Incremental and Predictive Interpretation:

Experimental evidence and possible accounts

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The main question

What is the nature of real-time semantic interpretation?

- Do we build meaning representations of the kind that are pervasive in formal semantics incrementally and predictively when language is used in real time?

- ... in much the same way that the real-time construction of syntactic representations has been argued to be incremental and predictive (Steedman 2001, Lewis and Vasishth 2005, Lau 2009, Hale 2011 among many others)

Previous / related work

- significant amount of work in psycholinguistics on incremental interpretation (Hagoort et al. 2004, Pickering et al. 2006 among many others), but this research usually focuses on:
  - the processing of lexical semantic and syntactic representations, and
  - the incremental integration of world knowledge into the language interpretation process

- The processing of logical representations of the kind formal semanticists are interested in is much less studied.

Previous / related work

- similarly, significant amount of work in natural language processing / understanding on incremental interpretation (Poesio 1994, Hough et al. 2015 among many others)

- but this research usually discusses it from a formal and implementation perspective, and focuses much less on the cognitive aspects of processing semantic representations

  (Steedman 2001 and related work is a notable exception.)

The phenomena

- We're interested in the incremental processing of *semantic* representations.
- Major challenge: what phenomena can tease apart the syntactic and semantic components of the interpretation process?
- The pervasive aspects of meaning composition that are syntax based / driven cannot provide an unambiguous window into the nature of semantic representation building
- The incremental and predictive nature of real-time compositional interpretation could be primarily or exclusively due to our processing strategies for building syntactic representations.

The phenomena

The interaction of:

- presupposition resolution, and
- conjunctions vs. conditionals

  (where conditionals have a sentence-final antecedent)

promises to provide us with the right kind of evidence.

Consider the contrast between these two 'cataphoric' examples:

(1) Tina will have coffee with Alex again AND she had coffee with him at the local café.

(2) Tina will have coffee with Alex again IF she had coffee with him at the local café.

The phenomena

1. Tina will have coffee with Alex again AND she had coffee with him at the local café.
2. Tina will have coffee with Alex again IF she had coffee with him at the local café.

If the construction of semantic representations is:

- incremental – the interpreter processes IF as soon as it is encountered, and
- predictive – the interpreter builds a semantic evaluation structure s.t. the upcoming *if*-clause provides (some of) the interpretation context for the previously processed matrix clause

then we expect to see:

- a facilitation / speed-up in the second clause *she had coffee with him . . .*) after IF (2) compared to AND (1)

Preview: which is what our experimental results actually show.

The phenomena

1. Tina will have coffee with Alex <u>again</u> AND she had coffee with him at the local café.
2. Tina will have coffee with Alex <u>again</u> IF she had coffee with him at the local café.

In more detail:

- we expect the second conjunct in (1) to be more difficult than the antecedent in (2)
- AND in (1) signals that an antecedent that could resolve the *again*-presupposition is unlikely to come after this point

  . . . since the second conjunct is interpreted relative to the context provided by the first conjunct
- but IF in (2) leaves open the possibility that a suitable resolution for the *again*-presupposition is forthcoming

  . . . since the first clause is interpreted relative to the context provided by the second clause

The phenomena

1. Tina will have coffee with Alex again AND she had coffee with him at the local café.
2. Tina will have coffee with Alex again IF she had coffee with him at the local café.

Note: the different expectations triggered by the interaction of

- the presupposition trigger *again*, and
- the operators AND vs. IF

are semantically driven.

Nothing in the syntax of conjunction vs. *if*-adjunction could make a successful presupposition resolution more or less likely.

Why do we (as formal semanticists) care?

Exploring the formal semantics / cognitive psychology divide and searching for ways to bridge it is firmly rooted in the tradition of dynamic semantics. Kamp (1981) begins like this:

> *Two conceptions of meaning have dominated formal semantics of natural language.*
>
> *The first of these sees meaning principally as that which determines conditions of truth. This notion, whose advocates are found mostly among philosophers and logicians, has inspired the disciplines of truth-theoretic and model-theoretic semantics.*
>
> *According to the second conception meaning is, first and foremost, that which a language user grasps when he understands the words he hears or reads. This second conception is implicit in many studies [. . .] which have been concerned to articulate the structure of the representations which speakers construct in response to verbal input.*

Why do we (as formal semanticists) care?

> *[. . .] these two conceptions [. . .] have remained largely separated for a considerable period of time. This separation has become an obstacle to the development of semantic theory [. . .] The theory presented here is an attempt to remove this obstacle. It combines a definition of truth with a systematic account of semantic representations.* (*Kamp 1981, p. 189*)

The implicit overarching goal for us as (cognitive) scientists studying natural language meaning:

- a formally explicit account of natural language interpretive *behavior*
- i.e., a mathematically explicit, unified theory of semantic/pragmatic competence **and** performance

Specific goals and road map for the talk

- Present the full experimental setup for the self-paced reading experiment we ran to investigate these predictions
- Experimental setup: more complicated than initially expected; we discuss why that is and identify methodological issues related to using self-paced reading to study this kind of semantic issues
- To this end, we begin with another self-paced reading experiment that used pronominal anaphora/cataphora (rather than cataphoric presupposition resolution)
- The results of that experiment were suggestive, but not strong enough, which prompted us to:
  - complicate the experimental design
  - use presuppositional *again* to elicit stronger responses
- Outline two different types of accounts that capture the incremental and predictive nature of real-time construction of meaning representations
  - in the semantics: Incremental Dynamic Predicate Logic
  - in the processor: An ACT-R based left-corner style DRT parser

Donkey cataphora

Donkey cataphora: "a configuration in which a pronoun precedes and depends for its interpretation on an indefinite that does not c-command it." (Elbourne 2009, p. 1)

(3) If it is overcooked, a hamburger doesn't taste good. (Chierchia 1995, p. 129)

(4) If she finds it spectacular, a photographer takes many pictures of a landscape. (Chierchia 1995, p. 130)

(5) If it enters his territory, a pirate usually attacks a ship. (Chierchia 1995, p. 130)

(6) If it spots a mouse, a cat attacks it. (Chierchia 1995, p. 130)

(7) If a foreigner asks him for directions, a person from Milan replies to him with courtesy. (Chierchia 1995, p. 130)

(8) John won't eat it if a hamburger is overcooked. (Elbourne 2009, p. 3)

Donkey cataphora

Certain configurations are not acceptable (Elbourne 2009, p. 2):

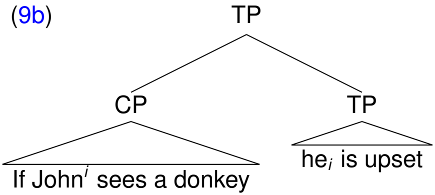
(9) a. John^i is upset if he$_i$ sees a donkey.

b. If John^i sees a donkey, he$_i$ is upset .

