Evidence of accurate logical reasoning in online sentence comprehension

34th Annual CUNY Conference on Human Sentence Processing

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Introduction

logic in thought

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Dictum de omni

All rats love to eat.

$\therefore$ All spotted rats love to eat.

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∴ All spotted rats love to eat.

- do such schemata capture the nature of thought?

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Birds have an ulnar artery. ∴ Robins have an ulnar artery.		Birds have an ulnar artery. ∴ Penguins have an ulnar artery.

Sloman (1993)

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

Kahneman (2011)

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  the logical notions are embedded in our deepest nature, in the very form of our language and thought

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All rats love to eat.

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Entailment directions

some: the first argument

some of *the cats* *chased a mouse*

first argument second argument

some: the first argument

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some: the first argument

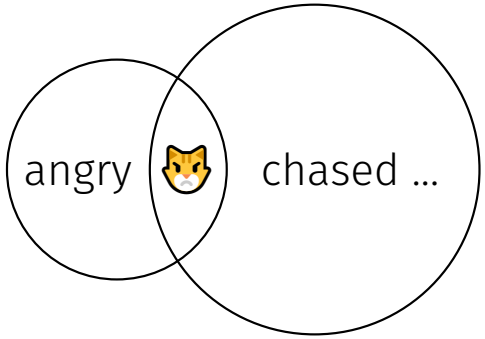
some of *the cats* *chased a mouse*

first argument second argument

subset

some of the angry cats chased a mouse

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



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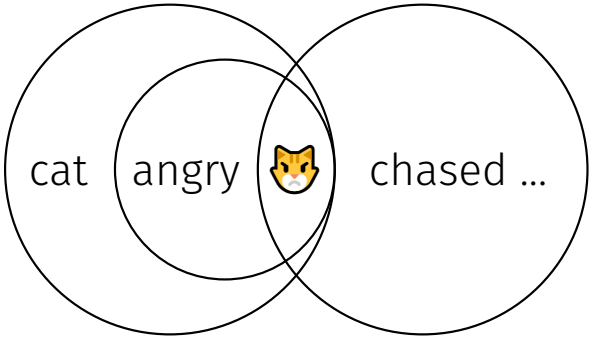

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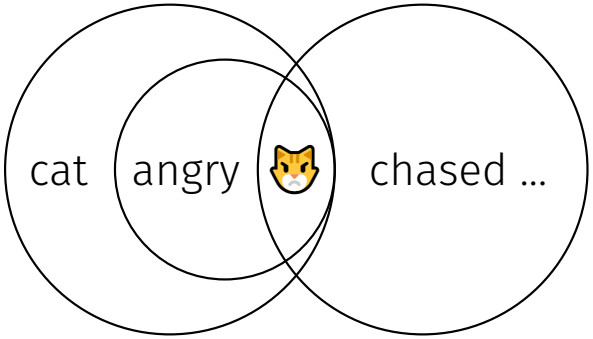

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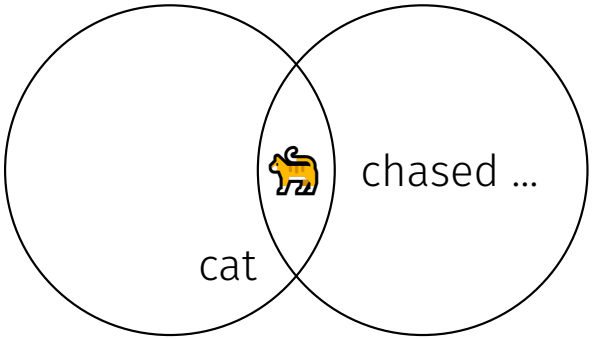

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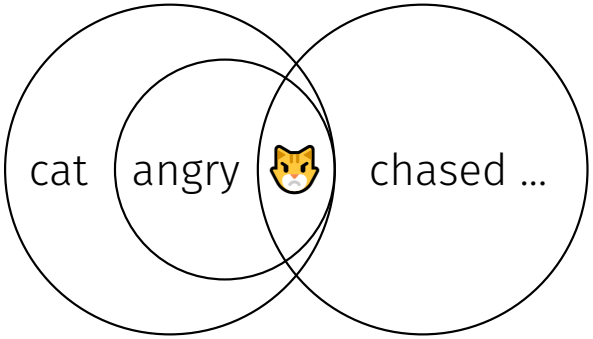

