Evidence of accurate logical reasoning in online sentence comprehension

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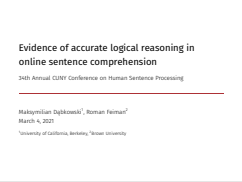

Introduction

logic in thought

- what is the status of logic in thought?

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logic in thought

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- logic studies relations among propositions

Logic, to characterize it broadly, is the formal study of relations which obtain among propositions.

logic in thought

- what is the status of logic in thought?
- logic studies relations among propositions

Dictum de omni

All rats love to eat.

∴ All spotted rats love to eat.

Logical schemata capture rules which govern correct inference. The example here is the *dictum de omni*, known at least since Aristotle, which is the principle that whatever is affirmed of a kind can be affirmed of its subkind. For example, if all rats love to eat, then since spotted rats are rats, it follows that all spotted rats love to eat.

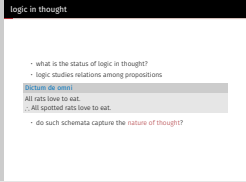
logic in thought

- what is the status of logic in thought?
- logic studies relations among propositions

Dictum de omni

All rats love to eat.
∴ All spotted rats love to eat.

- do such schemata capture the nature of thought?



While such schemata capture normatively accurate inferences, there has been a long standing debate over what their status is in human cognition. This is to say, are such logical schemata the rules of thought?

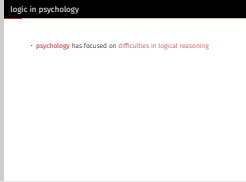
logic in psychology

logic in psychology

The status of logic in thought has been viewed very differently by the disciplines of psychology and linguistics.

logic in psychology

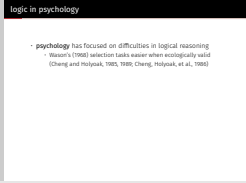
- psychology has focused on difficulties in logical reasoning



Research in psychology has tended to focus on documenting which logical tasks are more difficult than others and understanding why.

logic in psychology

- **psychology** has focused on difficulties in logical reasoning
  - Wason's (1968) selection tasks easier when ecologically valid (Cheng and Holyoak, 1985, 1989; Cheng, Holyoak, et al., 1986)



For example, Wason constructed a series of deductive reasoning puzzles which involved selecting cards. Subsequent research revealed that people are most logical on Wason selection tasks when the scenarios are ecologically valid. For example, when the imagined context involves enforcing a social rule.

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  - dual-process theories (Evans and Stanovich, 2013; Kahneman, 2011)

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  - dual-process theories (Evans and Stanovich, 2013; Kahneman, 2011)

Likewise, dual-process theorists of cognition have argued that normatively accurate reasoning requires effort and does not come naturally in the absence of logical training.

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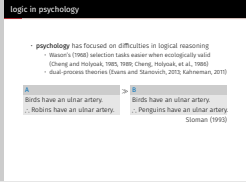
A		B
Birds have an ulnar artery. ∴ Robins have an ulnar artery.	≫	Birds have an ulnar artery. ∴ Penguins have an ulnar artery.

Sloman (1993)



Sloman, for example, demonstrates that when told that "birds have an ulnar artery", people are much more likely to endorse that "robins have an ulnar artery" than that "penguins have an ulnar artery."

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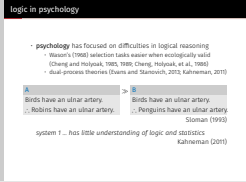
Sloman (1993)

system 1 ... has little understanding of logic and statistics

Kahneman (2011)



In accordance with such findings, Daniel Kahneman proposed that logic is not a forte of system 1, which is the system responsible for automatic fast reasoning.

logic in linguistics

- **formal semantics** presupposes logical ability

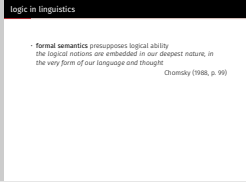
On on the hand, we have certain branches of linguistics, such as formal semantics, which—in trying to understand the compositional nature of language—posit that language has a kind of logical form. Thus, implicitly, linguists credit language-users with a rather high degree of logical sophistication.

logic in linguistics
· formal semantics presupposes logical ability

logic in linguistics

- **formal semantics** presupposes logical ability
  the logical notions are embedded in our deepest nature, in the very form of our language and thought

  Chomsky (1988, p. 99)



Noam Chomsky, for example, sees logical notions as embedded in our deepest nature, in the very form of language and thought.

logic in linguistics

- **formal semantics** presupposes logical ability
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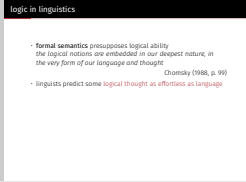
  Chomsky (1988, p. 99)
- linguists predict some logical thought as effortless as language



This view of language as, in some sense, fundamentally logical, allows for making sense of compositionality.

It also predicts that at least some inferences—those based in the logical form of language—should be as intuitive, automatic, and effortless as thought and language themselves.

logic in linguistics

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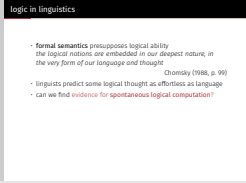
  Chomsky (1988, p. 99)
- linguists predict some logical thought as effortless as language
- can we find evidence for **spontaneous logical computation**?



Thus, the following question arises: Can we find some evidence for fast and automatic reasoning?

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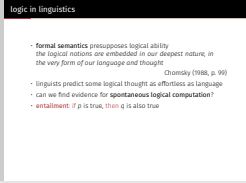
- linguists predict some logical thought as effortless as language
- can we find evidence for **spontaneous logical computation**?
- entailment: if *p* is true, then *q* is also true



I'm going to give you an example of one logical notion that has been argued to be based in the structure of language: entailment. Entailment is a relation between propositions such that when one proposition is true, another proposition is always also true.

logic in linguistics

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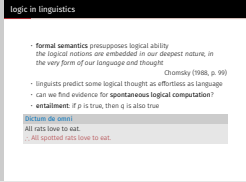
- can we find evidence for **spontaneous logical computation**?
- **entailment**: if p is true, then q is also true

Dictum de omni

All rats love to eat.

$\therefore$ All spotted rats love to eat.



We already saw an example of this reasoning in the dictum de omni.

Entailment directions

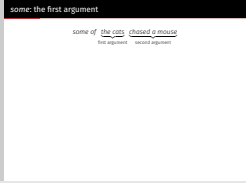
In our study, we will concern ourselves with the varying directions of entailment on the different arguments of the quantifiers: *some*, *all*, *not all*, and *none*. This is to say, the notion of upward and downward entailment.

