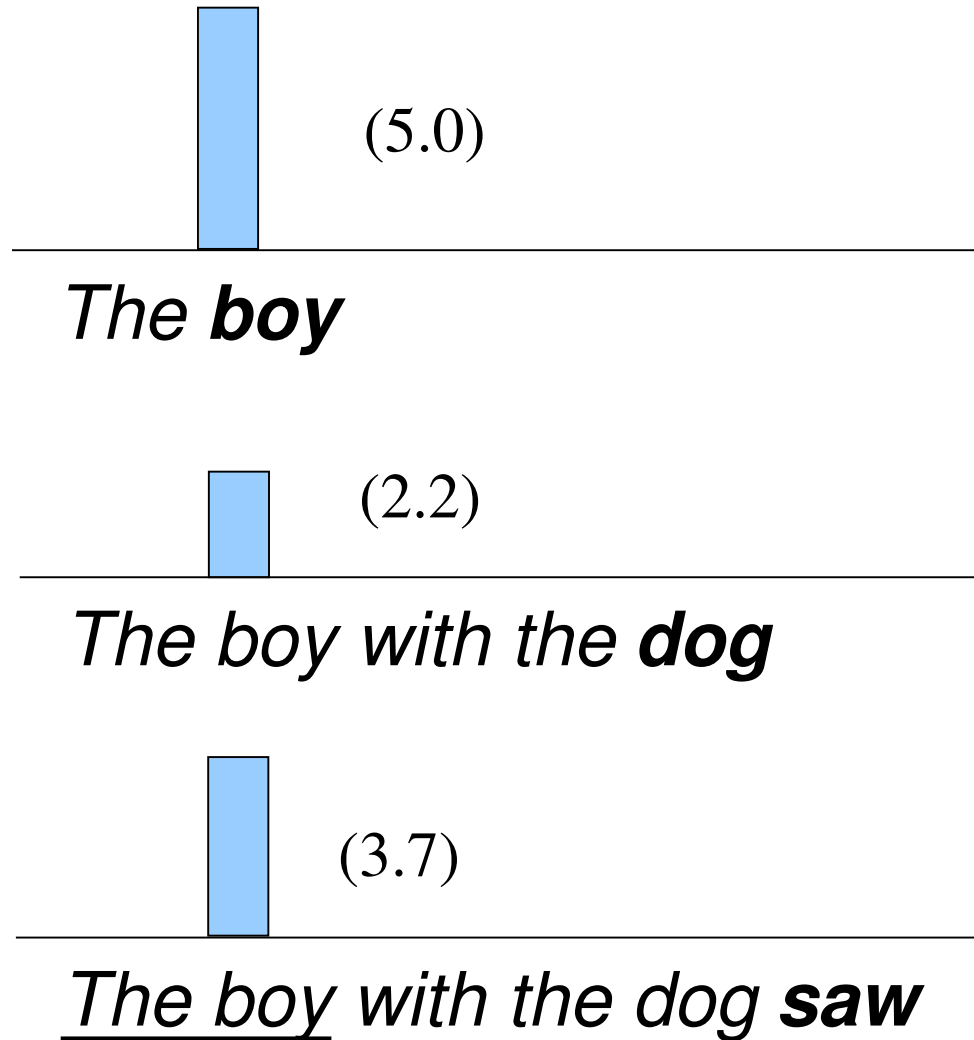# Syntactic attachment as cue-driven retrieval: RI and PI in parsing

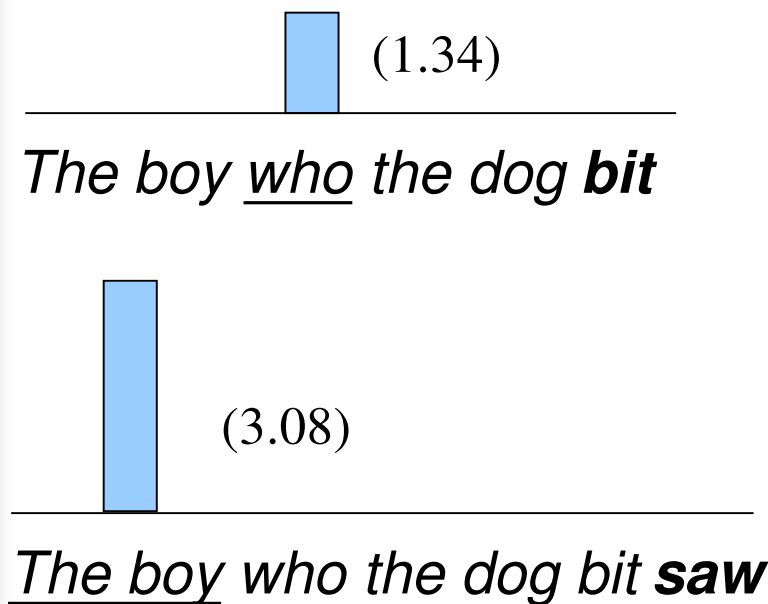*John-wa Bill-ni Mary-ga Sue-ni Bob-o introduced that said*
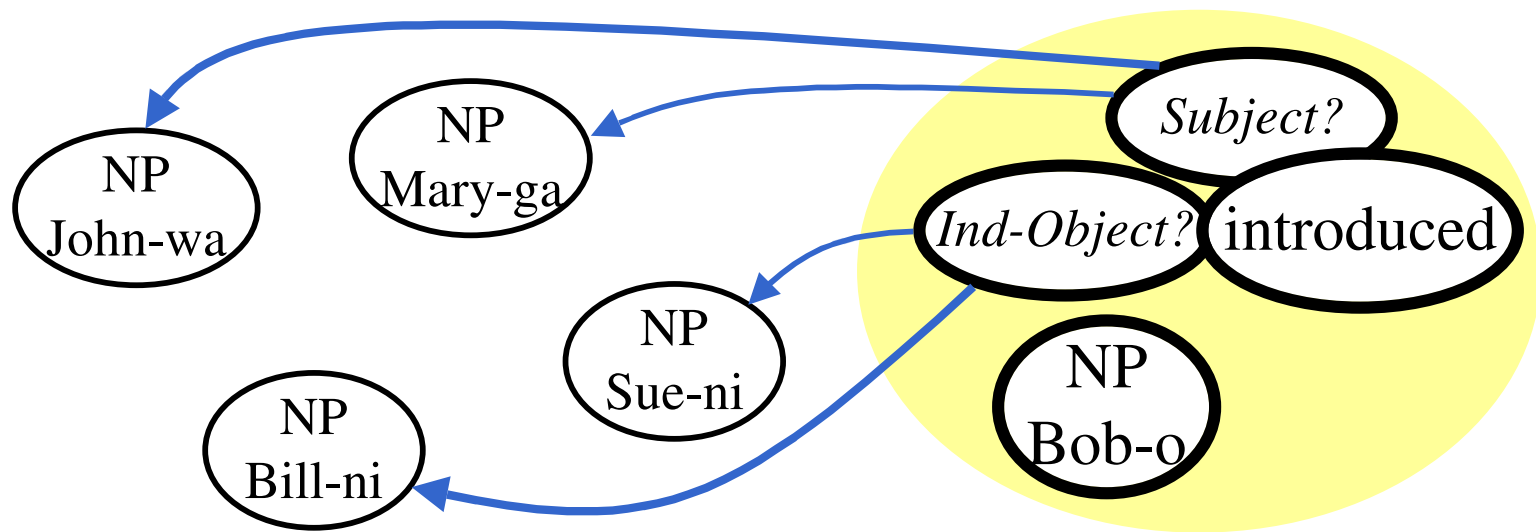
n Yields *Similarity-based Retroactive & Proactive Interference* (Lewis, 1996; 1998)

