Experimental work on the Semantics and Pragmatics of Modified Numerals

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1 Introduction

At least since Barwise and Cooper (1981), the dominant view on the semantics of natural language quantifiers has been that they express relations between sets. For example, *all* expresses the inclusion relation: *All men are mortal* is true if and only if the set of men is included in the set of mortal beings. Similarly, *some* expresses the overlap relation: *some politicians are corrupt* conveys that there is a non-empty intersection between the set of politicians and the set of corrupt individuals.

While the general idea behind this style of analysis for expressions of quantity is still in place as one of the pillars of formal semantics, the scope of what is collectively known as Generalized Quantifier Theory (GQT) (following Barwise and Cooper, 1981) has turned out to be quite limited. For instance, simply considering expressions like *many* or *most* to be relations between sets obscures the fact that at some level, such expressions are interpreted via mechanisms from the adjectival domain: The semantics of *many* is (related to) that of an adjective in its positive form (Solt, 2007, for instance); *most* is inherently superlative (Hackl, 2009).

Perhaps the clearest example of an area where the literature has diverged from the GQT conception of quantifiers is that of modified numerals. It is very easy to give a semantic analysis of modified numerals such as *more than 15* in terms of relations between sets: *More than 15* corresponds to the relation between sets where the overlap between the sets consists of more than 15 individuals. There are two (independent) issues with such an analysis. First, it is hard to understand how modified numerals can correspond to relations between sets of individuals given that there are good arguments that a DP like *more than 15 biscuits* has the structure [more than [15 biscuits]] rather than [[more than 15] [biscuits]] (Krifka, 1999; Geurts and Nouwen, 2007). Only the latter is compatible with the GQT view. The second issue, and one that is central to this chapter, is not so much whether modified numerals express relations between sets of entities, but rather, irrespective of how modified numerals express their cardinal content, whether their meaning can indeed be assumed to merely involve the counting of individuals. At the core of this part of the discussion is the observation, due to Geurts and Nouwen (2007), that *more than n* and *at*

least $n+1$ are not semantically equivalent. Clearly, if x is a natural number, then $x > n$ if and only if $x \geq n+1$, and so if modified numerals simply concern the cardinality of the overlap between two sets, then it remains a mystery as to where the source of the non-equivalence lies.

Geurts & Nouwen identify several semantic differences between *more than* and *at least*. Of these, the fact that they support different inference patterns has proven to have the most enduring appeal in the literature. Take for instance the premise that *The final paragraph contained three typos*. Geurts and Nouwen observe that while it clearly follows from this that *The final paragraph contained more than two typos*, it is not so clear that we may conclude that the paragraph in question contained *at least three typos*.

The intuition behind what blocks the inference is that somehow *The paragraph contained at least three typos* suggests that there may have been more. Intuitively, then, *at least* conveys epistemic information about numerical alternatives. This is supported by examples like (1), which are odd since they appear to suggest that the speaker is ignorant about how many children s/he has. This oddness disappears in the parallel sentence with *fewer than*.

(1) ?I have at most 3 children.

(2) I have fewer than 4 children.

Nouwen (2010) argues that the difference between superlative (*at least/most*) and comparative (*more/fewer than*) modifiers is more accurately described as the former, but not the latter, imposing a RANGE REQUIREMENT on the values under consideration (compare Schwarz et al., 2012; Nouwen, 2015). For instance, (4) is felicitous as opposed to the infelicitous (3) since the number of sides of the base of a pyramid is one of a number of possible values (anything that exceeds 2), while there is just one possible number of sides to a triangle (namely, 3). This means that there is no salient way to interpret (3), except perhaps to interpret it with respect to a range of epistemic values (values that the speaker holds possible), but this suggests that the speaker does not know what a triangle is. Hence the oddness.

(3) ?A triangle has at least 3 sides.

(4) A base of a pyramid has at least three sides.

Nouwen (2010) furthermore observes that the difference between comparative and superlative modifiers extends to a larger set of modifiers, thereby establishing two distinct classes: Class A modifiers are modifiers that lack ignorance (or, more generally, range requirement) effects while class B modifiers display these inferences. It turns out that languages tend to have comparative modifiers and locative prepositions (*over*, *under*) as class A modifiers and superlative adverbs (*at least/most*, *maximally/minally*), directional prepositions (*up to*, *from*) and disjunctions (*n or more/fewer*) as class B modifiers.

A dominating theoretical trend has emerged over the past decade encompassing approaches that assume a partially pragmatic analysis for the observations above; one in

which the interpretation effects observed with superlative modifiers are related to the implicatures of disjunctive statements (Büring, 2008; Cummins and Katsos, 2010; Schwarz, 2013; Coppock and Brochhagen, 2013a; Kennedy, 2015; Nouwen, 2015). The idea shared by these approaches is that the mechanism responsible for ignorance and free choice implicatures in disjunctive statements is also responsible for the meaning component that distinguishes class B modifiers from class A.

Consider, for example, a disjunction like (5), which gives rise to the strong inference that the speaker does not know in which city John is.

(5) John is in Brussels or Antwerp.