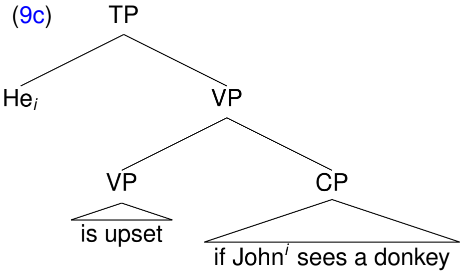
c. *He$_i$ is upset if John^i sees a donkey.

(9c) – presumably a Principle C violation given the low, VP-level adjunction site for sentence-final *if*-clauses.

(9b)



(9c)



Donkey cataphora

Evidence that a sentence-final *if*-clause is VP-adjoined (see Bhatt and Pancheva 2006 for more discussion):

- Condition C effects: (9b) vs. (9c) above

No such effects for the object position – (8) above, and also:

(10) Bill visits her_i if $Mary_i$ is sick.

- VP ellipsis

(11) a. I will leave if you do, and John will [~~leave if you do~~] too / do so too.

b. I will leave if you do, and John will [~~leave if you do~~] too / do so too.

- VP topicalization

(12) I told Peter to take the dog out if it rains, and [take the dog out if it rains] he will. (Iatridou 1991, p. 12)

Experiment 1: *and*/*if* and anaphora/cataphora

So no 'ordinary' syntax-mediated binding from a c-commanding position for DO donkey cataphora in conditionals with sentence-final *if* clauses ⇒ a 'true' example of donkey cataphora that we can use.

Exp.1: 2 × 2 design – *and*/*if* × DO anaphora / cataphora

(13) *and* & anaphora:
An electrician examined a radio for several minutes AND his helpful colleague held it that whole time.

(14) *if* & anaphora:
An electrician examined a radio for several minutes IF his helpful colleague held it that whole time.

(15) *and* & cataphora:
An electrician examined it for several minutes AND his helpful colleague held the radio that whole time.

(16) *if* & cataphora:
An electrician examined it for several minutes IF his helpful colleague held the radio that whole time.

Experiment 1: method

- self-paced reading (Just et al. 1982): the words are hidden (letters replaced with dashes) and only one word is uncovered at a time with a spacebar press
- if the sentence is:

`An electrician examined a radio for ...`

i. it is initially displayed as:

`-- ----------- -------- - ----- --- ...`

ii. after one spacebar press:

`An ----------- -------- - ----- --- ...`

iii. after another spacebar press:

`-- electrician -------- - ----- --- ...`

iv. after a third spacebar press:

`-- ----------- examined - ----- --- ...`

- the participant / reader decides when to press the spacebar to read the next word – hence, *self-paced* reading

Experiment 1: method

- Kazanina et al. (2007) successfully used self-paced reading to show that a cataphoric pronoun triggers an active search for an antecedent in the following material
- furthermore, this search takes into account structural constraints (principle C) from an early stage
- that is, cataphoric dependencies are processed with a syntactically constrained search mechanism

  (similar to the mechanism used for processing long-distance *wh*-dependencies; Stowe 1986, Traxler and Pickering 1996, Wagers and Phillips 2009 a.o.)
- Kazanina et al. (2007) take the temporal priority of syntactic information to be evidence for the incremental and predictive nature of syntactic comprehension
- Our question: is this active search mechanism also semantically constrained?

Experiment 1: method

- each of the 4 conditions tested 7 times (28 items total)
- 107 fillers, monoclausal and multiclausal, conditionals, conjunctions, *when*-clauses, relative clauses, quant., adv.
- 62 native speakers of Eng. participated (UCSC u/g students)
- completed the exp. online for course (extra-)credit on a UCSC hosted installation of Alex Drummond's IBEX platform (`http://code.google.com/p/webspr/`)
- each item passed through all 4 conditions, 4 lists following a Latin square design; each list: every item appeared once, 7 items per cond.; items rotated through cond.s across the 4 lists
- participants rotated through the 4 lists; every participant responded to 135 stimuli (28 items + 107 fillers), order randomized for every participant (any two items separated by at least one filler)
- 54 comprehension questions with correct/incorrect answers, 9 after exp. items; 5 outlier participants excluded because of low accuracy (more than 20% incorrect answers)

Experiment 1: predictions

Predictions (assuming a deep enough, incremental & predictive interpretation):

- the regular anaphora cases provide the baseline
- in the baseline conditions, we expect the second clause to be more difficult after *if* because of extra cognitive load coming from two sources
    i. semantics of conditionals vs. conjunctions
    …for conditionals, we generate a hypothetical intermediate interpretation context satisfying the antecedent, and we evaluate the consequent relative to this context
    …we need to maintain both the actual, global interpretation context and this intermediate one to complete the interpretation of the conditional
    …no extra load like that for conjunctions

Experiment 1: predictions

ii. reanalysis of the matrix clause for conditionals, but not for conjunctions
…semantically, the matrix clause is analyzed / interpreted relative to the global context until *if* is reached
…at that point, the matrix clause has to be reinterpreted relative to the intermediate, antecedent-satisfying context
…no such semantic reanalysis for conjunctions

Experiment 1: predictions

- for the cataphora (non-baseline cases), we expect a cognitive load reversal
- *and* signals that no suitable antecedent for the cataphor is forthcoming

  ... since the second clause is interpreted relative to the context provided / updated by the first clause
- *if* triggers semantic reanalysis and leaves open the possibility that a suitable antecedent for the cataphor is forthcoming

  ... since the first clause is interpreted relative to the context provided / updated by the second clause
- so we expect to see a speed-up / negative interaction of *if* $\times$ cataphora

Preview: predictions only partially confirmed.

- baseline IF harder (statistically significant)
- IF $\times$ cataphora interaction negative, but not significant

Experiment 1: regions of interest

(13–16) An electrician examined a radio/it for several minutes and/if his helpful colleague held it/the radio that whole time.