Now, I will go through some intuitive reasoning and illustrate it with Venn diagrams to show how entailment can be understood formally.

some: the first argument

some of <u>*the cats*</u> <u>*chased a mouse*</u>

first argument second argument



Consider a sentence such as “some of the cats chased a mouse.” I will refer to the noun phrase such a “the cats” as the first argument of the quantifier *some*, and the verb phrase such as “chased a mouse” as its second argument. These are also known as, respectively, “the restrictor” and “the nuclear scope.”

some: the first argument

some of *the cats* *chased a mouse*

first argument second argument

First, we will tweak the first argument:

some: the first argument

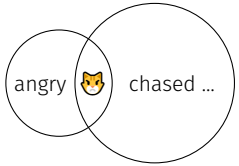
some of *the cats* *chased a mouse*

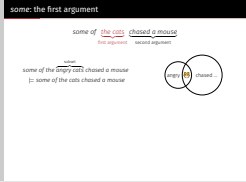
first argument second argument

subset

some of the angry cats chased a mouse

$\models$ *some of the cats chased a mouse*





"some of the ***angry*** cats chased a mouse."

some: the first argument

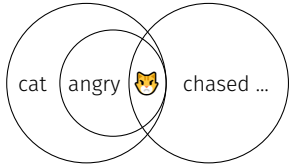
some of *the cats* *chased a mouse*

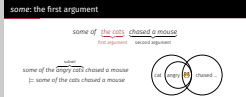
first argument second argument

subset

some of the angry cats chased a mouse

$\models$ *some of the cats chased a mouse*





Since angry cats are a subset of cats, then if “some of the angry cats chased a mouse” is true, it must also be the case that some of the cats chased a mouse. This is to say, the former sentence entails the latter.

In general, you can replace a subset, here “angry cats,” with a larger set, here “cats,” and the sentence stays true.

The Venn diagram captures this fact: the quantifier “some” means that the intersection of the two sets of angry cats and mice-chasers is non-empty. Adjectives such “angry” denote a subset of the noun they modify. Thus, the intersection of cats and mice-chasers is perforce also non-empty.

some: the first argument

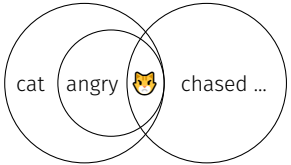
some of *the cats* *chased a mouse*

first argument second argument

subset

some of the angry cats chased a mouse

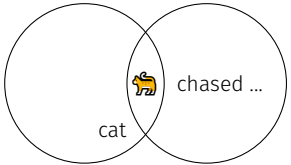
$\models$ *some of the cats chased a mouse*

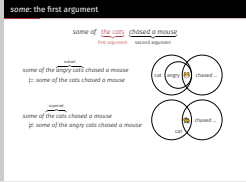


superset

some of the cats chased a mouse

$\not\models$ *some of the angry cats chased a mouse*





The other direction does not work, which is to say... you cannot infer that an angry cat chased a mouse if you know that a cat chased mouse. This is because,

some: the first argument

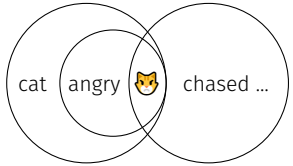
some of *the cats* *chased a mouse*

first argument — second argument

subset

some of the angry cats chased a mouse

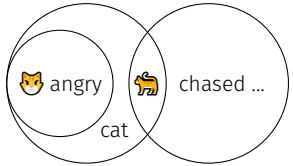
$\models$ *some of the cats chased a mouse*

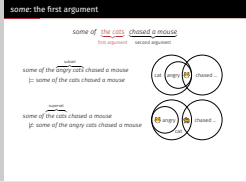


superset

some of the cats chased a mouse

$\not\models$ *some of the angry cats chased a mouse*





as the Venn diagram illustrates, it can be the non-angry cats that chased mice.

So we cannot go from a superset to a smaller set.

some: the first argument

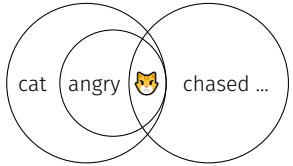
some of *the cats* *chased a mouse*

first argument second argument

subset

some of the angry cats chased a mouse

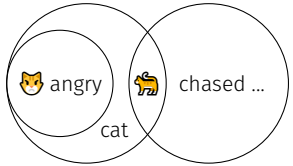
$\models$ *some of the cats chased a mouse*



superset

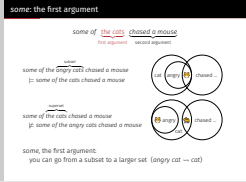
some of the cats chased a mouse

$\not\models$ *some of the angry cats chased a mouse*



some, the first argument:

you can go from a subset to a larger set (*angry cat* $\rightsquigarrow$ *cat*)



So, to reiterate, in tinkering with the first argument of *some* you can go from a subset to a larger set, but not in the other direction.

some: the second argument

some of $\underbrace{\textit{the cats}}_{\text{first argument}}$ $\underbrace{\textit{chased a mouse}}_{\text{second argument}}$

Now consider

some: the second argument
some of the cats chased a mouse
first argument second argument

some: the second argument

some of *the cats* *chased a mouse*

first argument second argument

manipulating the second argument of “some”—“chased a mouse.”

some: the second argument

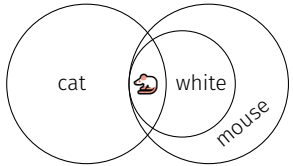
some of *the cats* *chased a mouse*

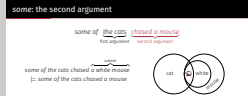
first argument second argument

subset

some of the cats chased a white mouse

$\models$ *some of the cats chased a mouse*





"Some of the cats chased a white mouse" entails "some of the cats chased a mouse."

some: the second argument

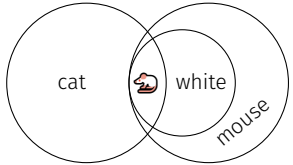
some of *the cats* *chased a mouse*

first argument second argument

subset

some of the cats chased a white mouse

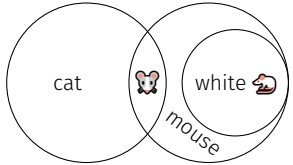
$\models$ *some of the cats chased a mouse*

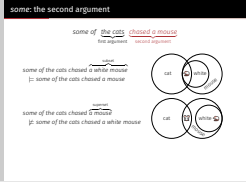


superset

some of the cats chased a mouse

$\not\models$ *some of the cats chased a white mouse*





But “some of the cats chased a mouse” does not entail “some of the cats chased a white mouse,” because the cats could have been chasing mice of other colors.

some: the second argument

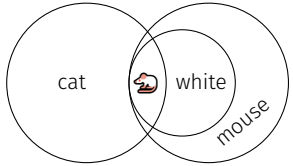
some of *the cats* *chased a mouse*

first argument second argument

subset

some of the cats chased a white mouse

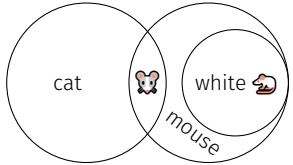
$\models$ *some of the cats chased a mouse*



superset

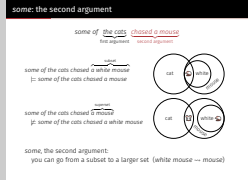
some of the cats chased a mouse

$\not\models$ *some of the cats chased a white mouse*



some, the second argument:

you can go from a subset to a larger set (*white mouse* $\rightsquigarrow$ *mouse*)



The result we arrive at here is the same as before: you can go from a subset to a larger set, but not in the other direction.

entailment direction

- *upward entailment*: can go from a subset to a larger set

This is known as upward entailment.

entailment direction

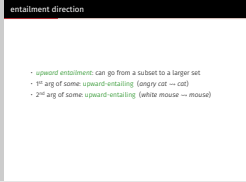
- *upward entailment*: can go from a subset to a larger set
- 1st arg of *some*: upward-entailing (*angry cat* $\rightsquigarrow$ *cat*)

entailment direction
- *upward entailment*: can go from a subset to a larger set
- 1st arg of *some*: upward-entailing (*angry cat* $\rightsquigarrow$ *cat*)