The ignorance inference for (5) is usually explained in terms of simple Gricean reasoning, as follows. Utterances come with sets of (stronger) alternatives. In accordance with the maxim of quantity, for each alternative p to (5), the hearer can assume that the speaker lacks the belief that p is true. If the speaker is furthermore assumed to be knowledgable, then the hearer can conclude that the speaker must believe the falsity of p. Some alternatives are symmetric. For instance, for (5) both *John is in Brussels* and *John is in Antwerp* are more informative. However, the hearer cannot assume that the speaker is knowledgable about both: for in that case, given that neither of these alternatives was used, the speaker must lack the belief that either is true. And so, if the speaker were knowledgeable, then they must have had the belief that both of these alternatives are false, but then the utterance (5) itself would have been false as well. The conclusion the hearer can draw now is that the speaker must not know which of these alternatives is true (Sauerland, 2004; Fox, 2007).

Pragmatic theories of superlative modifiers assume that at some level of description, modified numerals like *at least 3* correspond to a disjunction of values, say 3 or 4 or 5 or 6 or .... One way to do this is to assume that *at least 3* has the alternatives of such a disjunction. That is, the pragmatically-active alternatives are given by the set {3, 4, 5, 6, ...}. The result of using *at least 3* is now that it is associated with a large number of symmetric alternatives. This explains why such modified numerals trigger ignorance inferences.

The parallel with disjunction goes further, however. Just like the ignorance implicatures for disjunctions can be obviated in the scope of quantifiers, the ignorance effect of *at least* and *at most* disappears in exactly the same environments. The most salient reading of (6) is that some people ate an apple, some ate a pear, and no one ate neither an apple or a pear. Similarly, (7) says that some found 3 typos, some found more, but no one found fewer.

(6) Everyone ate an apple or a pear.

(7) Everyone found at least 3 typos.

Given the parallel, the idea in the literature is that the pragmatic mechanisms responsible for ignorance and ignorance obviation with disjunction govern the interpretation of

superlative quantifiers too.

A slightly different way to implement the pragmatic approach is to assume that the alternatives are not pragmatic but semantic: Like disjunction, class B modified numerals have an alternative semantics. This alternative-inducing semantics triggers pragmatic effects like ignorance based on reasoning why the speaker used an alternative-inducing expression (Coppock and Brochhagen, 2013a).

As we said above, the pragmatic approach (in its various guises) dominates the field. We want to mention two views, though, that differ in interesting respects from what is now mainstream. First of all, Geurts and Nouwen (2007) propose an essentially semantic account in which superlative modifiers are inherently modal. According to their proposal, the relation to the speaker's epistemic state is an explicit part of the lexical semantics of *at least*. The fact that this epistemic effect may be obviated is accounted for by means of assumptions about how modal statements may change flavour when embedded in other quantificational environments. There are some clear issues with this proposal, which we won't review here. In the context of experimentation, however, the theory is interesting since it generates predictions about what would happen if we were not to assume a pragmatic analysis of the inferences at issue.

An altogether different account is proposed by Cohen and Krifka (2014), who assume that superlative modifiers "are interpreted at the level of speech act." In a nutshell, according to Cohen and Krifka, *at least 3* expresses that 3 is the minimal number for which the speaker is unwilling to assert the negation of the sentence in question. For reasons of space, we cannot go into the details of this analysis, but where relevant we will try to evaluate its predictions below.

2 Ignorance inferences

A large series of experiments has recently been carried out to investigate the extent to which numeral modifiers give rise to ignorance inferences and whether these arise semantically or pragmatically. The experimental investigations differ in whether they tested these inferences directly or indirectly and in the designs and methodologies used.

2.1 Experimental support for the semantic account and the Class A/B distinction

The first experiment where ignorance effects seem to be attested with superlative numeral modifiers is reported in Geurts and Nouwen (2007). Geurts & Nouwen carried out two paper-and-pencil experiments in Dutch testing the inference patterns of the relevant superlative and comparative numeral modifiers. Participants had to judge the validity of arguments like the following:

(8) Premise: Beryl had *n* sherries.

(9) Conclusion: Beryl had {at least n / at most n / more than $n-1$ / fewer than $n+1$} sherries.

Conclusions with comparative modifiers were almost unanimously accepted, while conclusions with *at most* were accepted in 22% of the cases and those with *at least* in half of the cases. This difference between comparative and superlative modifiers can be attributed to the fact that the latter give rise to ignorance inferences and thus the relevant conclusions are at odds with the competence and certainty conveyed by the premises, e.g., (8). Geurts & Nouwen, who take this method to test for entailment relations, interpret these results as favouring their semantic account, whereby ignorance is encoded in the lexical semantics of superlative modifiers.

Geurts et al. (2010) found a similar contrast between comparative and superlative modifiers in a similar experiment: While the responses to statements with comparative numeral modifiers were at ceiling, only half of the participants judged statements with the corresponding superlative modifiers as valid. This distinction manifested itself in an online verification study, in which they found that items with superlative modifiers incurred longer decision times than items with comparative modifiers. Geurts et al. (2010) too take this contrast to indicate a semantic difference between comparative and superlative modifiers in favour of the semantic account in Geurts and Nouwen (2007).

Before we proceed to survey the experimental studies that aim to adjudicate between a semantic and a pragmatic account, we would like to mention two studies that found a difference in the acquisition time of superlative and comparative modifiers. Musolino (2004) tested 5-year-olds' understanding of the numeral modifiers *more than, at least, at most,* and *exactly* in a truth value judgement task. While the children performed well on items with *more than* and *exactly*, they performed at chance level on items with superlative modifiers. Geurts et al. (2010) partially replicated Musolino's (2004) findings with 11-year-old participants in an action-based task. Geurts et al., however, did not find a clear-cut distinction between comparative and superlative modifiers; rather, the significant difference was between the upward-monotone modifiers *at least* and *more than*, in which the children scored better, and the downward-monotone modifiers *at most* and *less than*, for which scores were lower. The only significant superlative-comparative comparison was for *at most* and *less than*. Taken together, these acquisition studies show that the meaning of superlative modifiers is acquired later than that of comparative modifiers.