 • Strength of association decreases as associated items increase; Most recent does not suffer PI
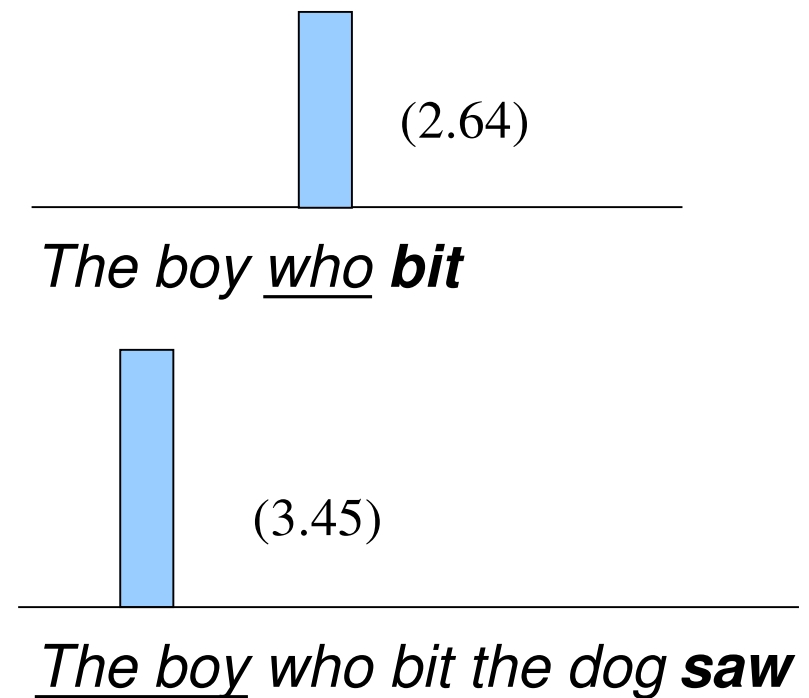
Example: Distal subject attachment
(Results from model implemented in ACT-R)

(5.0)

The ***boy***

(2.2)

*The boy with the **dog***

(3.7)

*The boy with the dog **saw***

Contrasts in center-embedding: Subject vs. object relatives

(1.34)

The boy who the dog bit

(2.64)

The boy who bit

(3.08)