So far, we looked at ***both*** arguments of *some* and saw that *some* is upward-entailing on its first argument, because you can go from *angry cats* to *cats*.

entailment direction

- *upward entailment*: can go from a subset to a larger set
- 1st arg of *some*: upward-entailing (*angry cat* $\rightsquigarrow$ *cat*)
- 2nd arg of *some*: upward-entailing (*white mouse* $\rightsquigarrow$ *mouse*)



And it is also upward-entailing on the second argument because you can go from *white mice* to *mice*.

entailment direction

- *upward entailment*: can go from a subset to a larger set
- 1st arg of *some*: upward-entailing (*angry cat* $\rightsquigarrow$ *cat*)
- 2nd arg of *some*: upward-entailing (*white mouse* $\rightsquigarrow$ *mouse*)

- *downward entailment*: can go from a superset to a smaller set

entailment direction
- *upward entailment*: can go from a subset to a larger set
- 1st arg of *some*: upward-entailing (*angry cat* ⇝ *cat*)
- 2nd arg of *some*: upward-entailing (*white mouse* ⇝ *mouse*)
- *downward entailment*: can go from a superset to a smaller set

The opposite situation, where you can go from a superset to a smaller set is know as downward entailment. To see downward entailment in action, let's look at a sentence with the quantifier *all*.

all: both arguments

all of $\underbrace{\textit{the cats}}_{\text{first argument}}$ $\underbrace{\textit{chased a mouse}}_{\text{second argument}}$

all: both arguments

all of $\underbrace{\textit{the cats}}_{\text{first argument}}$ $\underbrace{\textit{chased a mouse}}_{\text{second argument}}$

... as in ***all*** *of the cats chased a mouse.*

all: both arguments

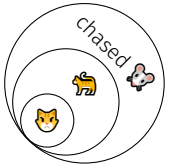
all of *the cats* *chased a mouse*

first argument second argument

superset

all of the cats chased a mouse

$\models$ *all of the angry cats chased a mouse*



"All of the cats chased a mouse" entails "all of the angry cats chased a mouse" because angry cats are a subset of cats. As the Venn diagram shows, "all" means that the set denoted by the first argument is a subset of the set denoted by the second argument. So you can go from a superset, to a smaller set in the first argument of "all."

all: both arguments

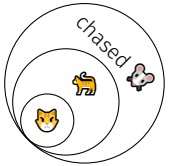
all *of* *the cats* *chased a mouse*

first argument second argument

superset

all of the cats chased a mouse

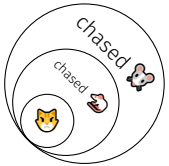
$\models$ *all of the angry cats chased a mouse*

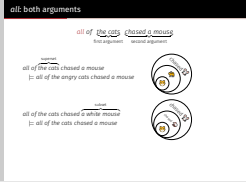


subset

all of the cats chased a white mouse

$\models$ *all of the cats chased a mouse*





At the same time, “all of the cats chased a white mouse” entails “all of the cats chased a mouse”—here, in the second argument, we can go from a subset to a larger set.

all: both arguments

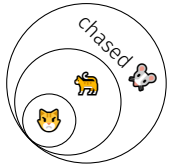
all of *the cats* *chased a mouse*

first argument second argument

superset

all of the cats chased a mouse

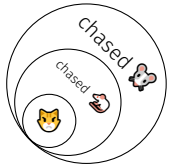
$\models$ *all of the angry cats chased a mouse*



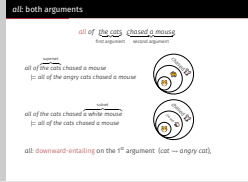
subset

all of the cats chased a white mouse

$\models$ *all of the cats chased a mouse*



all: downward-entailing on the 1st argument (*cat* $\rightsquigarrow$ *angry cat*),



So we see that “all” is downward entailing on the first argument, but

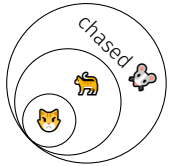
all: both arguments

all of *the cats* *chased a mouse*

first argument second argument

superset

all of the cats chased a mouse
⊨ *all of the angry cats chased a mouse*



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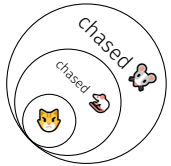
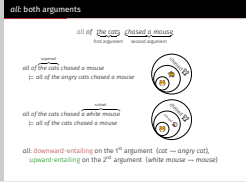
⊨ *all of the cats chased a mouse*



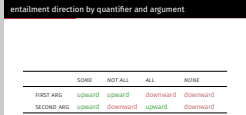
all: downward-entailing on the 1st argument (*cat* ⇝ *angry cat*),
upward-entailing on the 2nd argument (*white mouse* ⇝ *mouse*)



upward entailing on the second.

entailment direction by quantifier and argument

	SOME	*NOT ALL*	*ALL*	*NONE*
FIRST ARG	upward	upward	downward	downward
SECOND ARG	upward	downward	upward	downward



This tetrad is completed by “not all,” which is upward entailing on the first argument and downward-entailing on the second, and “none” which is downward entailing on both arguments. Thus, there is a quantifier for each combination of upward and downward entailment.

evidence for entailment computation

So what is entailment good for?

evidence for entailment computation

evidence for entailment computation

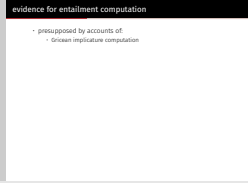
- presupposed by accounts of:

evidence for entailment computation
- presupposed by accounts of:

The notion of entailment is central to accounts of many linguistic phenomena.

evidence for entailment computation

- presupposed by accounts of:
  - Gricean implicature computation



Gricean pragmatics, for example, proposes that non-literal meaning arises as an implicature computed over what was said and what could have been said. Crucially, the computation relies on entailment asymmetries between propositions.

evidence for entailment computation

- presupposed by accounts of:
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  - distribution of negative polarity items (NPIs) (e.g. Ladusaw, 1983)

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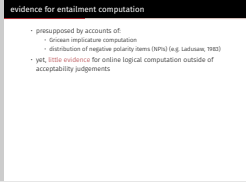
Likewise, most accounts of the distribution of negative polarity items invoke *entailment direction*, presupposing that this logical property can be computed effortlessly, accurately, and automatically by speakers without any logical training.

evidence for entailment computation

- presupposed by accounts of:
  - Gricean implicature computation
  - distribution of negative polarity items (NPIs) (e.g. Ladusaw, 1983)
- yet, little evidence for online logical computation outside of acceptability judgements



Importantly, however, outside of acceptability and felicity judgements, there is little evidence that speakers compute this logical property during sentence comprehension.

evidence for entailment computation

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- can be challenged on empirical grounds

Furthermore, the linguists' view of language competence might be challenged on empirical grounds.