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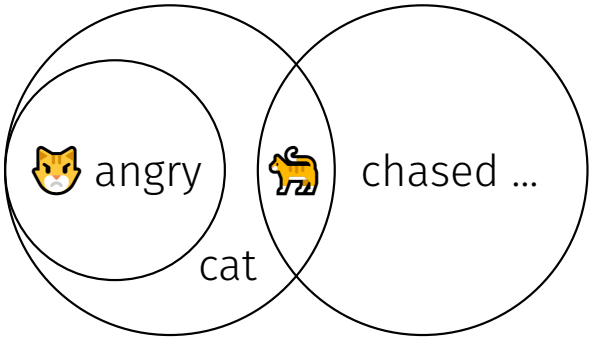

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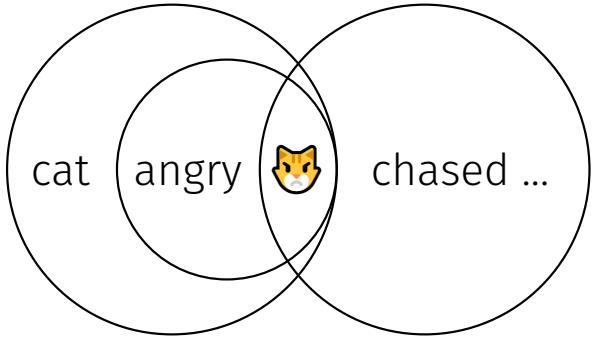

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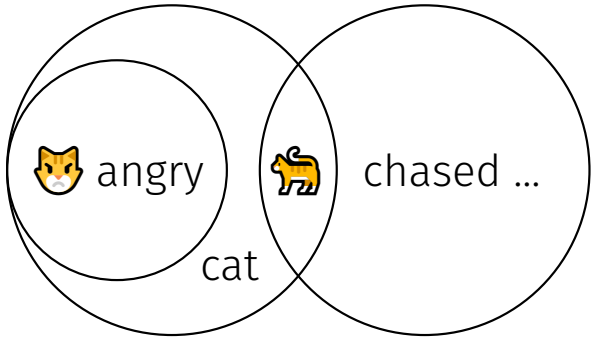

some, the first argument:

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

some: the second argument

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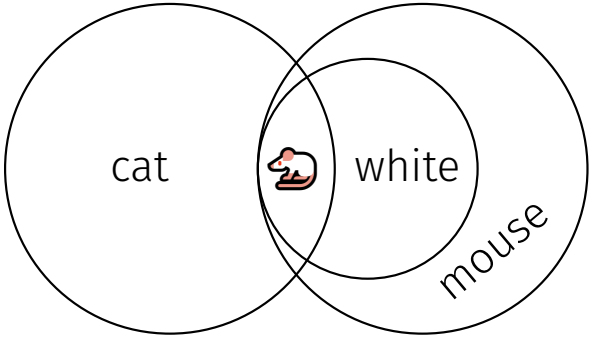

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first argument second argument

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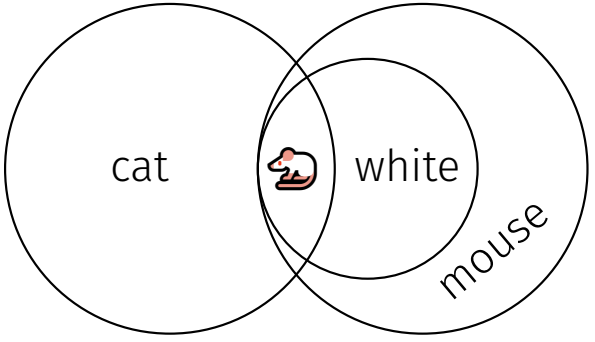
$\models$ *some of the cats chased a mouse*



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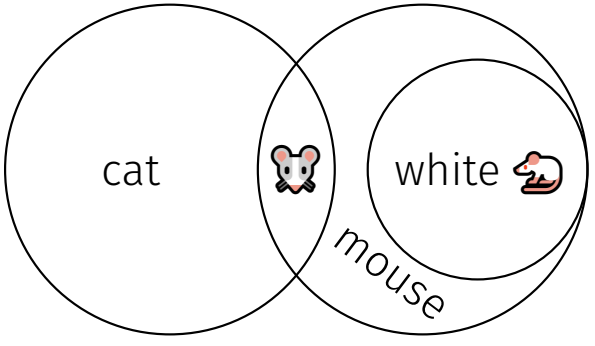