The boy who the dog bit saw

(3.45)
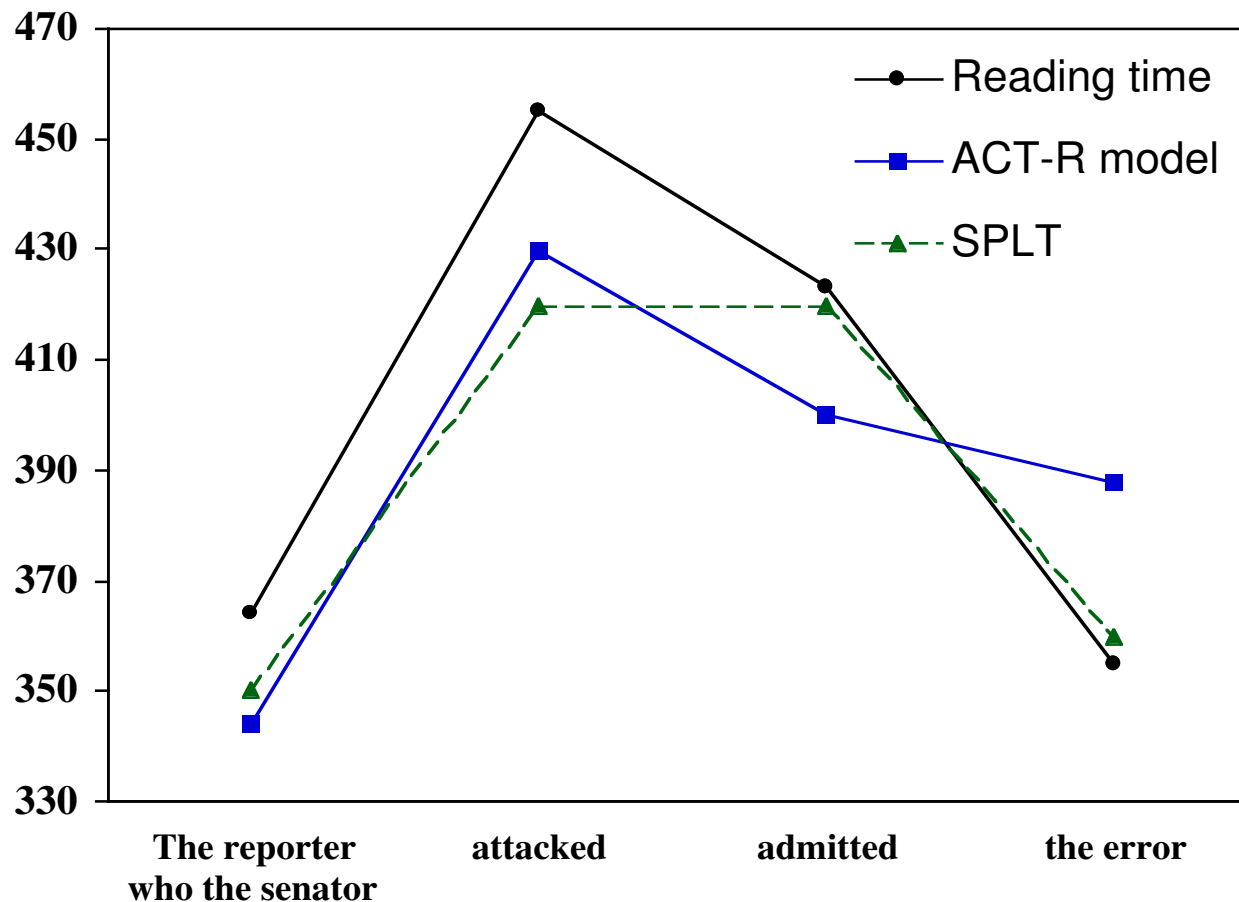
The boy who bit the dog saw
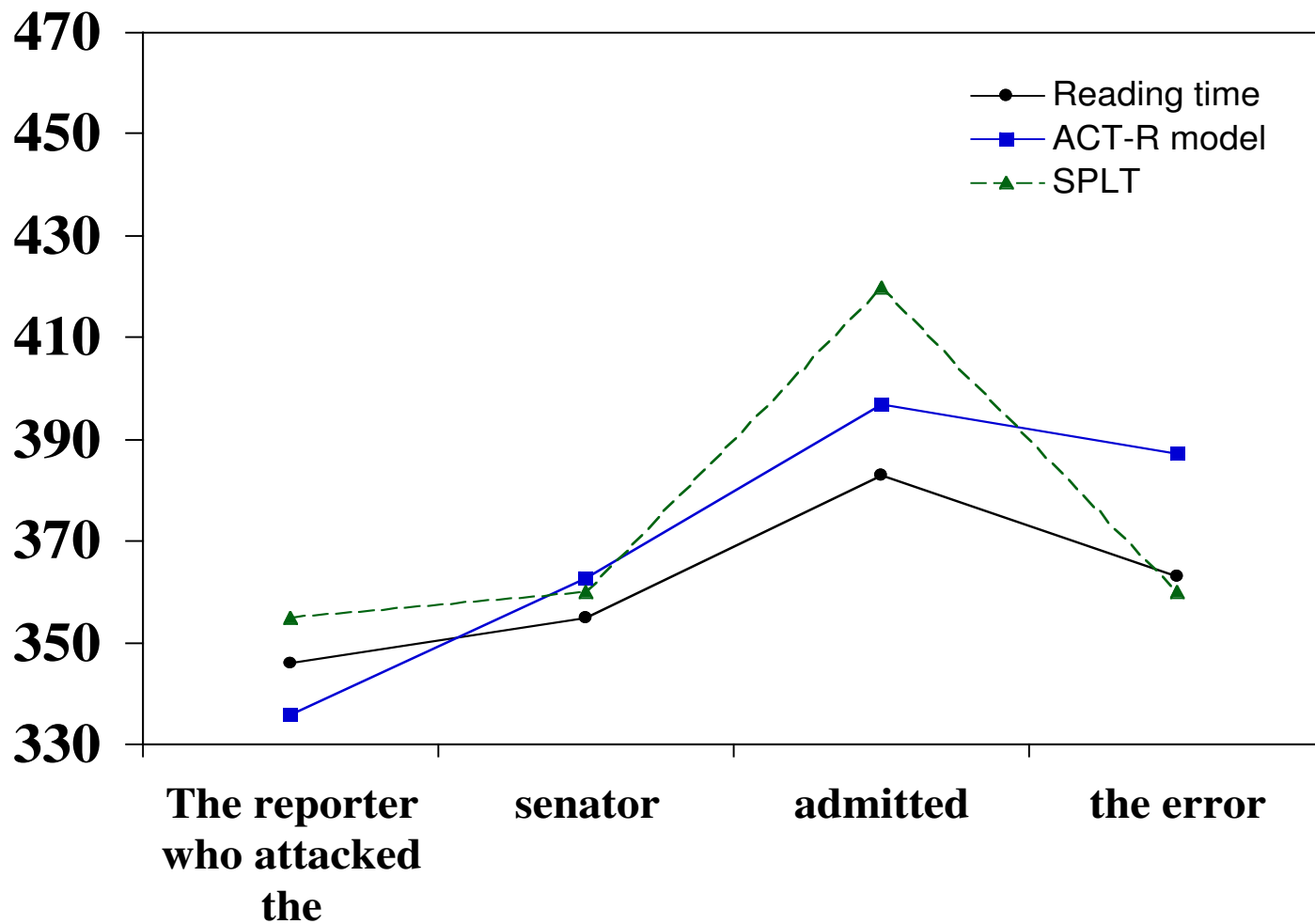
Object Relative

Subject Relative

Modeling OR reading times
(Gibson & Ko, 1998; in Gibson 1998)

n Use *longest attachment process* at each word to predict reading time for word

Modeling SR reading times

Legend:
- Reading time
- ACT-R model
- SPLT

X-axis labels: The reporter who attacked the | senator | admitted | the error

Y-axis: 330, 350, 370, 390, 410, 430, 450, 470

Distance vs. interference

n What is worst case for parser?