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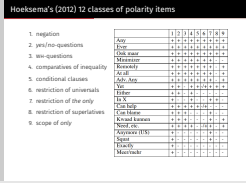
Hoeksema's (2012) 12 classes of polarity items

1. negation
2. *yes*/*no*-questions
3. WH-questions
4. comparatives of inequality
5. conditional clauses
6. restriction of universals
7. restriction of *the only*
8. restriction of superlatives
9. scope of *only*

	1	2	3	4	5	6	7	8	9
Any	+	+	+	+	+	+	+	+	+
Ever	+	+	+	+	+	+	+	+	+
Ook maar	+	+	+	+	+	+	+	+	+
Minimizer	+	+	+	+	+	+	+	-	-
Remotely	+	+	+	+	+	+	+	-	+
At all	+	+	+	+	+	+	+	-	+
Adv. Any	+	+	+	+	+	+	+	-	+
Yet	+	+	-	+	+	-/+	+	+	+
Either	+	+	-	+	-	-	-	-	-
In X	+	-	-	+	-	-	+	+	-
Can help	+	+	+	+	+	-/+	-	-	-
Can blame	+	+	+	-	-	-	+	-	-
Kwaad kunnen	+	+	+	-	-	-	+	-	+
Need, etc.	+	+	+	+	-	-/+	+	-	+
Anymore (US)	+	-	-	-	-	-	+	-	-
Squat	+	-	-	-	-	-	+	-	-
Exactly	+	-	-	-	-	-	-	-	-
Meer/mehr	+	-	-	-	-	-	-	-	-



Hoeksema, for example, shows that the distribution of negative polarity items cross-linguistically is very complex, which might cast doubt on weather a single logical notion such as entailment direction can truly be used to account for these facts.

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  - the distribution of NPIs is more complex (cf. Hoeksema, 2012)

- previous studies:

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[pause]

Several previous studies have investigated the online processing of entailment.

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  - Deschamps et al. (2015): signature of quantifier's direction of entailment

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For example, Deschamps and colleagues show that reaction times in sentence verification are affected by the quantifier's direction of entailment.

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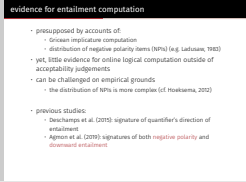
  - Deschamps et al. (2015): signature of quantifier's direction of entailment
  - Agmon et al. (2019): signatures of both negative polarity and downward entailment



And Agmon and colleagues show that **both** negative polarity and downward entailment contribute to processing complexity.

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- limitation: inferences tested indirectly

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However, previous studies have a limitation; they show processing differences between individual words and attribute these differences to underlying logical properties, but they don't test these inferences directly.

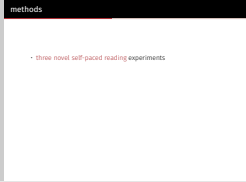
Methods

In our study, we looked for signatures of entailment processing in spontaneous language comprehension.

methods

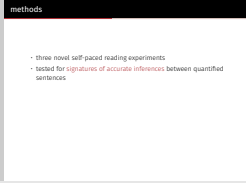
- three novel self-paced reading experiments

We designed three novel self-paced reading experiments. Two of those experiments are described in the abstract, whereas the third one is new; we *just* finished collecting and analyzing that data.



methods

- three novel self-paced reading experiments
- tested for signatures of accurate inferences between quantified sentences



We tested for signatures of normatively accurate logical inferences between quantified sentences during sentence comprehension.

methods

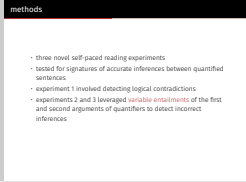
- three novel self-paced reading experiments
- tested for signatures of accurate inferences between quantified sentences
- experiment 1 involved detecting logical contradictions

methods
- three novel self-paced reading experiments
- tested for signatures of accurate inferences between quantified sentences
- experiment 1 involved detecting logical contradictions

Experiment 1 tested whether participants will detect a logical contradiction in the target sentence by manipulating preceding context.

methods

- three novel self-paced reading experiments
- tested for signatures of accurate inferences between quantified sentences
- experiment 1 involved detecting logical contradictions
- experiments 2 and 3 leveraged variable entailments of the first and second arguments of quantifiers to detect incorrect inferences



And Experiments 2 and 3 leveraged the variable entailment directions between the first and the second argument of a quantifier to test detecting something subtler, which is to say: incorrect inferences in the absence of downright contradictions.

methods

- three novel self-paced reading experiments
- tested for signatures of accurate inferences between quantified sentences
- experiment 1 involved detecting logical contradictions
- experiments 2 and 3 leveraged variable entailments of the first and second arguments of quantifiers to detect incorrect inferences
- preregistered design and analyses on OSF

We preregistered our design and analyses on OSF.

methods
- three novel self-paced reading experiments
- tested for signatures of accurate inferences between quantified sentences
- experiment 1 involved detecting logical contradictions
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Experiment 1

And now, Experiment 1.

experiment 1

- tested whether speakers detect logical contradictions

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experiment 1
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- tested whether speakers detect logical contradictions
- 400 participants on Amazon Mechanical Turk

We ran 400 participants on Amazon Mechanical Turk.

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- 12 target items displayed line by line

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Participants read 12 target items displayed line-by-line, with line breaks at clausal boundaries. They pressed [SPACE] to advance to the next line.

We also had 18 filler items which were just stories and did not have the structure of our test items.

experiment 1

- tested whether speakers detect logical contradictions
- 400 participants on Amazon Mechanical Turk
- 12 target items displayed line by line
- 6 conditions differing in quantifiers

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- tested whether speakers detect logical contradictions
- 400 participants on Amazon Mechanical Turk
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Across participants, each item appeared in six conditions which differed in what quantifiers were used.

experiment 1

- tested whether speakers detect logical contradictions
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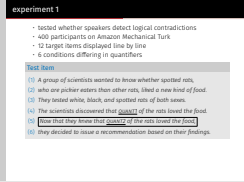
Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that QUANT1 of the rats loved the food.*
(5) *Now that they knew that QUANT2 of the rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*



Here, we can see an example item.
[read the item]
As you can see, each item contained a “premise” in line 4 and a “conclusion” in line 5, which began with *now that they knew that …*, presupposing that what comes next appeared earlier in the discourse. Otherwise, the two lines differed only in the quantifiers they used.

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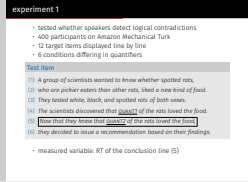
- measured variable: RT of the conclusion line (5)



And we measured the reading times of the boxed conclusion line as a proxy for processing costs.

We used a design where participants revealed the vignette line-by-line, as opposed to word-by-word, because we made no predictions about where exactly the processing difficulty would be, so we looked for a slowdown anywhere in that region.

In an earlier pilot study, we didn't find any difference between any of the conditions on line 6, so in the preregistered experiments we didn't plan on analyzing it.

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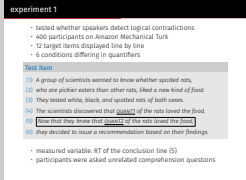
- measured variable: RT of the conclusion line (5)
- participants were asked unrelated comprehension questions



To ensure that participants comprehend the text, we asked them to make a true/false response to statements about each item. The statements were unrelated to our hypotheses, so as not to focus participants' attention on the entailment inferences.

experiment 1

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Test item

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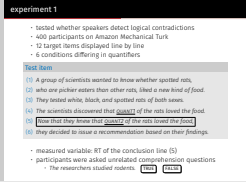
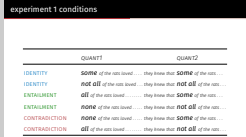
- measured variable: RT of the conclusion line (5)
- participants were asked unrelated comprehension questions
  - *The researchers studied rodents.* TRUE FALSE



For example, for the item above, participants would be asked to evaluate whether the statement ”The researchers studied rodents” is true.