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first argument — second argument

subset

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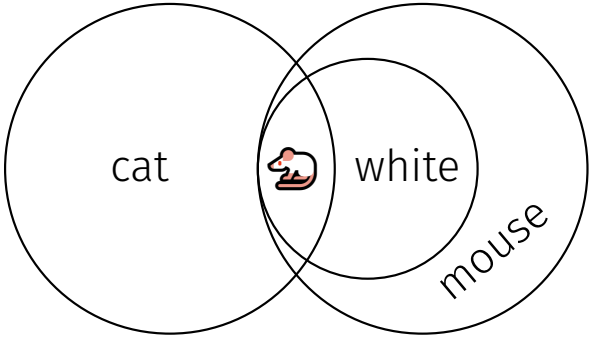

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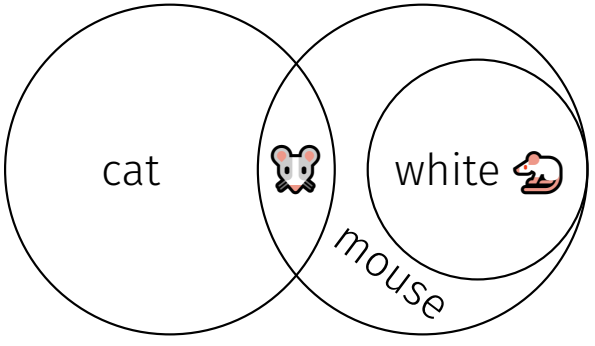

some, the second argument:

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

entailment direction

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

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- 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

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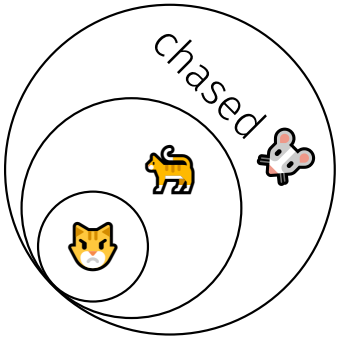

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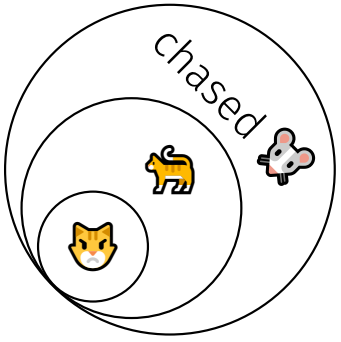

subset

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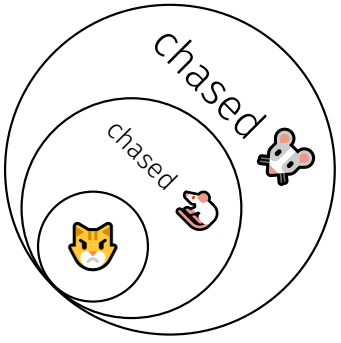

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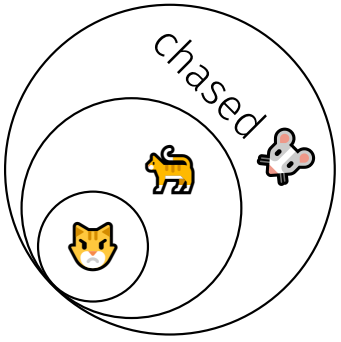

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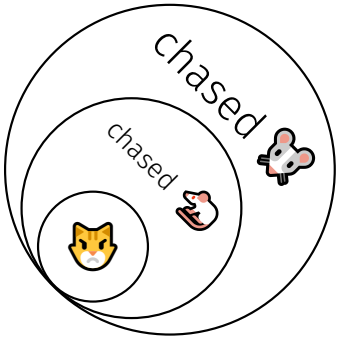

all: downward-entailing on the 1st argument (*cat* $\rightsquigarrow$ *angry cat*),

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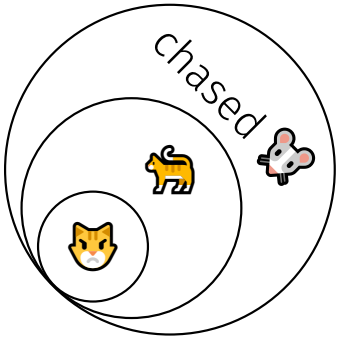