- Multiple [limited focus], distal [decay] attachments, with multiple similar candidates [interference]

(0.67)

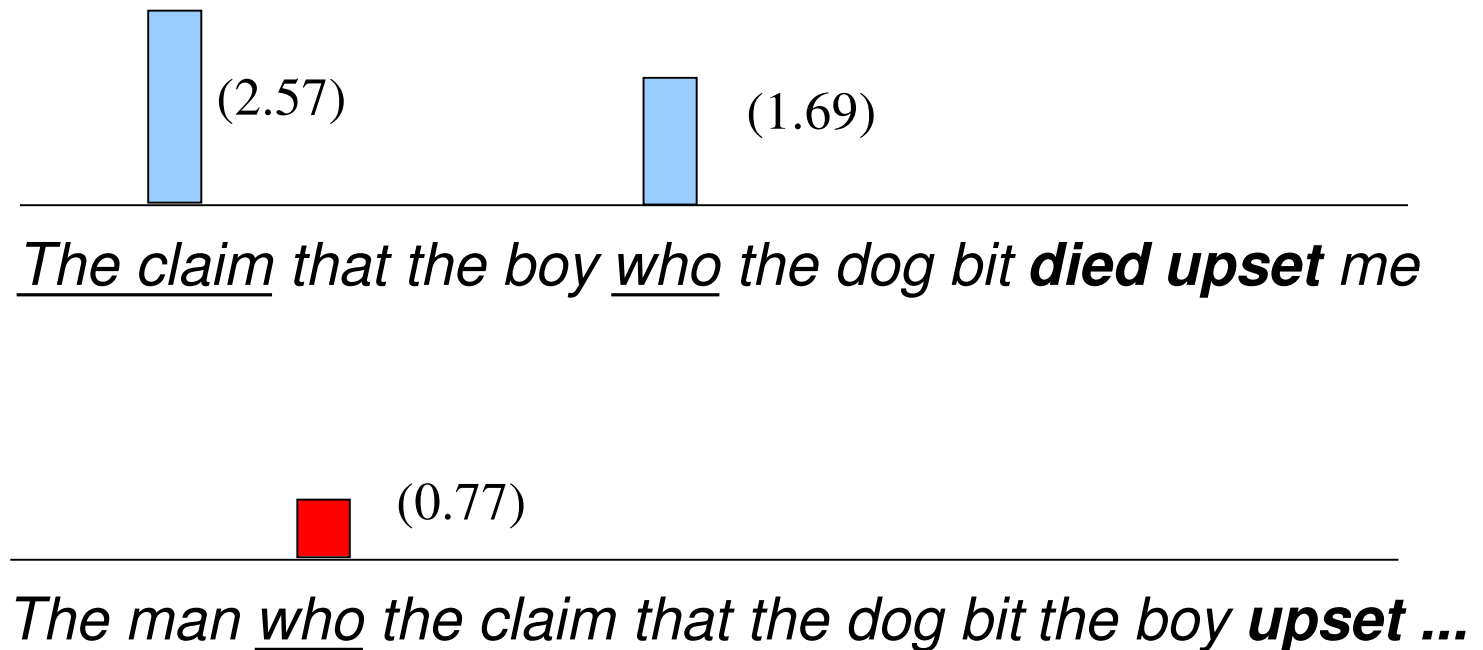*The boy <u>who</u> the dog that the fish saw **ate** was*

n But long-distance attachments still possible

(3.23)

<u>*The girl*</u> *with the dog with the boy with the fish with the ticket **was**....*

Effects of locality: RC/SC contrasts
(Gibson, 1998)

(2.57)

(1.69)

The claim that the boy <u>who</u> the dog bit **died upset** *me*

(0.77)

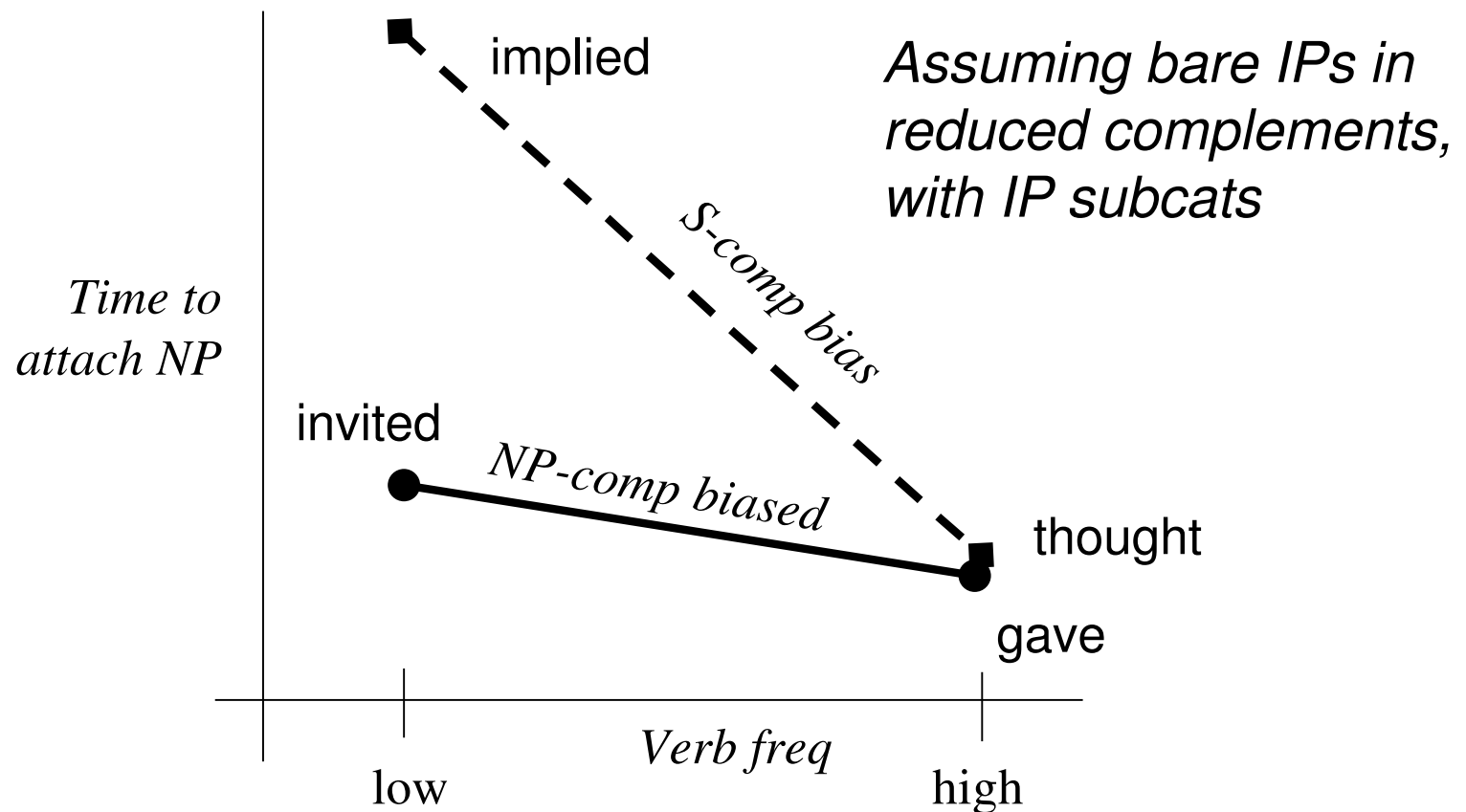*The man <u>who</u> the claim that the dog bit the boy* **upset ...**