experiment 1 conditions

	QUANT1	*QUANT2*
IDENTITY	***some*** *of the rats loved . . . .* *they knew that* ***some*** *of the rats . . .*
IDENTITY	***not all*** *of the rats loved . . .* *they knew that* ***not all*** *of the rats . . .*
ENTAILMENT	***all*** *of the rats loved . . . . . .* *they knew that* ***some*** *of the rats . . .*
ENTAILMENT	***none*** *of the rats loved . . . . .* *they knew that* ***not all*** *of the rats . . .*
CONTRADICTION	***none*** *of the rats loved . . . . .* *they knew that* ***some*** *of the rats . . .*
CONTRADICTION	***all*** *of the rats loved . . . . . .* *they knew that* ***not all*** *of the rats . . .*



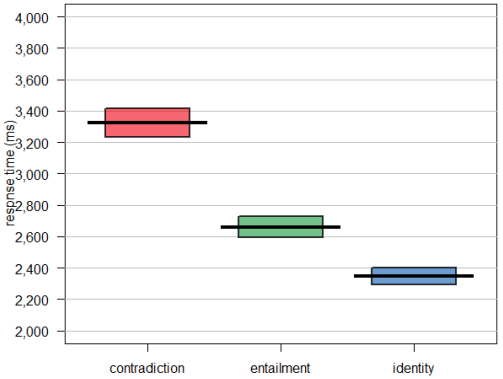
Our design was such that there were two conditions where the premise was identical to the conclusion, two conditions where it differed from but entailed the conclusion, and two conditions where it contradicted it.

In the identity conditions, the conclusion followed trivially from the premise. For example, “some of the rats loved the food” trivially entails “some of the rats loved the food.”

In the entailment conditions, the conclusion was not identical, but it was entailed by the premise. For example, it follows from “all of the rats loved the food” that “some of the rats loved the food”

In the contradiction conditions, the conclusion contradicted the premise. For example, “some of the rats loved the food” contradicts “none of the rats loved the food.”

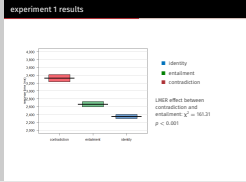
experiment 1 results



- identity
- entailment
- contradiction

LMER effect between contradiction and entailment: $\chi^2 = 161.31$

$p < 0.001$



All of the conditions were significantly different from each other. In particular, we were interested in comparing the contradiction condition and the entailment condition.

We see that participants took significantly longer to advance to the conclusion line when it contradicted the premise than when it was entailed by the premise. This is consistent with rapid, normatively accurate sensitivity to the logical relations between these clauses.

While the entailment condition was slower than the identity condition, this might be for at least two reasons. First, the entailment condition might actually involve a kind of inference. And second, the identity condition involves a repetition of the exact same constituent, which might create a priming effect.

Experiment 2

experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)

experiment 2
- same paradigm to detect subtler unlicensed inferences (n = 400)

Experiment 2 used the same paradigm to test for the capacity to detect subtler unlicensed inferences, even in the absence of strict contradictions.

experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

experiment 2
- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

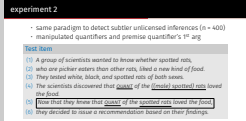
We manipulated the quantifiers in both the premise and the conclusion ... ... as well as the noun phrase in first argument of the quantifier in the premise.

experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that* QUANT *of the ((male) spotted) rats loved the food.*
(5) *Now that they knew that* QUANT *of the spotted rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*



We used test items such as this one.
The first three lines and line 6 were identical to Experiment 1. We changed lines four and five to manipulate whether the conclusion was entailed by the premise.
Note that in general, there is absolutely no reason why statements that come later in the discourse should be entailed by what comes earlier. In fact, this is the unusual state of affairs. What we had to do here is to build in a strong enough presupposition trigger to bring out the effect. The best we could come up with was *now that they knew that*.
So, here, lines four to six went ... [read lines 4-6]
Unlike experiment 1, in experiment 2, the quantifier was kept constant between the premise line and the conclusion line. The premise noun phrase appeared with two modifiers, one modifier, or no modifiers. The conclusion noun phrase always appeared with one modifier.

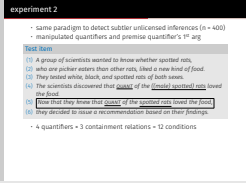
experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that* QUANT *of the ((male) spotted) rats loved the food.*
(5) *Now that they knew that* QUANT *of the spotted rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*

- 4 quantifiers × 3 containment relations = 12 conditions


experiment 2
- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item
(1) A group of scientists wanted to know whether spotted rats,
(2) who are pickier eaters than other rats, liked a new kind of food.
(3) They tested white, black, and spotted rats of both sexes.
(4) The scientists discovered that QUANT of the ((male) spotted) rats loved the food.
(5) Now that they knew that QUANT of the spotted rats loved the food,
(6) they decided to issue a recommendation based on their findings.

- 4 quantifiers × 3 containment relations = 12 conditions

So our design was such that the premise noun phrase was a subset, identical to, or a superset of the conclusion noun phrase. **Four** quantifiers and **three** containment relations yielded twelve experimental conditions in total. But don't worry; they actually reduce to a two-by-two. I will walk you through how. Depending on the combination of the quantifier and containment,

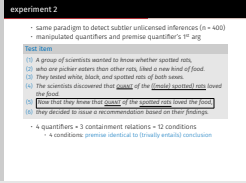
experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that QUANT of the ((male) spotted) rats loved the food.*
(5) *Now that they knew that QUANT of the spotted rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*

- 4 quantifiers × 3 containment relations = 12 conditions
  - 4 conditions: premise identical to (trivally entails) conclusion



there were four conditions where the premise was identical to the conclusion, and so it trivially entailed it, (these conditions will be shown in blue,)

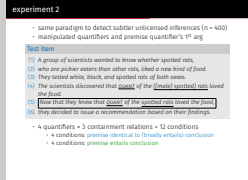
experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that QUANT of the ((male) spotted) rats loved the food.*
(5) *Now that they knew that QUANT of the spotted rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*

- 4 quantifiers × 3 containment relations = 12 conditions
  - 4 conditions: premise identical to (trivally entails) conclusion
  - 4 conditions: premise entails conclusion



four conditions in green where the premise differed from but entailed the conclusion,

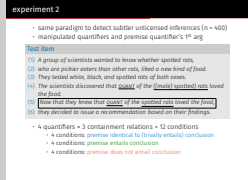
experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that QUANT of the ((male) spotted) rats loved the food.*
(5) *Now that they knew that QUANT of the spotted rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*

- 4 quantifiers × 3 containment relations = 12 conditions
  - 4 conditions: premise identical to (trivally entails) conclusion
  - 4 conditions: premise entails conclusion
  - 4 conditions: premise does not entail conclusion



and four orange conditions where the premise did not entail the conclusion.