2.2 Evidence for a pragmatic account

In order to determine whether ignorance inferences are semantic or pragmatic, Cummins and Katsos (2010) employ a more elaborate method that distinguishes between logical contradictions and pragmatic infelicities. They tested whether sentence continuations in which an utterance like (10) with a numeral modified by *exactly* follows an utterance with a numeral modifier are judged as entailing, contradictory or pragmatically degraded continuations. Participants were asked to judge how coherent an utterance consisting

of a pair of sentences is on a Likert scale from –5 (*incoherent*) to 5 (*coherent*). Katsos and Bishop (2011) find that when asked to provide gradient, rather than binary, ratings for utterance-felicity, participants successfully differentiate between semantic entailments, logical contradictions, and pragmatically infelicitous statements. Based on these observations, Cummins and Katsos (2010) predicted that logical contradictions will be judged as incoherent, scoring at the lower part of the Likert scale, continuations where the second sentence entails the first (henceforth *logical entailments*) would be judged as coherent, with scores at the upper part of the scale, and continuations that deny pragmatic inferences (i.e. implicature cancellations) would be judged more coherent than the former, but yet less coherent than the latter, scoring at the middle of the scale.

(10) Jean has $\left\{\begin{matrix}\text{at least / more than}\\ \text{at most / fewer than}\end{matrix}\right\}$ n houses. (target item)

$\left\{\begin{matrix}\text{Specifically}\\ \text{In fact}\end{matrix}\right\}$, she has exactly $\left\{\begin{matrix}n+1 \ / \ n\\ n-1 \ / \ n\end{matrix}\right\}$ houses.

(11) Jean has some houses. (control item)

$\left\{\begin{matrix}\text{Specifically}\\ \text{In fact}\end{matrix}\right\}$, she has $\left\{\begin{matrix}\text{none}\\ \text{half}\\ \text{all}\end{matrix}\right\}$ of the houses.

The control conditions (i.e., logical contradictions, logical entailments, and pragmatic infelicities, respectively, in (11)) obtained scores as predicted. The continuations *at least n ... exactly n-1* and *at most n ... exactly n+1* received higher scores than the test logical contradictions and lower than their comparative counterparts (i.e., *more than n ... exactly n+1* and *fewer than n ... exactly n-1*), the latter scoring as high as control logical entailments. The difference between superlative and comparative modifiers was found for items in which the second sentence was introduced by *specifically* or by *in fact*, with the latter conditions receiving higher coherence scores in general.

The fact that participants found the second sentence less acceptable when following a sentence with a superlative modifier rather than a comparative modifier can be attributed to the ignorance effect triggered by the former, which clashes with the knowledgeability expressed by the sentence with the numeral modifier *exactly*. Moreover, the above comparison of superlative modifiers with the test logical contradictions suggests that ignorance effects with superlative modifiers are pragmatic inferences, whose cancellation yields infelicity, similarly to the control pragmatic infelicities with *some* in (11), although less robustly, as the cancelled ignorance inferences were judged as more felicitous than the cancelled scalar implicature. Cummins and Katsos's (2010) findings go against the semantic account by Geurts and Nouwen (2007) and are taken to support their own pragmatic account of ignorance, where superlative modifiers are interpreted as disjunctions and ignorance arises as a quantity implicature. Recall that Geurts and Nouwen's (2007) and Geurts

et al.'s (2010) results did not exhibit wholesale rejection of utterances that deny ignorance inferences and could therefore be accommodated, too, by an account where ignorance is derived via a pragmatic mechanism.

McNabb and Penka (2015) use a similar methodology, where the task also involves judging coherence on a Likert scale. In contrast to Cummins and Katsos, McNabb and Penka use rich discourse contexts as in (12), followed by the target sentence (13).

(12) After the soccer practice, Cassandra sent Eduard to collect all of the soccer balls lying around in the court. He collected the n balls that were scattered around the court. When he was done, he went back to Cassandra and said:

(13) "I collected { *at least / at most* } { $n-1$ / n / $n+1$ } balls."

The results replicated the findings of Cummins and Katsos in that combinations like (12)-(13) were judged to be more coherent than logical contradictions (i.e., *at least* $n+1$/*at most* $n-1$). Again, this finding challenges the semantic account in Geurts and Nouwen (2007).

There is also evidence against the semantic account that does not involve coherence judgments. Coppock and Brochhagen (2013b) argue that Geurts et al.'s (2010) methodology might not be exclusively testing for entailment relations, as what seems to matter in validity judgement tasks is whether the conclusion and premise(s) share common information, be it truth-conditional or pragmatic (see also Ariel (2004) on the difference between lexical semantic content and semantic-pragmatic truth compatibility). Thus, it is very likely that pragmatics might have played a role in Geurts and Nouwen's and Geurts et al.'s tasks, calling into question those authors' interpretation of the relevant findings in favour of Geurts and Nouwen's semantic account of ignorance. Coppock and Brochhagen (2013b) use a truth value judgement task, under the assumption that this is a better method for identifying entailments as it blocks pragmatic intrusion. In their task, native speakers of English had to judge whether a sentence like (14) was true or false given a picture of n objects of type X.

(14) There are { at least n / at most n / more than $n-1$ / fewer than $n+1$ } Xs in the picture.