Frequency effects: Major category bias (Boland 1998; Corley & Crocker 1998)

- n Base activation of lexical entries reflects frequency; determines retrieval latencies
- n <u>Ambiguous</u>: bias affects resolution
  - *the German **makes** the beer/are cheaper…
    the warehouse **prices** the beer /are cheaper*
  - All things being equal, base-level activations will determine which lexical entry is attached first
- n <u>Unambiguous</u>: bias affects processing times
  - Lower base-levels = slower times for subordinate
  - *…the German **make** is cheaper than ..*

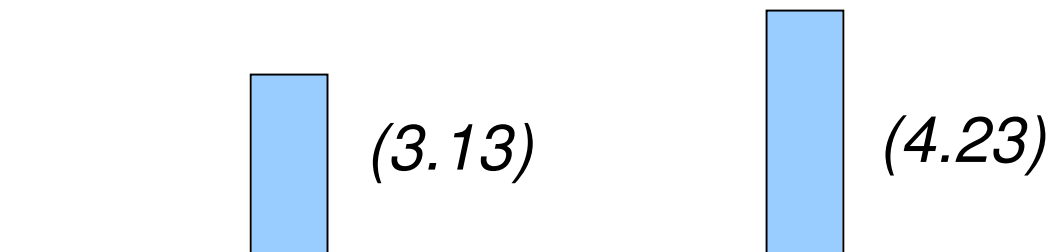# Effects of <u>subcategory</u> bias...
(Trueswell, et al 1993; Juliano & Tanenhaus, 1994)

n Reading time on NP following low/high frequency S-comp/NP-comp biased verb

Time to attach NP

implied

Assuming bare IPs in reduced complements, with IP subcats

S-comp bias

invited

NP-comp biased

thought

gave

Verb freq

low   high

2-site RC/PP modifier attachment
(Gilboy et al 1995; Hemforth, et al 1996)

(3.13)   *(4.23)*

The steak with _the sauce_ **that**...

Discourse salience effects

- n *But*: Changing thematic-assigner status of NP affects RC attachment preferences (Gilboy et al 1995; Frazier & Clifton, 1996)
  - *the driver of the car that….*
  - Most languages: Prefer to attach N1; English: closer to equi-biased (also affected by definiteness, prosody, focus)
- n But doesn't affect PP attachment (Hemforth, Konieczny & Scheepers, 1996)
  - Hemforth et al (1996; 1998): Two factors affect RC attachment: anaphor binding (prefers salient discourse referents) & syntactic attachment (prefers recent sites)
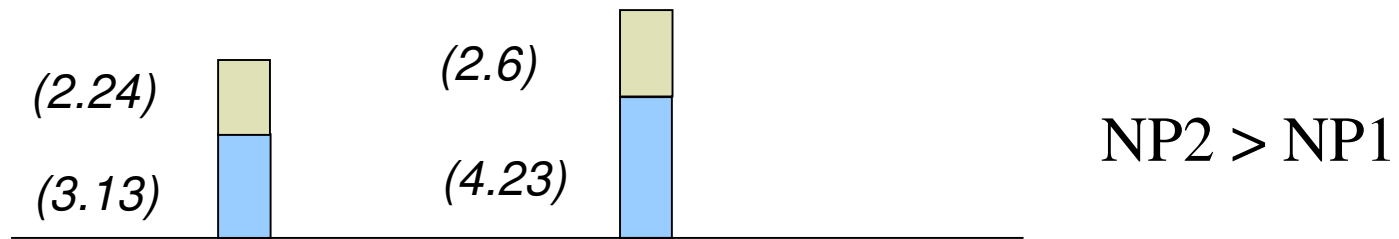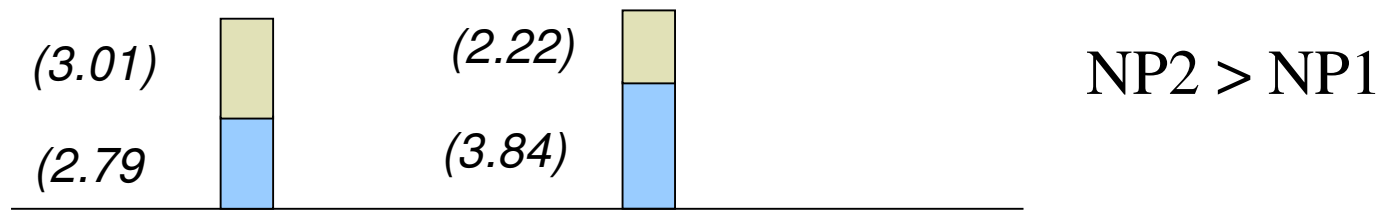
A race between binding and attachment

n Assume separate representation of discourse entities (with their own activations)

n Binding anaphors (such as relative operators) requires retrieving discourse elements

- In RC attachment, two possibilities: bind anaphor first, or attach first; both processes happen in parallel, *a race commences*
- Precisely the Hemforth et al model

2-site and 3-site NP/RC attachment
(Hemforth et al, 1996; Gibson et al 1996)

(2.24)   *(2.6)*   NP2 > NP1

(3.13)   *(4.23)*

the steak with the sauce **that**...