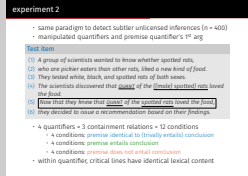
experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
- manipulated quantifiers and premise quantifier's 1st arg

Test item

(1) *A group of scientists wanted to know whether spotted rats,*
(2) *who are pickier eaters than other rats, liked a new kind of food.*
(3) *They tested white, black, and spotted rats of both sexes.*
(4) *The scientists discovered that QUANT of the ((male) spotted) rats loved the food.*
(5) *Now that they knew that QUANT of the spotted rats loved the food,*
(6) *they decided to issue a recommendation based on their findings.*

- 4 quantifiers × 3 containment relations = 12 conditions
  - 4 conditions: premise identical to (trivally entails) conclusion
  - 4 conditions: premise entails conclusion
  - 4 conditions: premise does not entail conclusion
- within quantifier, critical lines have identical lexical content

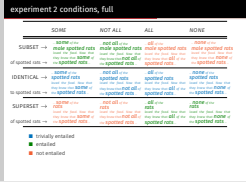


An elegant feature of our design is that within quantifier, we're looking at differences in reading times among lines that have identical lexical content, so whatever the difference is on the critical line, that difference *must be* due to preceding context.

experiment 2 conditions, full

	SOME	*NOT ALL*	*ALL*	*NONE*
SUBSET → of spotted rats →	… **some** of the **male spotted rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **male spotted rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **male spotted rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **male spotted rats** loved the food. Now that they knew that **none** of the **spotted rats** …
IDENTICAL → to spotted rats →	… **some** of the **spotted rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **spotted rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **spotted rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **spotted rats** loved the food. Now that they knew that **none** of the **spotted rats** …
SUPERSET → of spotted rats →	… **some** of the **rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **rats** loved the food. Now that they knew that **none** of the **spotted rats** …

- trivially entailed
- entailed
- not entailed

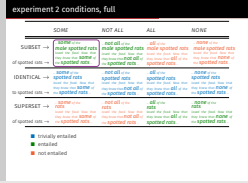


Here, you can see the twelve conditions schematized.

experiment 2 conditions, full

	SOME	*NOT ALL*	*ALL*	*NONE*
SUBSET → of spotted rats →	… **some** of the **male spotted rats** *loved the food. Now that they knew that* **some** *of the* **spotted rats** …	… **not all** of the **male spotted rats** *loved the food. Now that they knew that* **not all** *of the* **spotted rats** …	… **all** of the **male spotted rats** *loved the food. Now that they knew that* **all** *of the* **spotted rats** …	… **none** of the **male spotted rats** *loved the food. Now that they knew that* **none** *of the* **spotted rats** …
IDENTICAL → to spotted rats →	… **some** of the **spotted rats** *loved the food. Now that they knew that* **some** *of the* **spotted rats** …	… **not all** of the **spotted rats** *loved the food. Now that they knew that* **not all** *of the* **spotted rats** …	… **all** of the **spotted rats** *loved the food. Now that they knew that* **all** *of the* **spotted rats** …	… **none** of the **spotted rats** *loved the food. Now that they knew that* **none** *of the* **spotted rats** …
SUPERSET → of spotted rats →	… **some** of the **rats** *loved the food. Now that they knew that* **some** *of the* **spotted rats** …	… **not all** of the **rats** *loved the food. Now that they knew that* **not all** *of the* **spotted rats** …	… **all** of the **rats** *loved the food. Now that they knew that* **all** *of the* **spotted rats** …	… **none** of the **rats** *loved the food. Now that they knew that* **none** *of the* **spotted rats** …

- trivially entailed
- entailed
- not entailed

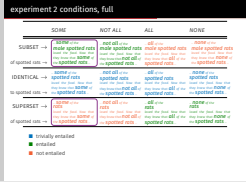


For example, if we look at a quantifier which is upward entailing on its first argument, such as “some,” when the premise noun phrase is a subset of the noun phrase in the conclusion, the conclusion follows from the premise. For example, “some of the male spotted rats loved the food” entails “some of the spotted rats loved the food.”

experiment 2 conditions, full

	SOME	*NOT ALL*	*ALL*	*NONE*
SUBSET → of spotted rats →	… **some** of the **male spotted rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **male spotted rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **male spotted rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **male spotted rats** loved the food. Now that they knew that **none** of the **spotted rats** …
IDENTICAL → to spotted rats →	… **some** of the **spotted rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **spotted rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **spotted rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **spotted rats** loved the food. Now that they knew that **none** of the **spotted rats** …
SUPERSET → of spotted rats →	… **some** of the **rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **rats** loved the food. Now that they knew that **none** of the **spotted rats** …

- trivially entailed
- entailed
- not entailed

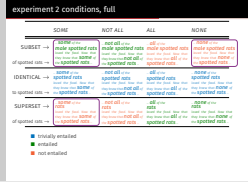


When the premise noun phrase is a superset of the conclusion noun phrase, [read], we get an unlicensed inference.

experiment 2 conditions, full

	SOME	*NOT ALL*	*ALL*	*NONE*
SUBSET → of spotted rats →	… **some** of the **male spotted rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **male spotted rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **male spotted rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **male spotted rats** loved the food. Now that they knew that **none** of the **spotted rats** …
IDENTICAL → to spotted rats →	… **some** of the **spotted rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **spotted rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **spotted rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **spotted rats** loved the food. Now that they knew that **none** of the **spotted rats** …
SUPERSET → of spotted rats →	… **some** of the **rats** loved the food. Now that they knew that **some** of the **spotted rats** …	… **not all** of the **rats** loved the food. Now that they knew that **not all** of the **spotted rats** …	… **all** of the **rats** loved the food. Now that they knew that **all** of the **spotted rats** …	… **none** of the **rats** loved the food. Now that they knew that **none** of the **spotted rats** …

- trivially entailed
- entailed
- not entailed

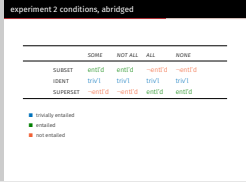


When we look at a quantifier that is downward-entailing on its first argument, such as “none,” the pattern reverses, and it is the inferences from a subset to a larger set that are unlicensed. Thus [read] presents the reader with an unlicensed inference.

experiment 2 conditions, abridged

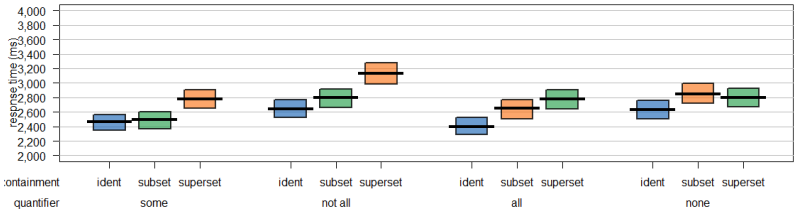
	SOME	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	entl'd	¬entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	¬entl'd	entl'd	entl'd

- trivially entailed
- entailed
- not entailed



The twelve conditions can also be represented in this abridged fashion where the particular lexical items are abstracted away and only the information about the entailment relation is retained.

experiment 2 results

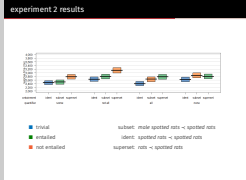


- trivial
- entailed
- not entailed

subset: *male spotted rats* ≺ *spotted rats*

ident: *spotted rats* ≺ *spotted rats*

superset: *rats* ≺ *spotted rats*



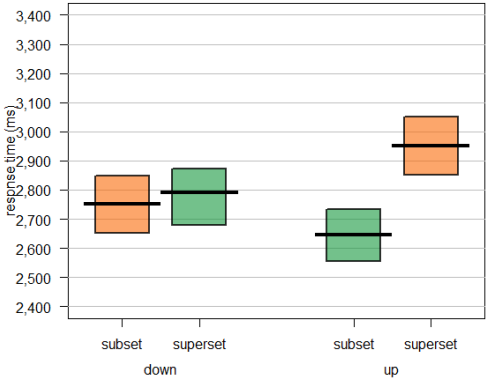
Now, let's have a look at the results of Experiment 2.