Regions of interest (ROIs):

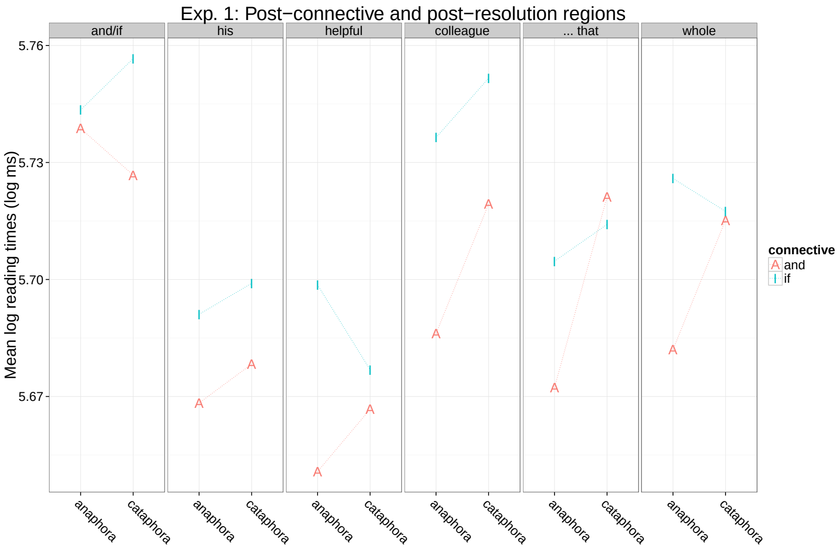
- the post-connective ROIs: . . . his helpful colleague . . .
- (secondarily) the post-resolution ROIs: . . . that whole . . .

The post-resolution ROIs are of merely secondary interest because of the asymmetry between:

- the anaphora conditions, which contain an indefinite (*a radio*)
- the cataphora conditions, which contain an definite (*the radio*)

We introduced a definite in the cataphora conditions because we wanted the items to be more natural overall. This doesn't affect the ROIs of primary interest, which precede the definite.

Experiment 1: plots



(created with `R` and `ggplot2`; R Core Team 2014, Wickham 2009)

Experiment 1: data analysis

- linear mixed-effects models (estimated with `R`, `lme4`, `lmerTest`; R Core Team 2014, Bates et al. 2014, Kuznetsova et al. 2014)
- response: log-transformed readings times (log RTs) to mitigate right-skewness of RTs
- predictors (fixed effects): main effects of CONNECTIVE and ANA/CATAPHORA, and their interaction
- CONNECTIVE: AND (reference level) vs. IF
- ANA/CATAPHORA: ANAPHORA (reference level) vs. CATAPHORA
- crossed random effects for subjects and items
- maximal random effect structure that converged (Barr et al. 2013), usually subject and item random intercepts, and subject and item random slopes for at least one of the two main effects

Experiment 1: data analysis

	his			**helpful**			**colleague**		
	MLE	SE	*p*	MLE	SE	*p*	MLE	SE	*p*
INT.	5.67	0.04	0	5.65	0.04	0	5.69	0.04	0
IF	0.02	0.02	0.3	**0.05**	**0.02**	**0.04**	**0.05**	**0.02**	**0.04**
CATA	0.01	0.02	0.7	0.02	0.02	0.4	0.03	0.02	0.16
IF $\times$ CATA	-0.003	0.03	0.9	-0.04	0.03	0.15	-0.02	0.03	0.6

	that			**whole**		
	MLE	SE	*p*	MLE	SE	*p*
INT.	5.68	0.04	0	5.69	0.04	0
IF	0.03	0.02	0.20	0.03	0.02	0.24
CATA	**0.04**	**0.02**	**0.07**	0.03	0.02	0.18
IF $\times$ CATA	-0.03	0.03	0.26	-0.03	0.03	0.43

Exp. 1: generalizations and their consequences

- baseline IF (i.e., IF & ANAPHORA) is more difficult than baseline AND (i.e., AND & ANAPHORA)
- this is compatible with the hypothesis that to interpret conditionals, we need to maintain both
  - the actual, global interpretation context, and
  - the intermediate, antecedent-satisfying context
- ...and/or with the hypothesis that the matrix clause is reanalyzed in conditionals with a final *if*-clause
  - initially interpreted relative to the global context until *if* is reached,
  - then reinterpreted at that point relative to the intermediate, antecedent-satisfying context

Exp. 1: generalizations and their consequences

- CATAPHORA seems to be more difficult than ANAPHORA for AND, but the effect never reaches significance

  (close to significant in the first ROI after cataphora is resolved)
- maybe the AND & CATAPHORA condition is simply too hard, so readers stop trying to fully comprehend the sentence and speed up; this will obscure the IF $\times$ CATA interaction
- there is a negative interaction between IF and CATAPHORA in all ROIs, i.e., IF seems to facilitate CATAPHORA,

  (as expected if sem. evaluation is incremental and predictive)

  but this effect is not significant either
- the consistent negative interaction is promising, so let's elicit it with a hard presupp. trigger like *again* (Abusch 2010, Schwarz 2014 a.o.), which might have a larger effect
- and let's add a (mis)match manipulation to control for readers speeding up through conditions that are too hard

Exp. 2: (mis)match and *and*/*if* and $+/-$ cataphora

2 × 2 × 2 design: *(mis)match* × *and*/*if* × nothing/cataphora

(17) match & *and* & cataphora:
Jeffrey will *argue* with Danielle again AND he *argued* with her in the courtyard last night.

(18) match & *and* & nothing:
Jeffrey will *argue* with Danielle AND he *argued* with her in the courtyard last night.

(19) match & *if* & cataphora:
Jeffrey will *argue* with Danielle again IF he *argued* with her in the courtyard last night.

(20) match & *if* & nothing:
Jeffrey will *argue* with Danielle IF he *argued* with her in the courtyard last night.

Exp. 2: (mis)match and *and*/*if* and $+/-$ cataphora

(21) mismatch & *and* & cataphora:
Jeffrey will *argue* with Danielle <u>again</u> AND he *played* with her in the courtyard last night.

(22) mismatch & *and* & nothing:
Jeffrey will *argue* with Danielle AND he *played* with her in the courtyard last night.

(23) mismatch & *if* & cataphora:
Jeffrey will *argue* with Danielle <u>again</u> IF he *played* with her in the courtyard last night.