(3.01)   *(2.22)*   NP2 > NP1

(2.79   *(3.84)*

the driver of the car **that**...

NP3 > NP1 > NP2

(2.41)   *(2.67)*   *(1.99)*

(2.59)   *(2.16)*   *(3.29)*
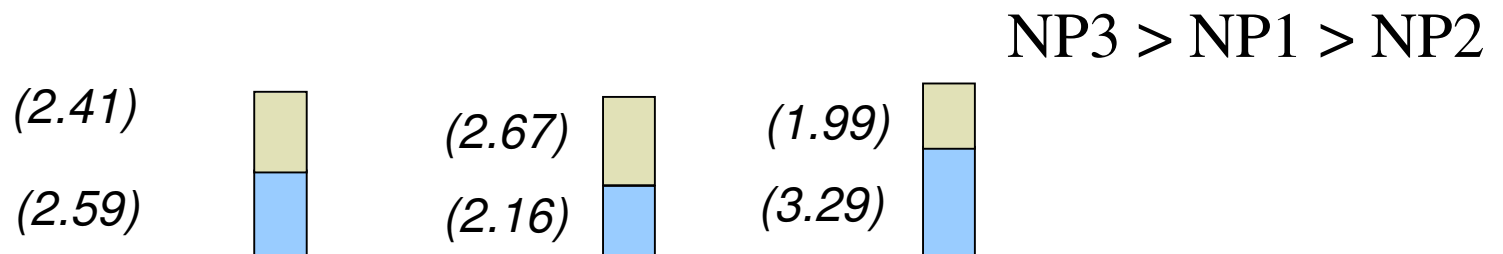
the daughter of the driver of the car **that**...

2-site and 3-site NP/RC attachment
(Hemforth et al, 1996; Gibson et al 1996)

Discourse object

NP

$NP2 > NP1$

the steak with *the sauce* **that**...
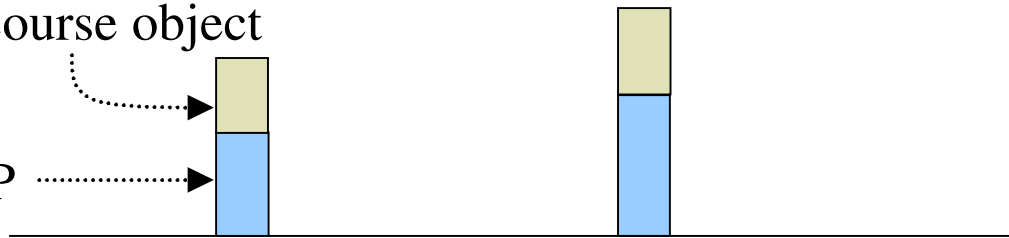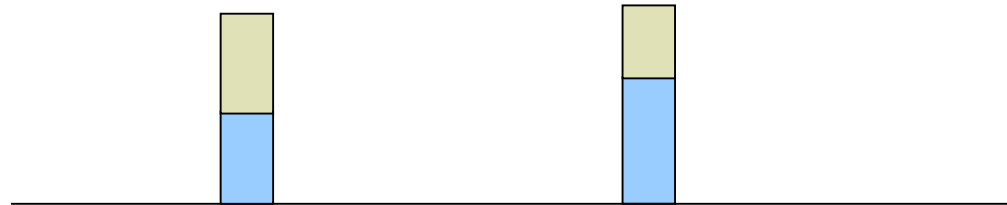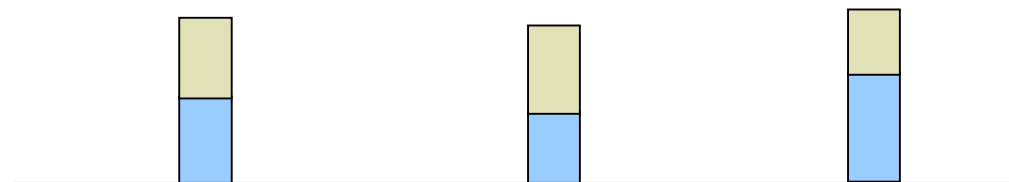
$NP1 > NP2$

the driver of *the car* **that**...

$NP3 > NP1 > NP2$

the daughter of *the driver* of *the car* **that**...

Salience principles or STM effects?

n Effects just described depend on variations in discourse object activations as function of thematic role assignment, topic salience

- *Some* independent salience principles *must* be necessary (e.g., in focus constructions)

n But: These patterns actually arose without explicitly manipulating d-object activations

- Arose from interference effects, and activation boost due to assigning a thematic role
- Against backdrop of N2 > N1 and N3 > N1 > N2 for syntactic attachment (due to recency and interference)

Recency vs . Visibility

n This account more in spirit of "Visibility" (Frazier & Clifton, 1998) than "Recency"

- Predicts effects on unambiguous structures (Stevenson, 1994)
- Could be modulated by focus, other factors

n But contrasts with view of syntactic constituents having smooth decay over time

- Hemforth et al (1996); Stevenson (1994); Vosse & Kempen (1997)

3-site VP attachment

n 3-site VP modifier attachment produces different profile (Pearlmutter & Gibson 1997)