The twelve conditions are grouped by quantifiers. The ident conditions, where the conclusion is trivially entailed are in blue, and you can see that they are faster than the other two cases, which is a good sanity check. The conditions where the conclusion is entailed—but not identical—are in green, and where it is not entailed are in orange.

We find a main effect of containment, with superset conditions generally slower than subset. This is expected because in the subset conditions, the critical line only contains lexical material present in the premise (for example, *male spotted rats* to *spotted rats*), whereas in the superset condition, there is a new word (for example, *rats* to *spotted rats*).

What matters, however, is the interaction of entailment and containment, which you can see as the difference between the green bars and the orange bars within each quantifier.

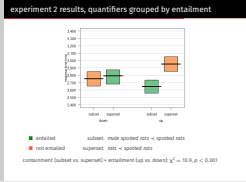
experiment 2 results, quantifiers grouped by entailment



■ entailed — subset: *male spotted rats* ≺ *spotted rats*

■ not entailed — superset: *rats* ≺ *spotted rats*

containment (subset vs. superset) × entailment (up vs. down): $\chi^2 = 10.9$, $p < 0.001$



Here, we group the upward- and downward-entailing quantifiers together and drop the "ident" conditions to show the relevant interaction of containment and entailment more clearly. This interaction is significant, showing rapid sensitivity to logical relations between clauses.

Experiment 3

At last, Experiment 3.

experiment 3

- manipulated quantifiers and premise quantifier's 2nd arg

Experiment 3 differed from Experiment 2 only in that we manipulated the quantifier's second argument.

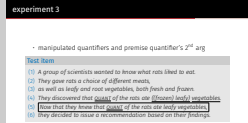
experiment 3
- manipulated quantifiers and premise quantifier's 2nd arg

experiment 3

- manipulated quantifiers and premise quantifier's 2nd arg

Test item

(1) *A group of scientists wanted to know what rats liked to eat.*
(2) *They gave rats a choice of different meats,*
(3) *as well as leafy and root vegetables, both fresh and frozen.*
(4) *They discovered that QUANT of the rats ate ((frozen) leafy) vegetables.*
(5) *Now that they knew that QUANT of the rats ate leafy vegetables,*
(6) *they decided to issue a recommendation based on their findings.*



We use items such as this one, where we manipulated not the set of rats, but rather the vegetables they ate. Thus, the premise contained clauses such as "some, all, or none of the rats like vegetables, leafy vegetables, or frozen leafy vegetables."

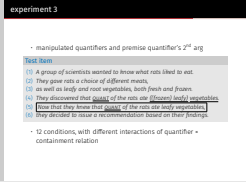
experiment 3

- manipulated quantifiers and premise quantifier's 2nd arg

Test item

(1) *A group of scientists wanted to know what rats liked to eat.*
(2) *They gave rats a choice of different meats,*
(3) *as well as leafy and root vegetables, both fresh and frozen.*
(4) *They discovered that QUANT of the rats ate ((frozen) leafy) vegetables.*
(5) *Now that they knew that QUANT of the rats ate leafy vegetables,*
(6) *they decided to issue a recommendation based on their findings.*

- 12 conditions, with different interactions of quantifier × containment relation

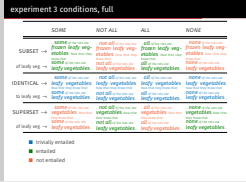


We had 12 conditions as in Experiment 2 but whether the premise entailed or failed to entail the conclusion was different according to the profile of the quantifier.

experiment 3 conditions, full

	SOME	*NOT ALL*	*ALL*	*NONE*
SUBSET →	… **some** of the rats ate **frozen leafy vegetables**. Now that they knew that	… **not all** of the rats ate **frozen leafy vegetables**. Now that they knew that	… **all** of the rats ate **frozen leafy vegetables**. Now that they knew that	… **none** of the rats ate **frozen leafy vegetables**. Now that they knew that
of leafy veg. →	**some** of the rats ate **leafy vegetables** …	**not all** of the rats ate **leafy vegetables** …	**all** of the rats ate **leafy vegetables** …	**none** of the rats ate **leafy vegetables** …
IDENTICAL →	… **some** of the rats ate **leafy vegetables**. Now that they knew that	… **not all** of the rats ate **leafy vegetables**. Now that they knew that	… **all** of the rats ate **leafy vegetables**. Now that they knew that	… **none** of the rats ate **leafy vegetables**. Now that they knew that
to leafy veg. →	**some** of the rats ate **leafy vegetables** …	**not all** of the rats ate **leafy vegetables** …	**all** of the rats ate **leafy vegetables** …	**none** of the rats ate **leafy vegetables** …
SUPERSET →	… **some** of the rats ate **vegetables**. Now that they knew that	… **not all** of the rats ate **vegetables**. Now that they knew that	… **all** of the rats ate **vegetables**. Now that they knew that	… **none** of the rats ate **vegetables**. Now that they knew that
of leafy veg. →	**some** of the rats ate **leafy vegetables** …	**not all** of the rats ate **leafy vegetables** …	**all** of the rats ate **leafy vegetables** …	**none** of the rats ate **leafy vegetables** …

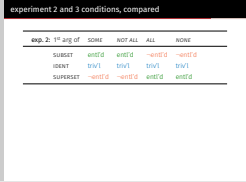
- trivially entailed
- entailed
- not entailed



Thus, the premise follows from the conclusion in the subset conditions for “some” and “all,” and in the superset conditions for “not all” and “none.”

experiment 2 and 3 conditions, compared

exp. 2: 1st arg of	*SOME*	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	entl'd	¬entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	¬entl'd	entl'd	entl'd

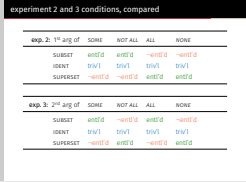


Recall that in Experiment 2, the premise followed from the conclusion in the subset conditions for "some" and "all" and in the superset conditions for "not all" and "none."

experiment 2 and 3 conditions, compared

exp. 2: 1st arg of	*SOME*	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	entl'd	¬entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	¬entl'd	entl'd	entl'd

exp. 3: 2nd arg of	*SOME*	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	¬entl'd	entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	entl'd	¬entl'd	entl'd

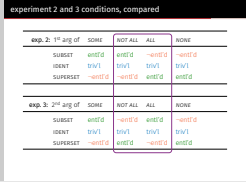


Here, we can compare Experiments 2 and 3 directly. The conditions with *some* and *none* stay the same across the two experiments. But—the conditions with *not all* and *all*

experiment 2 and 3 conditions, compared

exp. 2: 1st arg of	*SOME*	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	entl'd	¬entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	¬entl'd	entl'd	entl'd

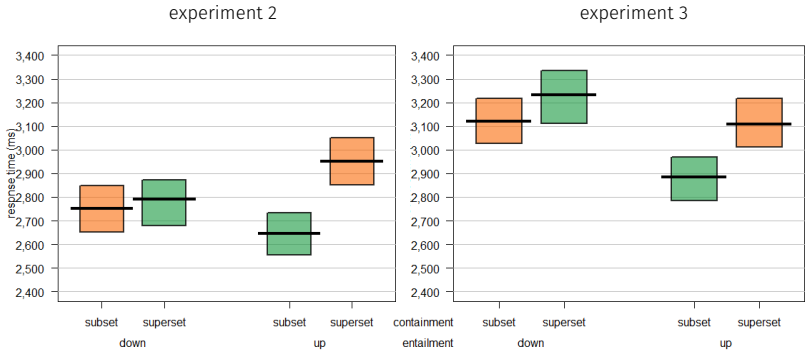
exp. 3: 2nd arg of	*SOME*	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	¬entl'd	entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	entl'd	¬entl'd	entl'd



flip!