Although their target sentences were very similar to those used in Geurts and Nouwen and Geurts et al. and had to be assessed against a similar context, albeit this time visually depicted and not written, Coppock and Brochhagen's results were very different. All (superlative and comparative) test conditions yielded surprisingly high percentages of *true* judgements, did not significantly differ from each other, but crucially differed from the control logical contradictions (i.e., *at least* $n+1$, *at most* $n-1$, *more than n*, *fewer than n*), which got very low percentages of *true* judgements, as expected. These results go against Geurts and Nouwen's semantic account of ignorance effects, which would predict that sentences with superlative modifiers would be judged as contradictions against a depiction of an exact number of objects, leading to superlative conditions patterning with contradic-

tions but not with comparative conditions. Coppock and Brochhagen therefore conclude that their findings lend support to a pragmatic account of ignorance.[1]

2.3 (More) direct investigations of ignorance inferences

Although ignorance inferences are a central characteristic that all theoretical accounts of numeral modifiers aim to capture, the experiments discussed so far did not include a direct investigation of ignorance inferences. McNabb and Penka (2015) were the first to directly test for ignorance inferences and arguably to provide direct evidence that ignorance effects are pragmatic inferences. McNabb and Penka investigated how speakers interpret superlative modifiers within an ignorance context by manipulating the speaker's epistemic state. In their experiment, superlative modifiers were embedded under universal and existential deontic modals, as the authors' greater aim was to determine which combinations of superlative modifiers and modals obviate ignorance inferences. In their experimental task, participants had to judge whether the speaker's utterance was compatible with a preceding context that explicitly described her epistemic state, as illustrated in (15), on the same type of Cummins and Katsos's (2010) modified Likert scale.

(15) a. +knowledgeable speaker: The secretary, who was involved in the selection process, said:
b. −knowledgeable speaker: The secretary apologized for not knowing the requirements for the application, and said:

"You are {allowed / required} to have {at least / at most} 3 works in the portfolio you send us."

In the +knowledgeable speaker condition, the combinations *allowed to* + *at most* and *required to* + *at least* received significantly higher coherence ratings than the combinations *allowed to* + *at least* and *required to* + *at most*. The authors argue that this difference arises because the latter combinations trigger ignorance inferences, which are in conflict with the epistemic state of the speaker in that particular context. They further conclude that the difference of these latter combinations from the control logical contradiction items suggests that ignorance with superlative modifiers is a pragmatic inference. Although the

[1] It is worth mentioning that both Coppock and Brochhagen (2013b) (experiment 3) and McNabb and Penka (in the experiment described above) found a contrast between *at least* and *at most*, which one could not explain under the previously mentioned assumption: *at most* $n+1$ was considered significantly less coherent than the similar *at most* n, *at least* n, and *at least* $n-1$ test conditions. The authors explain this asymmetry in the following terms: Participants have difficulties accepting the speaker's utterance *at most* $n+1$ given a quantity n introduced in the context, because she is stating the possibility that a greater quantity (i.e., $n+1$) is true while she knows that it is false given n in the preceding context. This is not the case for *at least* n, although this too allows for the possibility of a higher quantity than n that is not true given n in the context. The contrast arises because *at most* $n+1$, as opposed to *at least* n, explicitly states, or highlights in Coppock and Brochhagen's inquisitive semantic terminology, the possibility that a greater number than n is true.

control items were completely different items, this contrast indirectly shows that ignorance should not be accounted for in the style of Geurts and Nouwen (2007), but rather by a pragmatic analysis.

McNabb and Penka expected that in the −knowledgeable speaker condition all superlative modifier-modal combinations would be well-formed or at least not significantly different, under the assumption that all combinations have a potential parse that gives rise to an ignorance inference. However, the results in this condition were similar to the ones in the +knowledgeable speaker condition: *allowed to + at least* and *required to + at most* still got lower scores. The authors speculate that this could be because participants might have made the assumption that the speaker had in fact knowledge of the exact required or permitted amounts by virtue of them being, e.g., a secretary in the relevant company in (15), and thus this confound may have prevented the licensing of ignorance inferences.

Westera and Brasoveanu (2014) conducted two self-paced reading experiments in English, each followed by a validity judgement task, aiming to directly study the context-sensitivity of ignorance effects with numeral modifiers. They assume that in precise contexts, namely when there is a *how many* Question Under Discussion (QUD), superlative and comparative modifiers trigger ignorance effects to the same extent. Their next assumption is that, if there is an underspecified QUD, superlative modifiers are more likely to give rise to ignorance than comparative modifiers. They base these assumptions on a corpus study in which they find that superlative modifiers are more frequent in precise contexts, hence in underspecified contexts people are more likely to accommodate a precise context in the case of superlative modifiers, which is the right setting for triggering ignorance. Finally, in imprecise or coarse contexts no ignorance is expected to arise with superlative or comparative modifiers.

Participants in Westera and Brasoveanu (2014) were asked to read short exchanges between a judge and a witness in a court setting, as illustrated in (16). First, the judge's question, which set up the QUD, was presented in its entirety. Then, the witness's response, which contained the superlative modifier *at most* or the comparative *less than* and a perception verb, was presented word-by-word. The witness's statement was followed by the judge's conclusion that the witness did not know the exact quantity of the objects in question. Participants then had to assess how justified the judge's conclusion was on a Likert scale from 1 to 5, where 1 was *not justified at all* and 5 was *strongly justified*.