(24) mismatch & *if* & nothing:
Jeffrey will *argue* with Danielle IF he *played* with her in the courtyard last night.

Experiment 2: method

- similar to Exp. 1, but there are some differences
- self-paced reading + acceptability judgment at the end; 5-point Likert scale, 1 (very bad) through 5 (very good); acceptability judgment elicited on a new screen after every item or filler; every item followed by a comprehension question
- each of the 8 conditions tested 4 times (32 items total; one item had a typo, discarded from all subsequent analyses)
- 70 fillers, monoclausal and multiclausal, conditionals, conjunctions, *when*-clauses, relative clauses, quant., adv.
- 32 native speakers of Eng. participated (UCSC u/g students)
- completed the exp. online for course (extra-)credit on a UCSC hosted installation of the IBEX platform

Experiment 2: method

- each item passed through all 8 conditions, 8 lists following a Latin square design; each list: every item appeared once, 4 items per cond.; items rotated through cond.s across the 8 lists
- participants rotated through the 8 lists; every participant responded to 102 stimuli (32 items + 70 fillers), order randomized for every participant (any two items separated by at least one filler)
- fillers that were both acceptable (*Bob ate his burger and he rented something to watch, but he didn't say what*) and unacceptable (*Willem visited Paris because Sarah visited Amsterdam too*) were included; all participants exhibited the expected difference in acceptability ratings between these 2 types of fillers
- 72 comprehension questions with correct/incorrect answers, 32 after exp. items; accuracy for all participants above 80%

Experiment 2: predictions

- the 4 MATCH conditions are parallel to the 4 conditions in Exp. 1, so we make similar predictions for them
- the MISMATCH conditions allow us to control for readers speeding up through conditions that are too hard
- if AND & CATAPHORA is too hard and readers stop trying to fully comprehend the sentence, we won't see a difference between the MATCH and MISMATCH cases
- correspondingly, if readers interpret IF & CATAPHORA deeply enough, and incrementally and predictively, we expect a slow down for the MISMATCH condition
- that is, we expect a positive 3-way interaction for IF$\times$CATAPHORA$\times$MISMATCH: readers expect a suitable antecedent for the *again* presupposition, and the antecedent is not provided in the MISMATCH cases

  (surprisal $\Rightarrow$ difficulty $\Rightarrow$ higher RTs; see Hale 2001 and Levy 2008 a.o. for similar arguments w.r.t. syntactic comprehension)

Preview: predictions confirmed.

Experiment 2: regions of interest

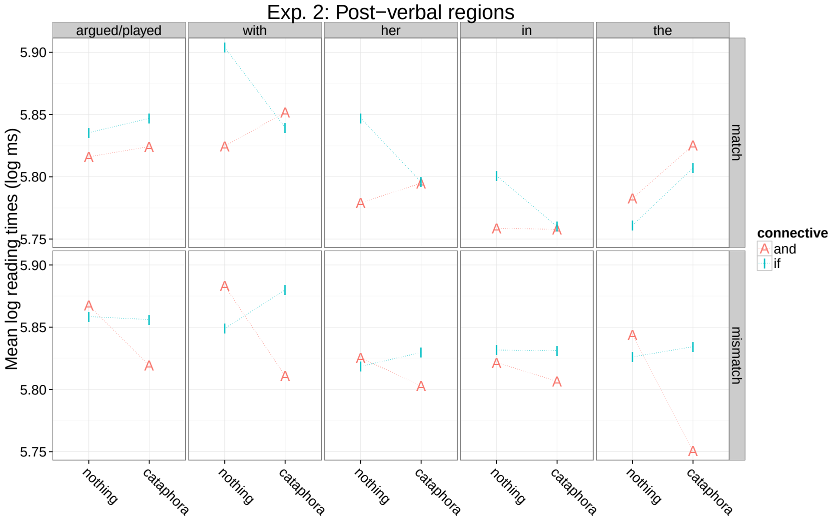
(17–24) Jeffrey will argue with Danielle ∅/again and/if he argued/played with her in the courtyard last night.

Regions of interest (ROIs):

- the post-verbal ROIs in the second clause:
  ...with her in the ...

Not more than 4 words because the 5th word was the final one for some items (wrap-up effect).

Experiment 2: plots



Experiment 2: data analysis

- linear mixed-effects models
- response: log RTs
- predictors (fixed effects): main effects of CONNECTIVE and NOTHING/CATAPHORA, MATCH/MISMATCH and their 2-way and 3-way interactions
- CONNECTIVE: AND (reference level) vs. IF
- NOTHING/CATAPHORA: NOTHING (reference level) vs. CATAPHORA
- MATCH/MISMATCH: MATCH (reference level) vs. MISMATCH
- crossed random effects for subjects and items
- maximal random effect structure that converged, usually subject and item random intercepts, and subject and item random slopes for at least two of the three main effects

Experiment 2: data analysis

	with			**her**		
	MLE	SE	p	MLE	SE	p
INT.	5.83	0.07	0	5.77	0.06	0
CATA	0.05	0.04	0.21	0.05	0.04	0.30
MISMATCH	0.05	0.04	0.25	0.04	0.04	0.33
IF	**0.08**	**0.04**	**0.054**	**0.07**	**0.04**	**0.084**
CATA × MISMATCH	**-0.11**	**0.06**	**0.056**	−0.05	0.06	0.42
CATA × IF	**-0.13**	**0.06**	**0.026**	**-0.11**	**0.06**	**0.077**
MISMATCH × IF	**-0.10**	**0.06**	**0.083**	−0.06	0.06	0.30
CATA × MISMATCH × IF	**0.20**	**0.08**	**0.015**	0.10	0.08	0.22

	in			**the**		
	MLE	SE	p	MLE	SE	p
INT.	5.76	0.06	0	5.78	0.07	0
CATA	0.03	0.04	0.50	0.05	0.04	0.23
MISMATCH	0.06	0.05	0.19	0.07	0.05	0.15
IF	0.05	0.04	0.24	−0.003	0.04	0.96
CATA × MISMATCH	−0.03	0.06	0.59	**-0.14**	**0.06**	**0.03**
CATA × IF	−0.08	0.05	0.15	−0.04	0.06	0.54
MISMATCH × IF	−0.02	0.05	0.73	−0.02	0.06	0.76
CATA × MISMATCH × IF	0.06	0.08	0.42	0.11	0.09	0.19