Thus, we predict that the conditions with “some” and ”none” will pattern in the same way across the two experiments. However, “not all” should pattern with “some” in Experiment 2 but with “none” in Experiment 3. Likewise, “all” should pattern with “none” in Experiment 2 but with “some” in Experiment 3.

experiment 2 and 3 results



- entailed
- not entailed

experiment 3

containment (subset vs. superset) × entailment (up vs. down):

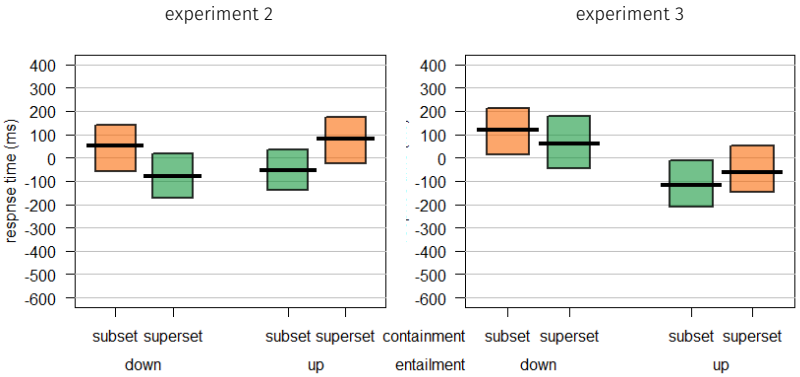
$\chi^2 = 6.21$

$p = 0.013$

I want to show you the results of experiment 3 together with experiment 2, with quantifiers grouped by entailment.

So in experiment 3, we again found a significant interaction of containment by entailment, which is consistent with rapid sensitivity to logical relations. However, due to the large effect of superset, the interaction of containment and quantifier is difficult to see. So now, I will show partial residual graphs to make the interaction more visible.

experiments 2 and 3, partial residual graphs

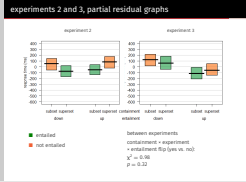


entailed

not entailed

between experiments

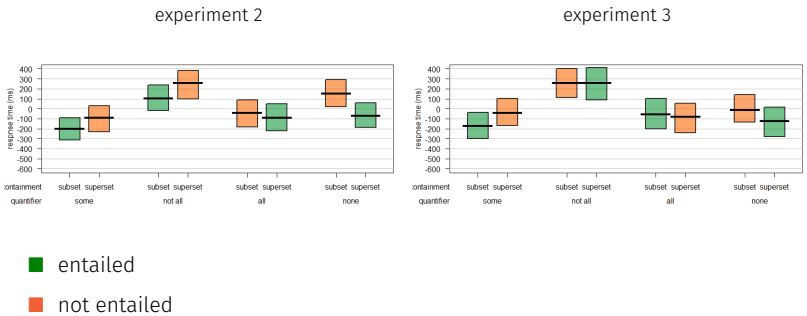
containment × experiment × entailment flip (yes vs. no):
$\chi^2 = 0.98$
$p = 0.32$



Here, within experiment, the subset trials have the *mean* of subset trials subtracted, and the same goes for the superset trials. This makes this interaction easier to see, by removing the main effect of containment.

Remember that we predict the same pattern of results in both experiments for *some* and *none* because they have the same direction of entailment on both their first and second arguments. However, we expected *all* and *not all* to flip, so this predicts a 3-way interaction between experiment, containment, and whether the quantifier flipped or not. Nevertheless, we didn't find a significant effect. This might be because not all quantifiers behave as we would expect them to. Recall that the grouping of quantifiers by entailment is different in Experiment 2 and Experiment 3.

experiment 2 and 3 partial residuals, by quantifier



Some and *none* have the same signatures across the two experiments, as predicted. We also see a change in the processing signatures for *not all* between experiment 2 and experiment 3, again as predicted. However, in the case of *all*, the difference between subset and superset is the same for the two experiments, contrary to our predictions. We don't have a good idea for why *all* is behaving differently here. But we welcome suggestions on how to interpret this data.

Discussion

discussion

- language involves accurate and spontaneous logical computations

In summary, our findings suggest that language processing involves automatic, accurate, and spontaneous logical computations, even in the absence of a task that requires making these inferences to verify text comprehension.

discussion
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discussion

- language involves accurate and spontaneous logical computations
- differs from dual-process theories of cognition

  it is assumed that people's intuitive logical knowledge emerges from a learning process in which key principles have been practiced to automaticity

  De Neys and Pennycook (2019)

This view differs from what is assumed by dual-process theories of cognition. For example, De Neys and Pennycook (2019) give an overview of recent advances in dual-process theorizing. They observe weak signatures of rapid, normatively accurate logical reasoning, but they explain them as a learning process in which key principles have been practiced to automaticity.

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On the other hand, our findings are anticipated by frameworks which take some logical inferences as naturally intuitive,

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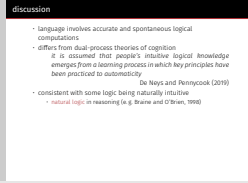

such as 'natural logic' in reasoning of Braine and O'Brien's (1998).

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Such inferences may even be *baked* ***into*** the grammar … along the lines of Gajewski's (2002) L-analyticity.

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Our ***main*** *suggestion* is that the compositionality of language and *some* inferential thought may both derive from the same cognitive mechanisms.

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But how can we square our findings with decades of psychological research arguing for the opposite?

A methodological consequence of our proposal is that *some* logical competence, specifically that which is required to account for *linguistic* competence, is more easily revealed by tasks which involve ecologically-valid language comprehension, and do not require test-taking or puzzle-solving, as those are designed to be challenging in a way which obscures ***natural*** logical competence.

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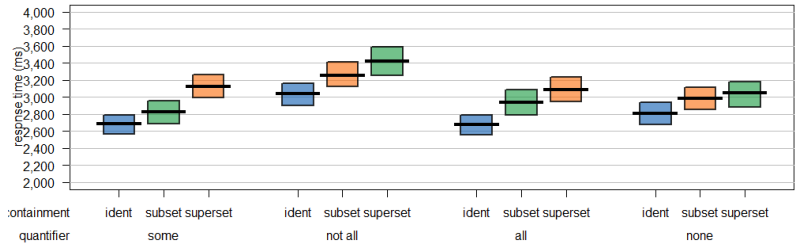
FINALLY, *our tasks* revealed processing signatures with adjectival modification. Obviously, there are other types of inference which *might not* ***follow*** from the compositional structure of language. Thus, we suggest that our findings may open up a whole new set of empirical questions about the relation of logic to thought.

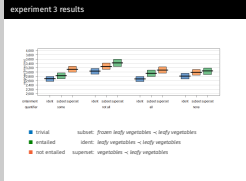
thank you!

thank you!

experiment 3 results



- trivial — subset: *frozen leafy vegetables* ≺ *leafy vegetables*
- entailed — ident: *leafy vegetables* ≺ *leafy vegetables*
- not entailed — superset: *vegetables* ≺ *leafy vegetables*



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