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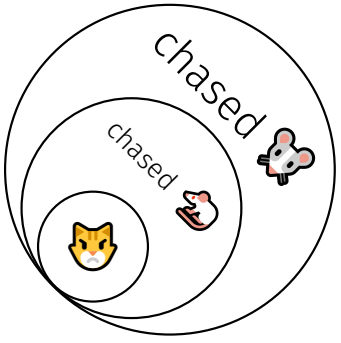

all: downward-entailing on the 1st argument (*cat* $\rightsquigarrow$ *angry cat*),
upward-entailing on the 2nd argument (*white mouse* $\rightsquigarrow$ *mouse*)

entailment direction by quantifier and argument

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

evidence for entailment computation

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- can be challenged on empirical grounds

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	+	-	-	-	-	-	-	-	-

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- limitation: inferences tested indirectly

Methods

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- preregistered design and analyses on OSF

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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.*

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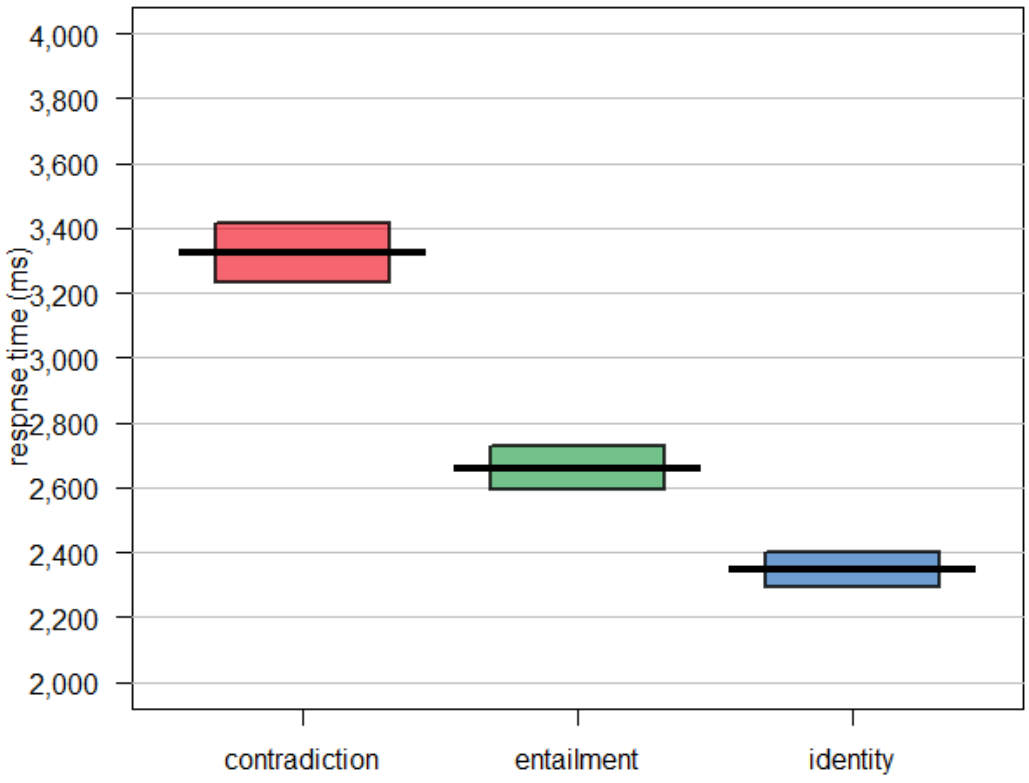
  - *The researchers studied rodents.* TRUE FALSE

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 . . .*

experiment 1 results



identity

entailment

contradiction

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

$p < 0.001$

Experiment 2

experiment 2

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

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)
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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 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.*

experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
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- 4 quantifiers × 3 containment relations = 12 conditions

experiment 2

- same paradigm to detect subtler unlicensed inferences (n = 400)
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  - 4 conditions: premise entails conclusion
  - 4 conditions: premise does not entail conclusion

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- 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

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

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

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

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** …
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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** …