(16) The judge asks:

a. Imprecise QUD: "Did you find {at most / less than} ten of the diamonds under the bed?"
b. Underspecified QUD: "What did you find under the bed?"
c. Precise QUD: "How many of the diamonds did you find under the bed?"

Witness: "I found {at most / less than} ten of the diamonds under the bed?"
Judge's conclusion: "The witness doesn't know exactly how many of the coins she saw under the bed."

Participants found the judge's conclusion to be more justifiable when the QUD was precise (*how many* QUD) or underspecified (*what* QUD) than when it was imprecise (polar QUD). In addition, when just considering the responses to a precise QUD, the judge's conclusion about the witness's ignorance was more justifiable when the witness had used *at most* vs. *less than*. Furthermore, when all the data were taken together, no interaction between the QUD and the numeral modifier factors was found, nor a main effect of the numeral modifier. These results indicate that the QUD does play a role in how people interpret sentences with numeral modifiers and and more specifically in the likelihood of ignorance readings to arise, regardless of the type of the numeral modifier. Interestingly, these results are not expected given an account that takes ignorance to be part of the lexical semantics of superlative modifiers, which predicts ignorance to arise in all QUD conditions to the same extent and only with *at most*.

In order to make sense of the difference between the superlative and comparative modifiers in the *how many* QUD condition, Westera and Brasoveanu hypothesize that this QUD is underspecified to some extent, citing corpus data that lend support to this hypothesis and further suggest that *what* questions might be interpreted more precisely. In order to further test for QUD-sensitivity, they modified the QUD conditions, as shown in (17).

(17) The judge asks:

a. Imprecise QUD: "Approximately how many of the diamonds under the bed?"
b. Precise QUD: "Did you find eight, nine, ten, or eleven diamonds under the bed?"
c. Precise QUD: "Exactly how many of the diamonds did you find under the bed?"

Witness: "I found {at most / less than} ten of the diamonds under the bed?"
Judge's conclusion: "The witness doesn't know exactly how many of the coins she saw under the bed."

Similarly to the first experiment, precise QUD conditions (*exactly how many* and multiple-choice questions) led to higher ignorance inferences than the imprecise QUD condition (*approximately how many* questions). Also, there was no difference between the numeral modifiers. These results too indicate that ignorance inferences are context-sensitive and that they arise with both comparative and superlative modifiers.

In the pursuit of a link between the degree of ignorance inferences and the time-course of these (and related) inferences, Westera and Brasoveanu analyzed reading times from their first experiment in the regions following the modified numeral in the witness's response. Reading times for the numeral region (e.g., *ten*) and (some) subsequent regions were slower in the witness's reply to the underspecified (16b) and precise (16c) QUDs than in the reply to the imprecise QUDs (16a). The word *under* was also read slower when a precise QUD was answered by the witness using a superlative modifier, but this was not the case for the precise QUD & comparative condition.

Westera and Brasoveanu link the increase in reading times in the underspecified and

precise QUDs vs. imprecise QUD to the increase of ignorance readings in these conditions in the offline task and the interaction they find between precise QUD and superlatives. They attribute the increased reading times to the costly on-line calculation of pragmatic ignorance inferences or to the relevant silent intonational effects during reading depending on the context. Surprisingly enough, in the second online task, which included more clear-cut QUD conditions, there was no significant effect of QUD condition. Westera and Brasoveanu blame this on a possible habituation effect, as in their second experiment the filler items included a judge inferring a witness's ignorance, too.

This study shows that ignorance inferences are (i) available with both superlative and comparative modifiers (depending on the context) and (ii) context sensitive, and as such they should be captured in pragmatic terms. However, apart from the replication failure of the findings of the first online experiment, another concern this study raises has to do with the use of perception verbs in the target sentences, which lead to a strong epistemic inference, thereby possibly clashing with the use of a numeral modifier in the underspecified and precise QUD conditions and thus affecting reading times. Note also that it is not entirely clear whether participants generated ignorance inferences on-line in the target sentences or whether they did so when prompted by the judge's conclusion about such inferences.

Alexandropoulou et al. (2016) carried out an eye-tracking reading study in Dutch with the aim of obtaining precise data on the real-time processing of ignorance inferences in −knowledgeability vs. +knowledgeability contexts. They manipulated the context preceding a target sentence with the superlative modifier *at least* in a way similar to that in McNabb and Penka (2015), as illustrated in (18) (translated from the original Dutch).

(18) Sophie is a figure skater and very dedicated. Last weekend she was going to try to train as intensively as possible.

(+knowledgeable:) I can tell you how much because I talked to her yesterday.
(-knowledgeable:) I'm not sure how much exactly, but this is what I think:

Sophie practiced at least seven hours on the ice. (target)

As is clear from (18), the −knowledgeable speaker context forces an ignorance reading, which is compatible with the core meaning of *at least* (e.g., $n \geq 7$ in the example item) as well as with the ignorance inference.[2] The +knowledgeable speaker context, in contrast, is compatible with the core meaning of *at least*, but at odds with the ignorance inference. This context manipulation was inspired by Breheny et al. (2006), who measured in a self-paced reading task reading times of scalar terms (*or* and *some*) in a context triggering a scalar implicature, which was compatible both with the semantics of the scalar term and the scalar implicature, and in a context that did not trigger that scalar implicature but was compatible with the semantics of the scalar term. Breheny et al. found a slowdown at

[2]Note that the speaker in −knowledgeability contexts has partial knowledge of the number at stake rather than complete ignorance, cf. *I'm not sure how much exactly* in (18). The assumption is that it would be extremely odd for a speaker with complete ignorance to utter any number.