(4.67) *(4.74)* *(5.87)*
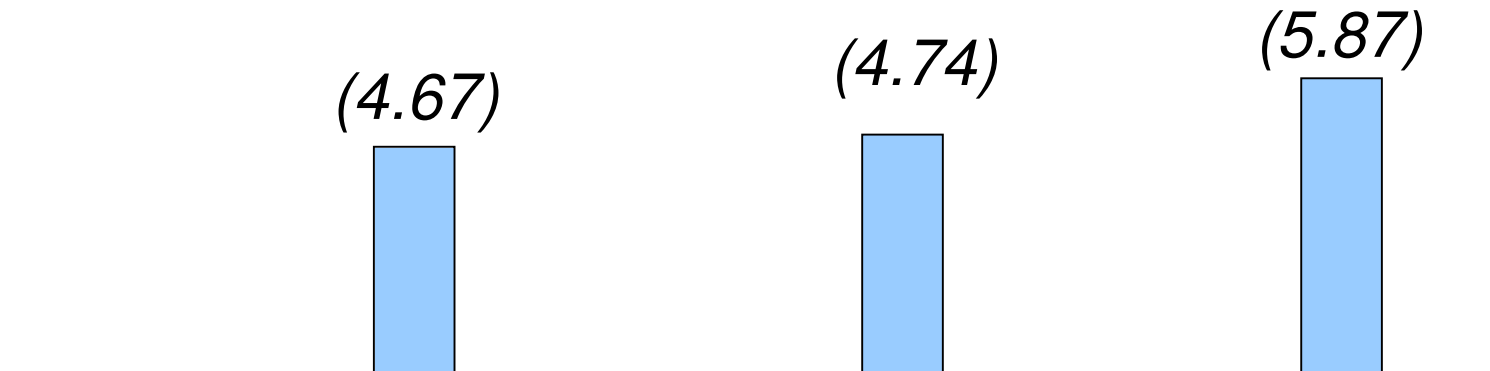
The boy <u>thought</u> that the man <u>said</u> that the dog <u>bit</u> the

n Why? Two factors decreasing relative contribution of interference vs. recency

- Additional processing associated with verbs; increased phrase length

Ambiguous can be easier
Van Gompel, Pickering & Liversedge (1998); Traxler, Pickering, &Clifton (1998)

n Eye tracking experiment examining *balanced syntactic* ambiguities

(a) *The advisor of the mayor that had been driven to the meeting had a lot of problems.*

(b) *The village of the mayor that had …*

(c) *The mayor of the village that had….*

n Result: regression path times shorter for *ambiguous condition* than *either* of the disambiguated conditions (which did not differ)

• Surprising for both competition & deterministic serial model; Authors adopt race-based account

Modeling the Van Gompel et al effect: Race, plus a little noise

n **Assume noise in activation levels (ACT-R)**

- Now can predict distribution of preferences

the advisor of *the mayor* **that...**

- On 20 runs: *High attach: 15, Low attach: 5*

n **Thus, predicts attachment is incorrect some of the time for *both disambiguating conditions***

- Plausible realization of *Unrestricted Race Model*

A simple theory

Activations of elements in WM & LTM are a function of similarity-based interference and decay/frequency

There is a limited focus of attention

Parsing involves a series of retrievals from WM and LTM; retrieval time is a function of activation level

Ambiguities are resolved by favoring the most rapidly computed structure

What s familiar

- Visibility vs. Recency (Stevenson 1994; Frazier & Clifton 1998)
- Race-based parsing (Frazier & Fodor 1978)
- Activation-based parsing; integrating structure & frequency in ambig. resolution (Stevenson 1994; Vosse & Kempen 1989)
- Unifying ambiguity resolution and structural complexity (Gibson, 1991)
- Multiple factors in modifier attachment (Hemforth, et al, 1996; Frazier & Clifton 1996)
- Interference in WM (Lewis, 1996; Gibson, 1998)
- Lexical frequency effects (MacDonald et al 1994, Crocker & Corley, 1998; Boland 1997)
- Modeling complexity of unambiguous and ambiguous structures in single architecture (Vosse & Kempen, 1997; Christiansen 1998)

What s new

- Two sources of independent motivation
  - Independently motivated WM theory
  - Independently motivated architectural base (ACT-R)
- Unification:
  - Visibility, recency, frequency, memory overload, unified via *memory retrieval*
    - Retrieval times model reading times in ambiguous and unambiguous structures
    - Retrieval failures model severe memory overload
    - Natural accommodation (explanation?) of visibility effects in multi-site attachment