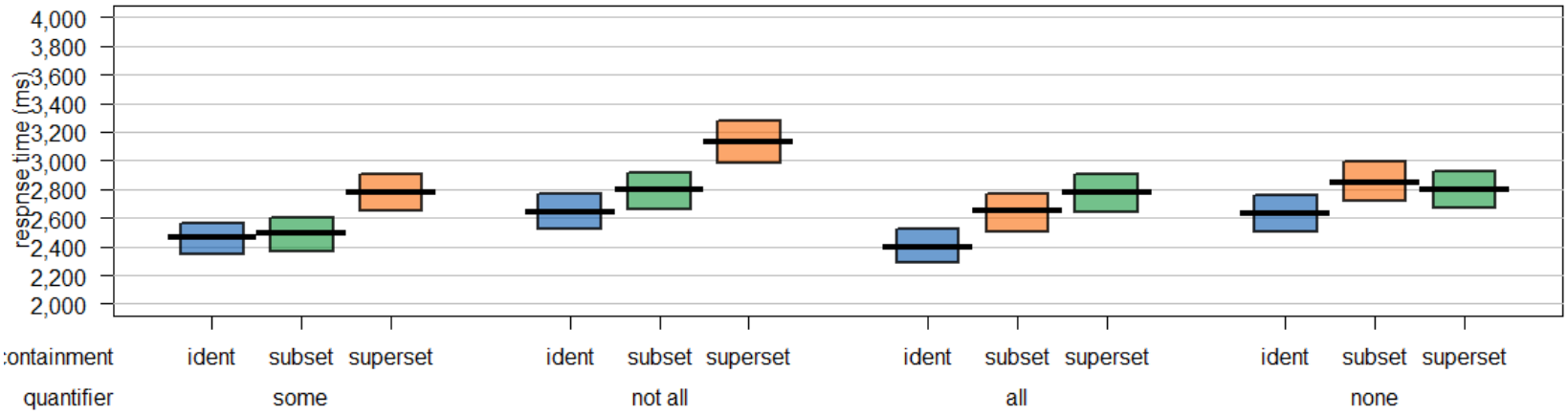
- trivially entailed
- entailed
- not entailed