the region of the scalar expression in the former (semantic and pragmatic compatibility) condition, which they associated with scalar implicature calculation occurring online and being costly. A similar effect was found by Panizza et al. (2009), who tested the interpretation of bare numerals (one-sided vs. two-sided) with an eye-tracking reading task with a similar context manipulation. According to this context design and Alexandropoulou et al.'s (2016) prediction, if ignorance with *at least* is a pragmatic inference, which has to be computed online and is costly, parallel to run-of-the-mill scalar implicatures (following Bott and Noveck, 2004; Breheny et al., 2006; Huang and Snedeker, 2009, inter alia), a similar effect should be attested in the ignorance-triggering context in which the speaker is −knowledgeable.[3]

The region of *seven hours*, where the interpretation of the whole modified numeral is completed, exhibited longer reading times when the target sentence was uttered by a −knowledgeable speaker as opposed to a +knowledgeable speaker (significant effect in total reading times, marginal in first pass and re-reading probability).[4] There was also a spillover effect of speaker's knowledgeability in the region of the PP *on the ice*, whereby the PP was more likely to be re-read in the −knowledgeability speaker condition than in the +knowledgeability speaker condition. These results are parallel to those found by Breheny et al. (2006) and Panizza et al. (2009) for other scalar expressions. Similarly to those studies, they are taken to be due to the online derivation of a pragmatic inference, i.e., of an ignorance implicature. As such this study offers a direct indication of the pragmatic status of ignorance inferences with superlative modifiers, disfavouring semantic accounts of ignorance. According to semantic accounts, an opposite effect should have been attested, that is, a slowdown in the +knowledgeability speaker condition, due to the contradiction of the speaker's epistemic state set up by the context and of that set up by the lexical semantics of *at least*.[5]

In summary, experiments investigating the availability of ignorance inferences with

[3]In addition to manipulating the speaker's epistemic state, Alexandropoulou et al. also added stimuli that contained a modal. For instance: *Sophie wanted to practice at least seven hours on the ice*. The idea was to test a prediction made by, e.g., Büring (2008) and Kennedy (2015), that in order for ignorance to arise with a modal verb, *at least* needs to take wide scope. Since this is presumably a costly operation (cf. Hackl et al. 2012), an interaction effect was predicted between verb type (modal versus non-modal) and speaker's epistemic state (ignorance versus knowledgeability). However, no such interaction effect was found.

[4]The numeral was grouped together with the noun to comply with the predominant syntactic structure, namely [more than [15 biscuits]] rather than [[more than 15] biscuits], as discussed in the introduction.

[5]An online experiment we haven't discussed so far, but which deserves mention nonetheless, is Hacohen et al.'s (2011), which was designed to test the predictions made by Cohen and Krifka (2014). According to this approach, *at least 3* expresses that 3 is the minimal number for which the speaker is unwilling to assert the negation of the sentence in question. This inference, which is derived by implicature, predicts a difference between true and false responses: A sentence containing *at least 3* would be semantically false if the actual exact number of the object in question is 2 and pragmatically true if the actual exact number is 4. Hacohen et al. indeed find that reaction times for true judgments were significantly longer than reaction times for false judgments. While Hacohen et al.'s (2011) assumptions on how the pragmatic inferences are derived are different than in the dominant family of accounts of numeral modifiers (Büring, 2008; Cummins and Katsos, 2010; Schwarz, 2013; Coppock and Brochhagen, 2013a; Kennedy, 2015; Nouwen, 2015), the results still support a pragmatic rather than a semantic account.

numeral modifiers, both offline and online, converge on the finding that ignorance inferences of superlative modifiers are derived by a pragmatic mechanism, be it in the neo-Gricean style of Büring (2008); Cummins and Katsos (2010); Kennedy (2015); Schwarz (2013), who derive them as scalar implicatures, or in the style of Coppock and Brochhagen (2013b), who derive them via a different independently-motivated pragmatic principle. In what follows, we discuss another type of inferences of numeral modifiers, i.e., the so-called variation effects, which are triggered when numeral modifiers appear in certain embedding environments.

3 Variation/distributivity effects

In the previous sections, we discussed experimental investigations of ignorance inferences that modified numerals give rise to. If, as such investigations suggest, these inferences are indeed pragmatic, and if they are indeed linked to similar inferences attested for disjunctive statements, then it is expected that obviation patterns may occur: Whenever a superlative quantifier is in the scope of another quantifier (be it nominal or modal), the ignorance inference is no longer obligatory. When modified numerals are embedded under universal nominal quantifiers (as well as plurals and generics), they give rise to VARIATION EFFECTS (Nouwen, 2015). To repeat the example from above: *Everyone found at least 3 typos* seems to have a reading on which it conveys that some found 3 typos and some found more. Most accounts of such variation inferences for modified numerals under universal nominal quantifiers derive these inferences pragmatically, though they differ in details (Büring, 2008; Mayr, 2013; Schwarz, 2013; Coppock and Brochhagen, 2013a; Nouwen, 2015).

Cummins and Katsos (2010) investigated statements with comparative and superlative modifiers embedded under the distributive quantifier *each*. Cummins and Katsos sought to find whether participants thought that (19a) implies (19b) and (20a) implies (20b), thereby indirectly investigating variation inferences. Recall that the inference that (19) and (20) give rise to is that the speaker knows precisely how many children each one of Anne and Brian has, as long as neither of them has fewer than three children.