Theoretical base: ACT-R

- General theory of cognitive architecture (Anderson 1993; Anderson & Liebere, 1998)
  - Activation-based declarative memory
  - Production rule system for procedural memory
  - Probabilistic learning components changing activations, strengths of memory elements
  - Yields detailed processing, latency traces
- Developed over ~20 + years
  - Domains range from STM serial recall tasks to skill acquisition in complex cognitive skill
  - Independent motivation from Bayesian rational analysis (Anderson, 1990)
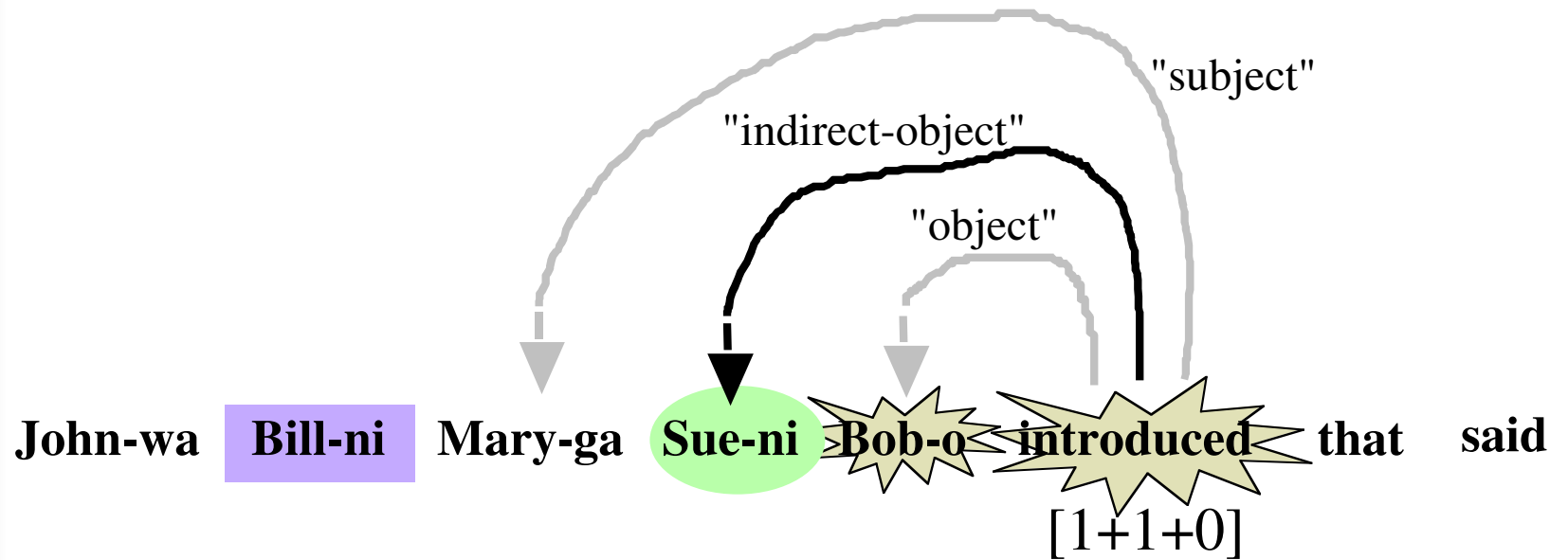
Implications for making syntactic attachments

- n Left alone $\Rightarrow$ constituents decay

- n More cues $\Rightarrow$ the less activation for each

- n More constituents associated with a cue $\Rightarrow$ the less effective the cue is

- n Worst case: multiple distal attachments with high interference

Attachments suffer from similarity-based proactive and retroactive interference (Lewis, 1996, 1998)

Similarity-based RI & PI

John-wa [**Bill-ni**] **Mary-ga** (**Sue-ni**) **Bob-o** **introduced** **that** **said**

"subject"

"indirect-object"

"object"

[1+1+0]

John-wa Bill-ni Mary-ga Sue-ni Bob-o syookai sita to it-ta.

Eliminating closure principles

n Closure principles often assume need to "clear out" memory, in e.g., long right-branching structures (Kimball, 1973; Frazier, 1979; Church, 1980; Gibson, 1991, 1998)

- But, this assumes memory limited by "*storage capacity*", rather than *retrieval effectiveness*
- Consider time to attach PP's in following

(201)   *(214)*   *(221)*   *(226)*
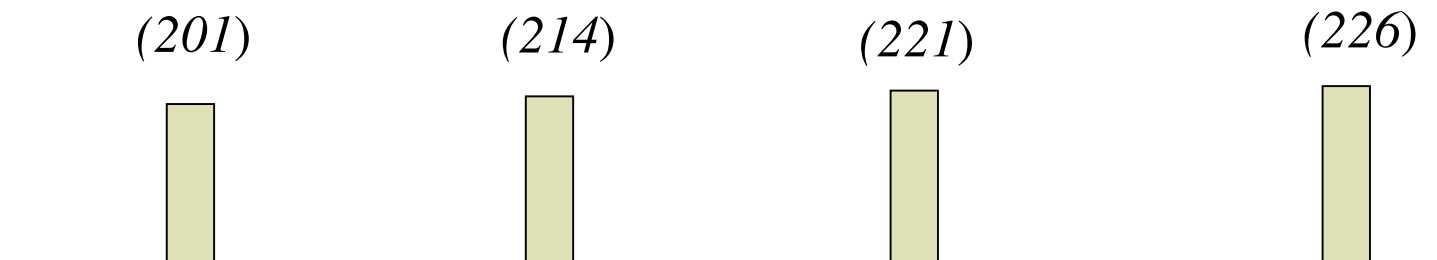
the boy with the man with the goose with the fish with the...

Minimal structure vs. frequency

- n Model still exhibits preference for NP-object
  - Even for verbs like *knew*, which are S-comp biased, following NP is initially taken as object
  - NP is taken as subject of incoming clause for only very strongly S-comp biased verbs (*thought*)
    - And for verbs with both weak IP and NP subcat entries (*implied*), NP is taken as object

- n Why? ACT-R's rational analysis
  - Attachment rule predicting an IP is less favored because predicts slightly greater future cost for achieving goal of processing sentence
    - Similar in spirit to Gorell's (1995) *Simplicity*; related to Rational Parsing proposal of Crocker, Chater et al. (1997)

Constraining the frequency explanations

n   Could any possible frequency effect be explained? *No.*

n   For a frequency effect to arise, must be some *locus* for that effect

- Architecturally-defined in ACT-R: declarative memory elements, production strengths, and associative strengths
- These memory elements and associations are functionally motivated by the task of parsing, or arise as a consequence of learning
- All has grounding in Anderson's (1990) rational analysis

Minimal Attachment, revisited

n This is clearly a kind of *Minimal Attachment* model

n Offers new answers to: *What determines the winner of the race?*

- Structural complexity, as determined by similarity-based intereference, recency (decay)
- Frequency of lexical forms and strengths of attachment procedures

The Kitchen Sink Objection

n Subcategory frequency, effects of thematic preposition, similarity interference, recency, race….

👉 *Isn't this everything but the kitchen sink?*

n NO. Shape of theory derives from a few principled architectural commitments
- Derived directly from ACT-R, but more general than ACT-R

Novel predictions?

n Many predictions implicit in model waiting for the theorist to catch up and make them explicit

n Some examples:

- Similarity of *serial position* contributes to processing difficulty as well
  - Japanese studies in progress to test this
- Primacy/recency effect in PP attachment as well as RC attachment