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

experiment 2 results



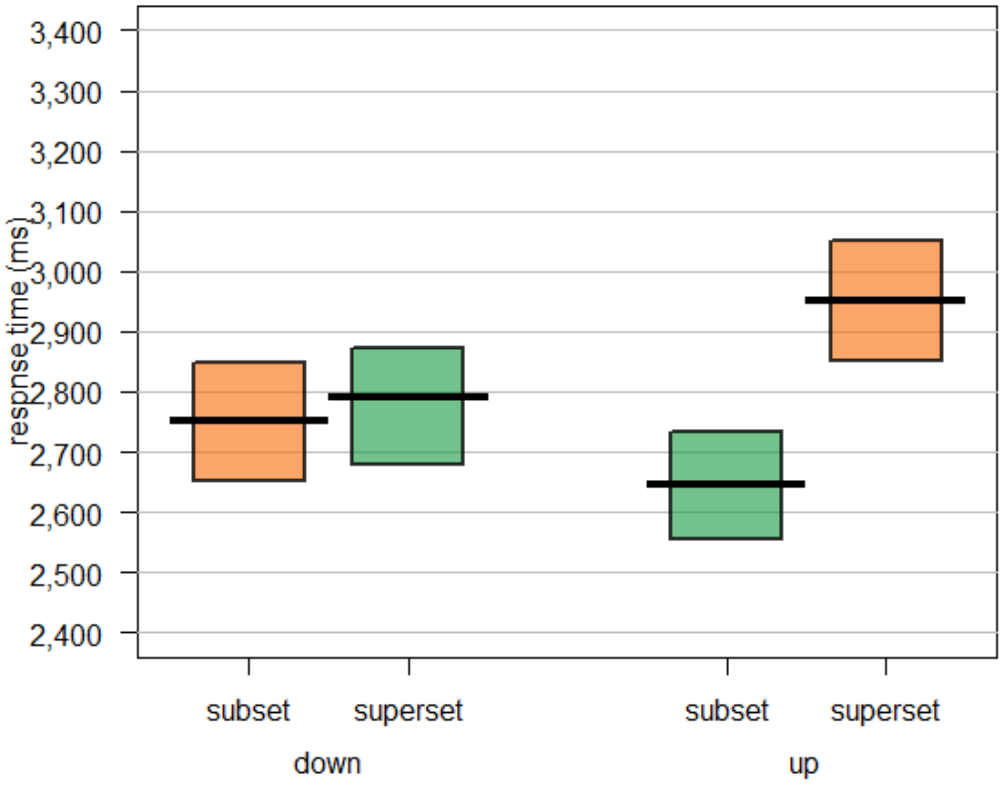
- trivial
- entailed
- not entailed

subset: *male spotted rats* $\prec$ *spotted rats*

ident: *spotted rats* $\prec$ *spotted rats*

superset: *rats* $\prec$ *spotted rats*

experiment 2 results, quantifiers grouped by entailment



- entailed
- not entailed

subset: *male spotted rats* $\prec$ *spotted rats*

superset: *rats* $\prec$ *spotted rats*

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

Experiment 3

experiment 3

- manipulated quantifiers and premise quantifier's 2nd arg

experiment 3

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

experiment 3 conditions, full

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

- trivially entailed
- entailed
- not entailed

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

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

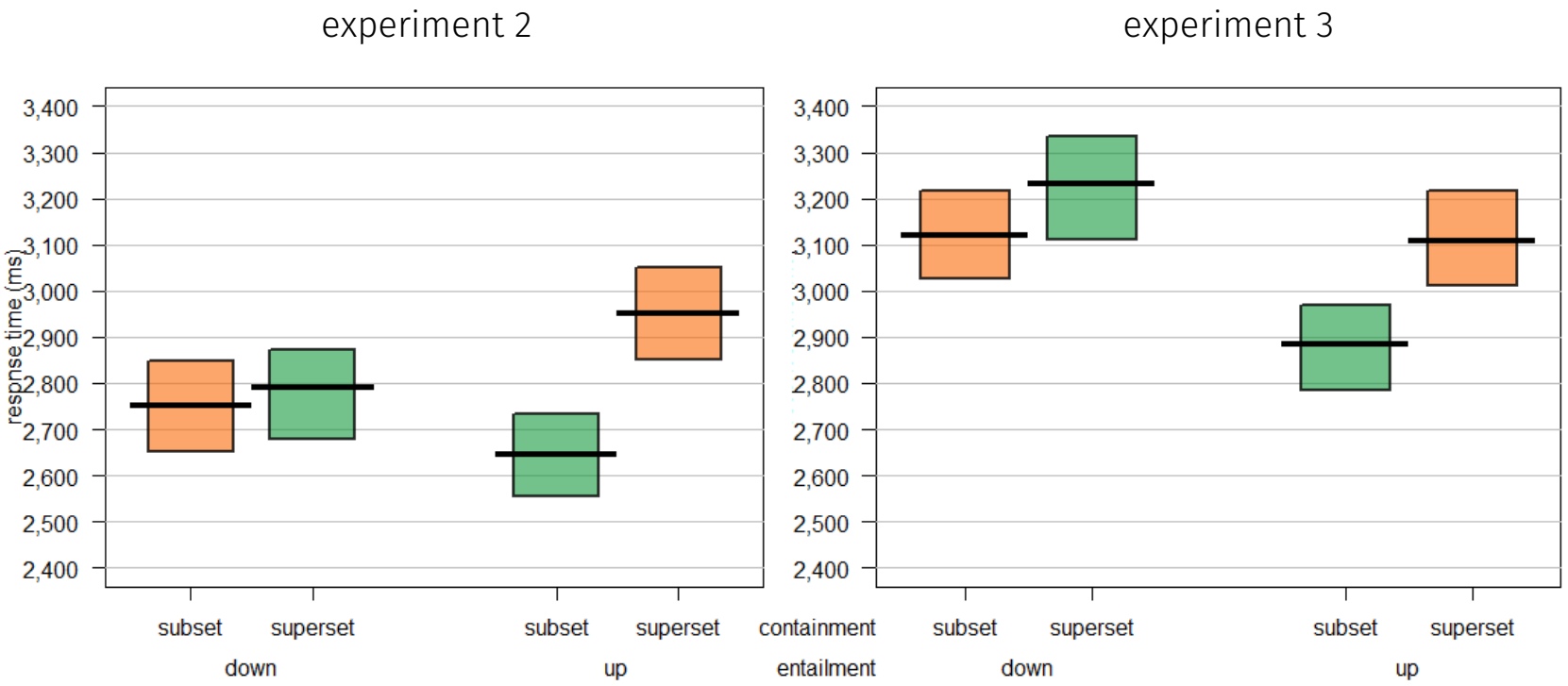
exp. 3: 2nd arg of	*SOME*	*NOT ALL*	*ALL*	*NONE*
SUBSET	entl'd	¬entl'd	entl'd	¬entl'd
IDENT	triv'l	triv'l	triv'l	triv'l
SUPERSET	¬entl'd	entl'd	¬entl'd	entl'd