(19) a. Anne has three children but Brian has at least four children.
b. Anne and Brian each have at least three children.

(20) a. Anne has three children but Brian has more than three children.
b. Anne and Brian each have more than two children.

Cummins and Katsos argue that the variation inference in (19) can be easily derived from their pragmatic, disjunctive-inference account of superlative modifiers but not from the semantic, modal account in Geurts and Nouwen 2007. They find that while the inference with *more than* in (20b) is accepted in 95% of the cases, the inference with *at least* in (19b) is accepted in 88% of the cases only (and even less frequently, at 68% of the time, with *at most*), showing that variation inferences are robust but the extent to which they

are generated depends on the type of numeral modifier.

Alexandropoulou (2015) tested the likelihood and strength of variation effects in superlative modifiers under universal nominal quantifiers as a way to gauge whether these inferences should be characterized as pragmatic or semantic inferences. In her experiments (conducted in Dutch), participants read statement-question pairs like the one in (21) and were asked to evaluate how reasonable the question was in response to the answer on a modified Likert scale.

(21) a. According to a random sample every bag contains at least 22 liquorice candies.
b. Do they all contain the same number of liquorice candies?

While the question in (21b) is not incongruent with the assertion in (21a), which can be paraphrased as 'for every bag the number n of liquorice candies is $\geq$ 22,' it is at odds with the potential inference that 'there is no specific n such that all bags contain exactly that many liquorice candies,' i.e., the variation reading. Following the methodology of the coherence experiments in Cummins and Katsos (2010), responses for target items like (21) were compared to ratings given to contradictory and semantically and pragmatically non-contradictory controls. Items like (21) were rated significantly better than semantic contradictions but lower than semantically and pragmatically non-contradictory controls, showing that variation effects indeed arise in sentences like (21a) and strongly suggesting that these inferences are pragmatic.

Alexandropoulou et al. (2015) replicated Alexandropoulou's (2015) results for constructions with *at least* and found them for *more than* as well. They further investigated the implicature mechanism involved in the generation of variation effects. Specifically, they tested two hypothetical strategies differing in the type of alternative propositions entertained. Both strategies assume that an expression like *at least 10* in (22) conveys a disjunctive choice of values, but they differ in which alternatives make up the disjunction. In the first strategy, illustrated in (23), the relevant alternatives are made up by individual numerical values, a strategy similar in spirit to, though differing in its details from, Coppock and Brochhagen (2013a) and Nouwen (2015). The output of this strategy, illustrated in (23) for (22), is that not everyone ate the same number of tacos. In other words, this strategy predicts that at least two different values are attested in the situation described by the sentence, but it does not say anything about which values these may be.

(22) Everyone ate at least 10 tacos.

(23) Partial variation with infinite disjunctions

Assertion	Alternatives	Implicatures
$\forall x[f_x \geq 10]$	$\forall x[f_x = 10]$	$\neg\forall x[f_x = 10]$
	$\forall x[f_x = 11]$	$\neg\forall x[f_x = 11]$
	$\forall x[f_x = 12]$	$\neg\forall x[f_x = 12]$
	... etc.	... etc.

It follows that:
$\neg\exists n\forall x[f_x = n]$
(partial variation)

The alternative strategy to viewing *at least 10* as an infinite disjunction of values assumes that *at least 10* is parallel to the binary disjunction *exactly 10 or more*, similarly to Büring (2008); Cummins and Katsos (2010) and Kennedy (2015), as illustrated in (24). The output of this strategy is that someone ate 10 tacos and that someone ate more. As such, (24), but not (23), predicts the inference from (22) that someone at 10 tacos. This difference in prediction allow Alexandropoulou et al. to test which alternatives modified numerals are associated with.

(24) Partial variation with binary disjunction

Assertion	Alternatives	Implicatures
$\forall x[f_x \geq 10]$	$\forall x[f_x = 10]$	$\neg\forall x[f_x = 10]$
	$\forall x[f_x > 10]$	$\neg\forall x[f_x = 10]$

It follows that:
$\exists x[f_x = 10]$
$\exists x[f_x > 10]$
(partial variation)

Using the same methodology as Alexandropoulou (2015), Alexandropoulou et al. (2015) had participants read dialogues between a researcher and an interviewer, the latter following up on the researcher's statement with a question. Participants were asked to evaluate whether the question made sense given the preceding statement. In order to test whether participants utilized the strategy in (23) or in (24), they compared a condition in which the interviewer's question included the smallest number asserted in the researcher's assertion (*n* in *at least n* and *n+1* in *more than n*) to a condition in which the number was higher than the one asserted.

(25) Smallest number condition:
During the event all streets were guarded by **at least four / more than three** policemen.
Interviewer: How did you find out that there was a street guarded by **four** policemen?

(26) Higher number condition:
During the event all streets were guarded by **at least four / more than three** policemen.
Interviewer: How did you find out that there was a street guarded by **five** policemen?

Alexandropoulou et al. (2015) found that follow-up questions with the lowest number compatible with the modified numeral scored better than semantic contradictions and worse than the non-contradictory controls (as in Alexandropoulou, 2015), and, most importantly, they were rated higher than the questions with higher numbers both in utterances with *at least* and *more than*—though the ratings for *at least* were higher than those for *more than*. These results show that the strategy in (24) is the more likely one for variation inferences and thus lend support to the accounts that predict it, e.g., Büring (2008); Cummins and Katsos (2010) and Kennedy (2015). This family of analyses, however, predict these inferences for *at least* only, to the exclusion of Mayr (2013), who predicts them for *more than*, too.