Exp. 2: generalizations and their consequences

- just as in Exp. 1, baseline IF (i.e., IF & NOTHING & MATCH) is more difficult than baseline AND (i.e., AND & NOTHING & MATCH)
- but in Exp. 2, this might happen because the IF condition (*Jeffrey will argue with Danielle if he argued with her in the courtyard last night*)

  is less felicitous than the corresponding AND condition (*Jeffrey will argue with Danielle and he argued with her in the courtyard last night*)
- this is not corroborated by the acceptability judgments: the only statistically significant fixed effect was a positive main effect for IF

  (we used mixed-effects ordinal probit models to analyze that data; full fixed-effect structure – main effects + all interactions; estimated with the `ordinal` package, Christensen 2013)
- that is, baseline IF is more acceptable than baseline AND

Exp. 2: generalizations and their consequences

- so Exp. 2 is compatible with the hypothesis that conditionals are harder than conjunctions because
  - we need to maintain two evaluation contexts, and/or
  - the matrix is semantically reanalyzed when *if* is reached
- the significant negative interaction of MISMATCH $\times$ IF (note: *again* is not present here) basically cancels out the main effect of IF
- that is, conditionals with non-identical VP meanings in the antec. and conseq. clauses are interpreted more easily than conditionals with identical VP meanings

  ... about as easily as conjunctions with non-identical VP meanings in the two conjuncts

Exp. 2: generalizations and their consequences

- there are no main effects of CATAPHORA and MISMATCH, but their 2-way interaction is negative and significant (or close to significant) in 2 out of 4 regions
- whenever (close to) significant, this interaction effectively cancels the main effects of both MISMATCH and CATAPHORA
- that is, the AND & CATAPHORA & MISMATCH condition is about as difficult as the reference condition AND & NOTHING & MATCH
- this suggests that participants stopped trying to properly interpret this difficult condition (AND & CATAPHORA & MISMATCH) and moved on / sped up

Exp. 2: generalizations and their consequences

- there is a (close to) significant negative interaction of CATAPHORA×IF in the two regions immediately following the verb (note: we are discussing MATCHING conditions)
- in both regions, this 2-way interaction effectively cancels out the positive main effects of CATAPHORA and IF put together
- this is exactly the configuration we were looking for in Exp. 1, only it didn't reach significance there
- that is, IF facilitates the processing of CATAPHORA, even though IF and CATAPHORA on their own are more difficult
- this supports the hypothesis that the construction of formal semantic representations is incremental and predictive

Exp. 2: generalizations and their consequences

- the statistically significant, positive 3-way interaction of CATAPHORA × IF × MISMATCH in the region immediately following the verb provides further empirical support for the hypothesis that the construction of formal semantic representations is incremental and predictive
- the MISMATCH is surprising because the human interpreter expects to find a suitable antecedent for the *again* presupposition, and that expectation is not satisfied

Summary

Exp. 1 and Exp. 2 provide coherent support for the incremental and predictive nature of the process of constructing meaning representations of the kind employed in formal semantics.

Should we account for this? If so, how?

The main questions at this point:

As formal semanticists, should we account for the incremental and predictive nature of the real-time semantic interpretation process? If so, how?

To contextualize this question a bit more – beyond the injunction in Kamp (1981) – consider the corresponding debate on the syntax side.

Phillips and Lewis (2013, p. 14) identify two reasonable positions that working linguists more or less implicitly subscribe to in practice:

- Principled extensionalism
- Strategic extensionalism

Should we account for this?

Principled extensionalism:

- A grammar / grammatical theory is merely an abstract characterization of a function whose extension is all and only the well-formed sentences of a given language.
- Individual components of a grammatical theory have no independent status as mental objects or processes: components of an abstract function, not of a more concrete description of a mental system.
- Beyond the reach of most empirical evidence aside from acceptability (or truth-value / entailment) judgments.
- The 'principled' part: the extensionalist enterprise is an end in itself, relevant even if lower-level characterizations of the human language system are provided (algorithmic / mechanistic, or implementation / neural level; Marr 1982) .
- The linguist's task: characterize what the human language system computes and distinguish it from how speakers actually carry that out (the psycholinguist's task).

Should we account for this?

Strategic extensionalism:

- Formulating a grammatical theory is not an end in itself, but a reasonable interim goal.
- Ultimate goal: move beyond extensional description to a more detailed, mechanistic understanding of the human language system.
- Describing an abstract function that generates all of the grammatical sentences of a language is just a first step in understanding how speakers actually comprehend / produce sentences in real time.
- We seek theories that capture how sentences are put together, and not just what their final form is.
- So we should try to account for left-to-right structure building mechanisms (both syntactic and semantic structure).

How should we account for this?

How to account for incremental & predictive sem. int.?

- This is the main open question for this investigation
- Two main types of approaches: account for this in the semantics vs. the processor
- Two proposals (one in each category); detailed empirical and theoretical evaluation left for a future occasion

I. In the semantics – parallel to the proposal in Phillips (1996, 2003) on the syntax side.

- Phillips (1996, 2003): syntactic structures are built left-to-right, not top-down / bottom-up; the incremental left-to-right system is the only structure-building system that humans have; 'the parser is the grammar'
- Our specific proposal on the semantics side: Incremental Dynamic Predicate Logic (IDPL), building on the incremental propositional logic system in Vermeulen (1994)

How should we account for this?

II. In the processor – parallel to the proposal in Hofmeister et al. (2013) on the syntax side.

- 'many of the findings from studies putatively supporting grammar-based interpretations of island phenomena have plausible, alternative interpretations rooted in specific, well-documented processing mechanisms.' (Hofmeister et al. 2013, p. 44)
- Our specific proposal on the processing side: an ACT-R based (Anderson and Lebiere 1998), left-corner style parser for DRT (Kamp and Reyle 1993)

  ...in the style of the (Lisp) ACT-R left-corner parser for syntactic representations in Lewis and Vasishth (2005)

  ...but we implement ours in Python ACT-R (Stewart 2007, Stewart and West 2007)

Incremental DPL vs. Left-corner style DRT Parser

Incremental DPL vs. Left-corner style DRT parser

What interpretation objects are incrementally constructed:

- IDPL builds trees of DPL info states (more like: trees of DPL denotations) incrementally
- the DRT parser ends up having to do a very similar thing to keep track of the accessibility relation between DRSs – needed for pronoun and cataphora resolution
- no clear difference here except for the fact that the ACT-R based DRT parser automatically makes specific predictions about the time-course of interpretation
- so as a theory, the DRT parser is more falsifiable but also less modular / possibly more brittle

Incremental DPL vs. Left-corner style DRT parser

How anaphoric / cataphoric pronouns are resolved:

- IDPL (just like DPL) says nothing about this
- especially for cataphora, it is pretty clear that a goal to resolve the pronoun has to be separately maintained as the regular incremental interpretation process keeps marching forward
- the cataphoric goal is (repeatedly) retrieved during the incremental processing of the post-cataphoric text and its resolution is attempted (exp. evidence: Kazanina et al. 2007, Exp. 2 above)
- in IDPL (or any other purely semantic / competence account), a separate mechanism has to be postulated to keep track of this unresolved goal
- no need for additional mechanisms in a performance theory: the idea that high-level cognitive processes are goal driven is at the core of ACT-R (and other cognitive architectures)

I. Incremental Dynamic Predicate Logic (IDPL)

Plan: extend the incremental semantics for Dynamic Propositional Logic (DPropL) in Vermeulen (1994) to Dynamic Predicate Logic (DPL; Groenendijk and Stokhof 1991).

We only give here a taste of how a left-to-right incremental dynamic semantics can be provided – just basic DPropL.

(25) **The syntax of DPropL.**
Given a set of atomic texts A (i.e., atomic prop. variables), the set of texts T_A based on A (i.e., the set of well-formed prop. formulas) is the smallest set s.t.:

a. $A \subseteq T_A$
b. $\bot \in T_A$
c. $\{\textbf{if}, \textbf{then}, \textbf{end}\} \subseteq T_A$
d. If $\varphi, \psi \in T_A$, then $\varphi; \psi \in T_A$ (conjunction, i.e., text merging / concatenation).

I. Incremental Dynamic Predicate Logic (IDPL)

- $\bot$ is the formula that is always false: $[\![\bot]\!] = \mathbb{F}$
- negation can be defined in terms of implication and $\bot$ following the classical abbrev. $\neg\varphi := \varphi \to \bot$; see (26)
- the formula $\top$ that is always true $[\![\top]\!] = \mathbb{T}$ is defined following the classical abbrev. $\top := \neg\bot \; (= \bot \to \bot)$
- disjunction can be defined via the De Morgan laws

(26) Abbreviations:

a. $\neg\varphi :=$ **if**; φ; **then**; $\bot$; **end**

b. $\top := \neg\bot$ (= **if**; $\bot$; **then**; $\bot$; **end**)

c. $\varphi \vee \psi := \neg(\neg\varphi;\ \neg\psi)$

I. Incremental Dynamic Predicate Logic (IDPL)

We want the semantics of DPropL to respect three principles (Vermeulen 1994, pp. 244-246):

i. Incrementality: we can interpret texts as we hear them.

ii. Pure compositionality: 'pure' – we do not assume that a full syntactic analysis precedes interpretation; unlike standard (neo)Montagovian semantics, or even the incremental DRS construction algorithm in Kamp and Reyle (1993)

iii. Break-in: every segment of a text should be interpretable, even if what comes after, or came before, is unknown; wherever we 'break in' in a text, interpretation should be possible

Together, (*i*-*iii*) entail associativity: text meanings have to form an algebra with an associative operation ('merger' / conjunction) by which the meanings can be glued together.
This is OK for texts that are actually conjoined:

(27) Bob inherited a donkey (*p*), and Jane bought it from him (*q*), and she sold it to Bill (*r*).

(28) $[\![(p; q); r]\!] = [\![p; (q; r)]\!]$

I. Incremental Dynamic Predicate Logic (IDPL)

The problem: conditionals do not have an associative semantics. The text in (29) is intuitively interpreted as in (30), not as in (31) (if *p* is false, the text is false, not true).

(29) The driver was not working that night (*p*) and if the butler was working that night (*q*), the butler committed the murder (*r*). $\rightsquigarrow p; \textbf{if}; q; \textbf{then}; r; \textbf{end}$

(30) Intended interpretation: $p; (\textbf{if}; q; \textbf{then}; r; \textbf{end})$
(in classical prop. logic: $p \wedge (q \rightarrow r)$)

(31) By associativity: $(p; \textbf{if}; q); \textbf{then}; r; \textbf{end}$
(in classical prop. logic, basically: $(p \wedge q) \rightarrow r$)

An incremental, fully associative semantics forces the bracketing in (32) – which is the incorrect interpretation in (31):

(32) $((((p; \textbf{if}); q); \textbf{then}); r); \textbf{end}$

I. Incremental Dynamic Predicate Logic (IDPL)

(30) $p; (\textbf{if}; q; \textbf{then}; r; \textbf{end})$

The basic solution: memory, i.e., semantic evaluation contexts are update histories. We interpret (30) as follows:

> *We store the information that p in our memory before we interpret q.*
>
> *This information [contributed by q] is again stored before we interpret r.*
>
> *Now we can construct from the information that we have stored the information that* **if** *q* **then** *r.*
>
> *Finally this information can be added to the information that p.*
>
> *[W]e do not need brackets to tell us how [. . .] to store the information: the special elements* **if**, **then** *and* **end** *will tell us exactly what has to be done. (Vermeulen 1994, p. 248)*

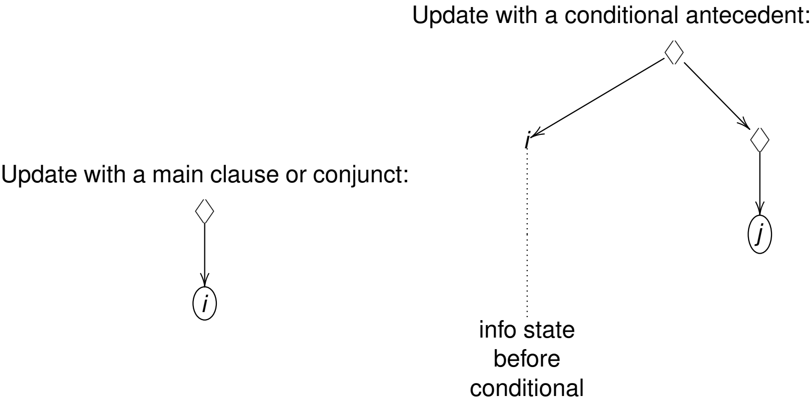
I. Incremental Dynamic Predicate Logic (IDPL)