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

experiment 2 and 3 results



- entailed
- not entailed

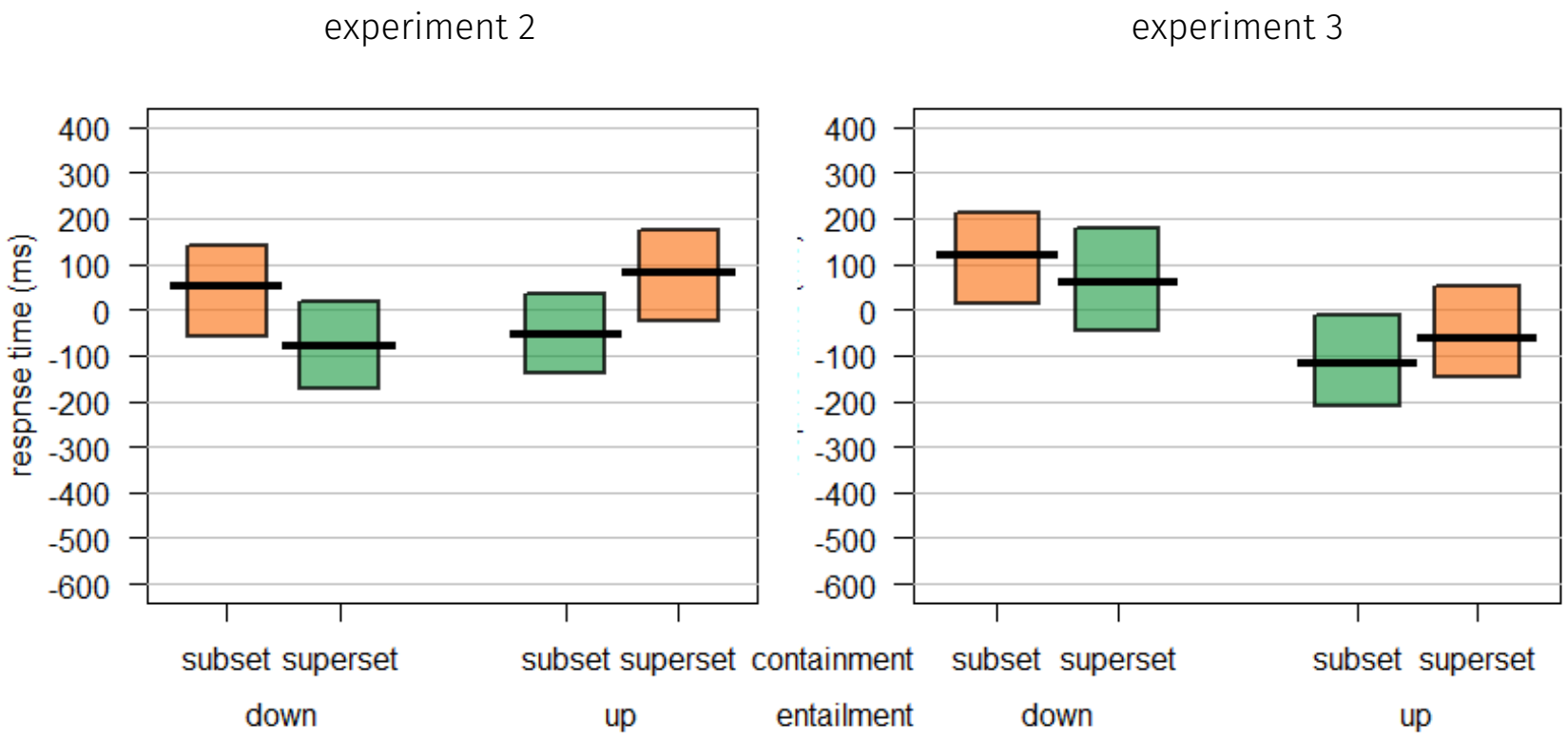
experiment 3

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

$\chi^2 = 6.21$

$p = 0.013$

experiments 2 and 3, partial residual graphs



- entailed
- not entailed

between experiments

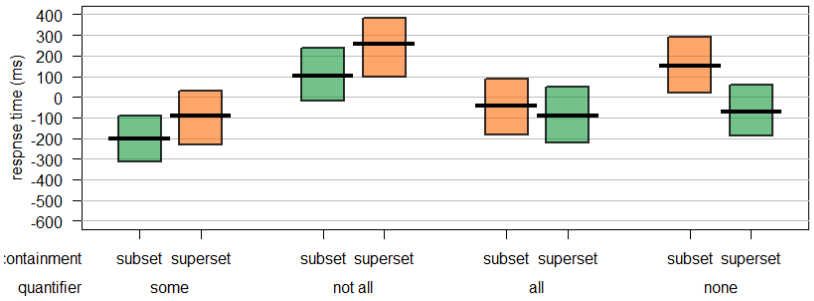
containment × experiment × entailment flip (yes vs. no):