Technically:

- we formalize DPropL models as extended monoids in the sense of Visser (2002)
- Vermeulen (1994) takes them to be Heyting algebras, but extended monoids are:
  - more general: useful when we move to DPL
  - more directly related to the relational models used in DPL, where formulas denote binary relations between variable assignments
- the elements in the extended monoid are updates / formula denotations
- ultimately, we follow Vermeulen (1994) and propose a 'tree based' incremental semantics for DPropL and DPL: the tree encodes update histories, the nodes in the tree are updates / formula denotations
- conditionals introduce embedded / subordinate update histories

I. Incremental Dynamic Predicate Logic (IDPL)

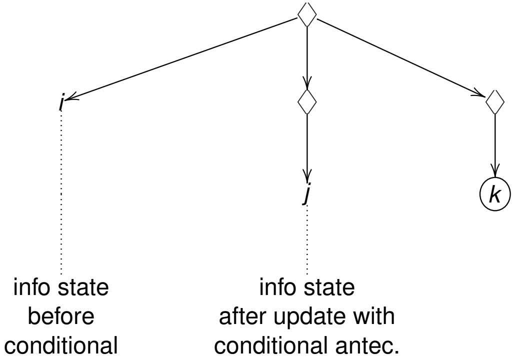
Figure : Types of updates (I)



I. Incremental Dynamic Predicate Logic (IDPL)

Figure : Types of updates (II)

Update with a conditional consequent:



In much more detail: 'Incremental interpretation and dynamic semantics' (Brasoveanu & Dotlačil 2015 ms.), **http://people.ucsc.edu/~abrsvn/inc_int_and_dyn_sem.pdf**

II. An ACT-R based left-corner DRT parser

Main idea (in the spirit of Lewis and Vasishth 2005):

- use an independently motivated, general cognitive architecture (ACT-R, Anderson and Lebiere 1998)

  with its theory of declarative memory one one hand, and procedural memory (cognitive skill) on the other,

  to give a mechanistic account of the specific task of simultaneous syntactic and semantic parsing
- on the syntax side: we incrementally and predictively assemble a tree-like representation by incrementally constructing feature structures / attribute-value matrices – chunks, in ACT-R terms – of the kind used in HPSG (Pollard and Sag 1994) a.o.
- on the semantics side: in parallel to syntactic parsing and in a similar way, we incrementally and predictively assemble a DRT (Kamp and Reyle 1993) representation for the meaning of a sentence

II. An ACT-R based left-corner DRT parser

Importantly, the proposal (and implementation) enables us to:

i. fully and explicitly integrate linguistic theory and experimental data: integrated end-to-end accounts of real-time language interpretation processes

- from detailed, structured syntactic and formal semantics analyses on one end
- to accuracy and latency measures of the kind provided by psycholinguistic experiments at the other end

ii. make specific, fully formalized claims about processing complexity attributable to various factors:

- syntactic and/or semantic reanalysis
- recency of activation of particular syntactic and/or semantic representations
- utility of procedural rules for incrementally and predictively constructing such representations

II. An ACT-R based left-corner DRT parser I

Proof-of-concept parse of sentence (8) (*John won't eat it if a hamburger is overcooked*):

```
>> INITIALIZING lex. mem. (adding lex. info for words)
>> INITIALIZING goal stack
   -- top goal: scan first word
   -- next goal: predicting an S & an empty DRS

>> [TIME: 50 ms] Scanned and requested lex. info
   for ' John '; moving to next goal

>> [TIME: 150 ms] Attaching NP, the word ' John ',
   and predicting VP
>> Top goal: scan next word;
   next goal: the predicted VP
>> Current parse tree and context DRS in
   declarative mem. (DM):
```

II. An ACT-R based left-corner DRT parser II

```
-S /NP/-John

 __________
| u        |
|----------|
| john(u)  |
|__________|

>> [TIME: 200 ms] Scanned and requested lex. info
   for ' won't-eat '; moving to next goal

>> [TIME: 300 ms] Placing VP in the theta buffer for
   linking with the object discourse referent (dref)
>> VP not in DM yet, so VP info missing
   in the parse tree and DRS below
>> Attaching V (trans.), the word ' won't-eat ',
   and predicting NP
>> Top goal: scan next word;
   next goal: the predicted NP
```

II. An ACT-R based left-corner DRT parser III

```
>> Current parse tree and context DRS in DM:

-S /NP/-John

 _________
| u       |
|---------|
| john(u) |
|_________|

>> [TIME: 350 ms] Scanned and requested lex. info
   for ' it '; moving to next goal

>> [TIME: 450 ms] Marked the DRS of the pronoun
   in the old goal.
>> Top goal: recall pronoun antecedent in current DRS

>> [TIME: 500 ms] Placed DM request for a pronoun
   antecedent in current DRS
```

II. An ACT-R based left-corner DRT parser IV

```
>> Top goal: Check if any antecedent
   was found in current DRS

>> [TIME: 550 ms] No antec. found; no parent DRS to
   move to; marking the antec. as unknown

>> [TIME: 600 ms] Marking the result of pronoun
   resolution in the lex. buffer
>> Top goal: the goal before the pron. resolution

>> [TIME: 650 ms] Top goal: scan next word
>> Current parse tree and context DRS in DM:

      /NP/-it
   /VP
-S|   \V /-won't-eat
  |
   \NP/-John
```

II. An ACT-R based left-corner DRT parser V

```
 ____________________
| u v                |
|--------------------|
| will_not_eat(u,v)  |
| john(u)            |
| unknown(v)         |
|____________________|
```

```
>> [TIME: 700 ms] Scanned and requested lex. info
   for ' if '; moving to next goal

>> [TIME: 800 ms] Attaching CP, C, the word ' if ',
   and predicting S
>> Top goal: scan next word;
   next goal: the predicted S
>> Current parse tree and context DRS in DM:
```

II. An ACT-R based left-corner DRT parser VI

```
      /-S
   /CP
  |   \C /-if
-S|
  |      /NP/-it
  |   /VP
   \S|   \V /-won't-eat
     |
      \NP/-John
```

II. An ACT-R based left-corner DRT parser VII

```
 _________________________________________
|                                         |
|-----------------------------------------|
|    __        _______________________    |
|   |  |      | u v                   |   |
|  (|--|  ->  |-----------------------|)  |
|   |__|      | will_not_eat(u,v)     |   |
|             | john(u)               |   |
|             | unknown(v)            |   |
|             |_______________________|   |
|_________________________________________|
```

```
>> [TIME: 850 ms] Scanned and requested lex. info
   for ' a '; moving to next goal

>> [TIME: 950 ms] Attaching Det, the word ' a ',
   and predicting N and VP
>> Top goal: scan next word; next goal: the predicted N
```

II. An ACT-R based left-corner DRT parser VIII

```
>> Current parse tree and context DRS in DM:

      /S /NP/Det-a
   /CP
  |   \C /-if
-S|
  |      /NP/-it
  |   /VP
   \S|   \V /-won't-eat
     |
      \NP/-John
```

II. An ACT-R based left-corner DRT parser IX

```
 _________________________________
|                                 |
|---------------------------------|
|    ___      __________________  |
|   | w |    | u v              | |
| (|---| -> |------------------|) |
|   |___|    | will_not_eat(u,v)| |
|            | john(u)          | |
|            | unknown(v)       | |
|            |__________________| |
|_________________________________|
```

```
>> [TIME: 1000 ms] Scanned and requested lex. info
   for ' hamburger '; moving to next goal

>> [TIME: 1100 ms] Attaching N,
   and the word ' hamburger '
>> Top goal: scan next word
```

II. An ACT-R based left-corner DRT parser X

```
>> Current parse tree and context DRS in DM:

            /N /-hamburger
      /S /NP
   /CP       \Det-a
  |   |
  |   \C /-if
-S|
  |      /NP/-it
  |   /VP
   \S|   \V /-won't-eat
     |
      \NP/-John
```

II. An ACT-R based left-corner DRT parser XI

```
 _____________________________________________
|                                             |
|---------------------------------------------|
|     ______________       ___________________ |
|    | w            |     | u v               |    |
|  ( |--------------| ->  |-------------------| )  |
|    | hamburger(w) |     | will_not_eat(u,v) |    |
|    |______________|     | john(u)           |    |
|                         | unknown(v)        |    |
|                         |___________________|    |
|_____________________________________________|
```

```
>> [TIME: 1150 ms] Saved current goal;
   placed DM request for the cataphoric NP
>> Crucial START time: 1.15

>> [TIME: 1426 ms] Placed DM request for
   the original DRS of the cataphora
```

II. An ACT-R based left-corner DRT parser XII

```
>> [TIME: 1526 ms] Setting parent DRS as current DRS;
   DM request for a cataphora antec. in current DRS

>> [TIME: 1626 ms] Found cata antec.; marking it in
   the lex. buffer and adding it to DM
>> Crucial STOP time: 1.62616356782
>> Top goal: scan next word

>> [TIME: 1676 ms] Scanned and requested lex. info for '

>> [TIME: 1776 ms] Attaching VP, V (intrans.),
   and the word ' is-overcooked '
>> Top goal: scan next word
>> Current parse tree and context DRS in DM:
```

II. An ACT-R based left-corner DRT parser XIII

```
          /VP/V /-is-overcooked
       /S|
      |  |   /N /-hamburger
    /CP   \NP
   |  |      \Det-a
   |  |
-S|    \C /-if
   |
   |      /NP/-it
   |   /VP
    \S|   \V /-won't-eat
      |
       \NP/-John
```

II. An ACT-R based left-corner DRT parser XIV

```
 ______________________________________________
|                                              |
|----------------------------------------------|
|     _______________         ___________________     |
|    | w             |       | u v               |    |
|  ( |---------------|  ->   |-------------------| )  |
|    | overcooked(w) |       | (v = w)           |    |
|    | hamburger(w)  |       | will_not_eat(u,v) |    |
|    |_______________|       | john(u)           |    |
|                            |___________________|    |
|______________________________________________|

>> DONE!
Crucial STOP-START time (rounded to 3 digits): 0.476
```

II. An ACT-R based left-corner DRT parser XV

In much more detail: 'An ACT-R based left-corner style DRT parser: General design considerations and an implementation in Python ACT-R' (Brasoveanu & Dotlačil 2015 ms.), **http://people.ucsc.edu/~abrsvn/ACT-R_based_DRT_parser.pdf**

For an intro to Python ACT-R, see 'Introduction to (Python) ACT-R' (Brasoveanu 2015 ms.), **http://people.ucsc.edu/~abrsvn/Intro_to_Python_ACT-R.pdf** and references therein.

Summary and conclusions

- We used the interaction of:
  - cataphora and presupposition on one hand, and
  - conjunctions vs. conditionals on the other

  to provide evidence for the incremental and predictive nature of real-time meaning representation construction (the kind of meaning representations that are pervasive in formal semantics)
- a suitable experimental setup proved to be more complicated than initially expected: participants give up on interpreting stimuli that are too hard, hence misleading low RTs
- We outlined two types of accounts: capture the incremental and predictive nature of real-time semantic interpretation
  - in the semantics: Incremental Dynamic Predicate Logic (IDPL)
  - in the processor: an ACT-R based left-corner style DRT parser

Summary and conclusions

- Which (type of) account is right? Open question (for now, we hope)
- But both types need to be properly explored
- When we analyze phenomena in purely syntactic and/or semantic terms, we implicitly classify them as essentially belonging to the grammar
- Maybe we should consider alternative, processing based/laced explanations more systematically
- Hard to know *a priori* what the best explanation for a phenomenon is; e.g., the variety of accounts of NPI licensing proposed over the last 50 years or so

  (the mainly syntactic approach in Klima (1964), the semantic approach in Ladusaw (1979), the recent discussion of NPI processing effects in Vasishth et al. (2008) a.o.)

Summary and conclusions

- Enriching semantic evaluation contexts and providing a finer-grained recursive definition of truth and satisfaction for natural language interpretation (as in IDPL) might be the right thing to do
- But an independently needed theory of the real-time processing of semantic and syntactic representations (formulated in an independently motivated cognitive architecture) might also be able to account for crucial aspects of the phenomena under investigation
- Or a ‘hybrid’, semantic and processing, approach might be the right way to go
- But the only way to begin exploring this space of alternative explanations: formulate mathematically explicit theories of how formal semantic representations are processed in real time and evaluate them empirically and theoretically

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