$\chi^2 = 0.98$

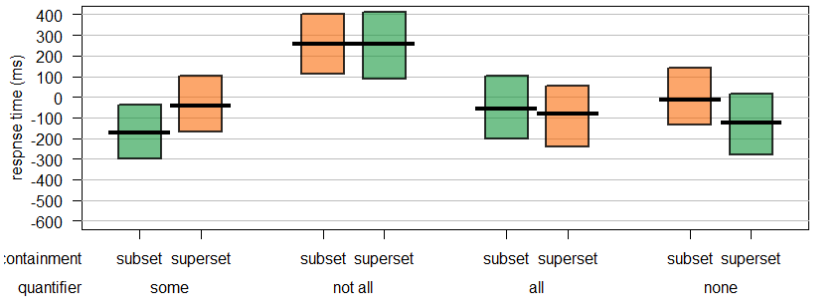
$p = 0.32$

experiment 2 and 3 partial residuals, by quantifier

experiment 2



experiment 3



entailed

not entailed

Discussion

discussion

- language involves accurate and spontaneous logical computations

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- 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)

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- consistent with some logic being naturally intuitive

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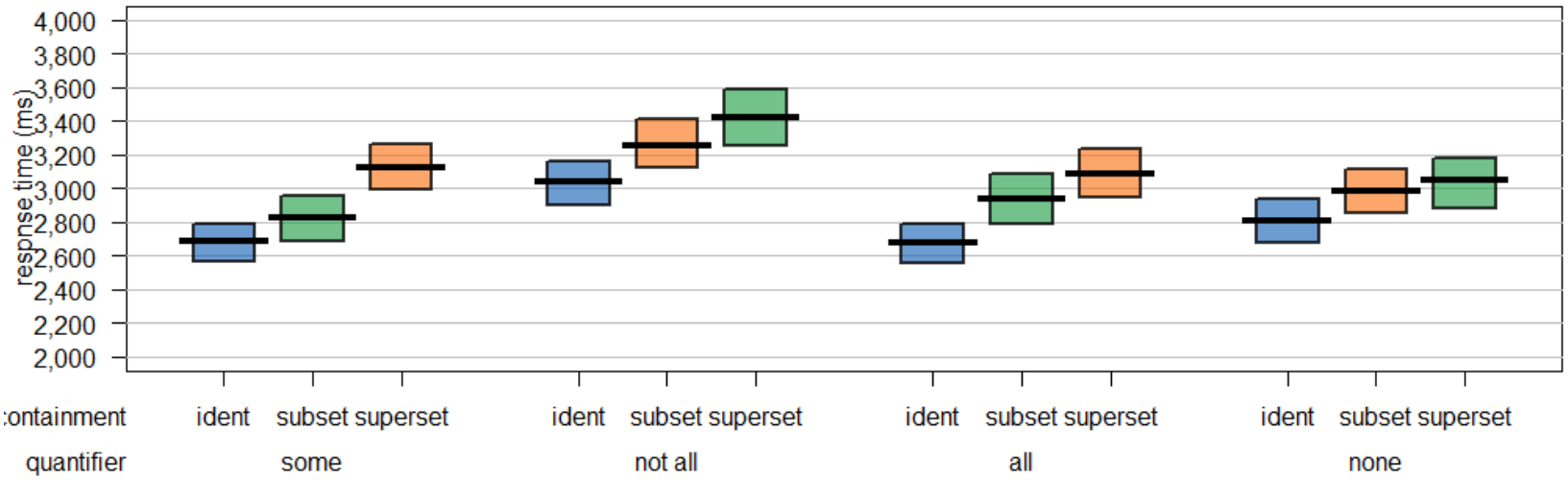
  - logic (L-analyticity) in grammar (e. g. Gajewski, 2002)
- inference derives from compositionality?
- some logical competence revealed more easily in natural language comprehension than in puzzles and tests
- new empirical terrain: which inferences follow from structure of language?

thank you!

experiment 3 results



- trivial
- entailed
- not entailed

subset: *frozen leafy vegetables* $\prec$ *leafy vegetables*

ident: *leafy vegetables* $\prec$ *leafy vegetables*

superset: *vegetables* $\prec$ *leafy vegetables*

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