This series of experiments is an example of how experimental studies can shed light on competing theoretical analyses, which may sometimes differ drastically in terms of the assumptions they make but lead to very subtly different predictions. The results of these studies did not only help adjudicate between the analyses but also led to additional observations: In contrast with previously-detected differences between *at least n* and *more than n* with respect to obligatory ignorance inferences in unembedded contexts, under universal nominal quantifiers, these two numeral modifiers both give rise to variation effects, however in varying degrees.

4 Discussion/Conclusion

The theoretical and experimental crossover has proven beneficial to our understanding of the semantic-pragmatic sources of ignorance inferences and variation effects of numeral modifiers. There is now a large set of results pointing to the pragmatic, rather than semantic, nature of ignorance inferences. Moreover, by looking at finer properties of ignorance and variation effects, it is possible to draw conclusions on what that pragmatic mechanism involves in more detail. Experiments have also allowed the discovery of factors that are not components of any of the standard theoretical accounts. One example we discussed above is how ignorance inferences are dependent on the QUD.

The experimental route has also posed some interesting challenges. We would like to briefly discuss two that are salient in light of the experiments discussed above, one on the experimental side of things and one on the theoretical side.

4.1 Probing pragmatics

The first challenge stems from the subtlety of experimental results, when it comes to distinguishing semantic and pragmatic content. The methodologies developed for investigating the meaning of modified numerals are for the most part adopted from psychological studies and adapted to the study of linguistic meaning. The interpretation of behavioural data as (a way of) reflecting how speakers interpret propositions in context and make additional inferences is a challenging pursuit. There are two sides to this. First of all, quite a few of the studies discussed above use Likert scales to obtain coherence / naturalness scores for combinations of sentences or combinations of a sentence and a context (Cummins and Katsos, 2010; Westera and Brasoveanu, 2014; McNabb and Penka, 2015; Alexandropoulou et al., 2015; Alexandropoulou, 2015). As we explained above, following Katsos and Bishop (2011), the idea is that logical contradictions can be identified by scores clustering at the bottom of the scale, logical consistencies can be identified by clusters at the top and combinations that are semantically compatible, but not pragmatically compatible, can be identified by scores that fall between these extremes. In practice, many studies find not just that combinations that are pragmatically odd are associated with the middle

region of the scale, but also that they come with much more variance. This poses a danger of overinterpretation, since the pragmatic realm is associated with a very large grey area. Any response pattern that is not absolutely contradictory or unequivocally coherent is going to be classed as pragmatic in nature. This ties in with a general issue: Few theoretical semantic and pragmatic analyses make explicit predictions regarding the likelihood of inferences, implicature strength or processing (though see Hackl, 2009; Panizza et al., 2009, among others).

A second issue has to do with the inherent subtlety of pragmatic phenomena. While most experimental research is on scalar expressions like *some* and their relatively straightforward quantity implicatures (see @reference to relevant handbook chapter@), the kind of inferences associated with modified numerals have properties that are not necessarily well-understood. The extent to which ignorance inferences are defeasible, for instance, is part of an ongoing debate (Aloni and Port, 2015). Moreover, the experiments in Chemla and Bott (2014) suggest that the free choice inferences that come with disjunction have a processing profile that is different from that of run-of-the-mill quantity implicatures. If there is indeed a parallel between disjunction and modified numerals, as the dominant theories suggest, we may not expect all inferences associated with *at least* and its kin to compare directly with findings about, say, the implicatures of *some*. In sum, probing pragmatic inferences is made difficult by variation in the prominence of the inferences. In turn, this makes the connection to theory difficult, since the dominant pragmatic frameworks simply distinguish defeasible inferences, which are pragmatic in nature, from non-defeasible ones, which are semantic. Such frameworks do not factor in anything like the likelihood of the inference. As such, the findings discussed in this chapter are in line with an emerging realisation that, at least from the perspective of performance, not all implicatures are alike (Doran et al., 2009, 2012; Van Tiel et al., 2016).

4.2 The comparative - superlative (A-B) distinction revisited

While there has been an incredible amount of work on modified numerals in the past decade, much of that work is devoted to explaining the inferences of superlative quantifiers only. The original motivation to study modified numerals, however, has sprung from the stark contrast between superlative and comparative quantifiers. In sum, while we are definitely closer to understanding why superlative modifiers trigger ignorance inferences, it is not so clear why comparative modifiers do not.

Some of the experimental studies discussed above add an interesting twist to this. While many studies find a clear contrast between comparative and superlative modifiers, others suggest that the inferences we detect for *at least/most* may be attested for *more/fewer than*. For example, it was shown that ignorance inferences can also arise with comparative modifiers, depending on the context (Westera and Brasoveanu, 2014), and that variation effects can arise with comparative modifiers, albeit to a lesser degree than with superlative modifiers, contrary to most analyses (Alexandropoulou et al., 2015). Moreover, other studies unearth unexpected differences between lower-bound and upper-

bound superlative modifiers (Coppock and Brochhagen, 2013b; McNabb and Penka, 2015) that do not lend themselves to analyses that assume a symmetrical treatment of, e.g., *at least* and *at most*.

Speculating somewhat, the experimental route has the potential to provide us with a crucial insight: What we originally thought to be about the absence or presence of inferences turns out to be about something much more subtle. The difference between superlatives and comparatives is due to the degree to which the various inferences are hard-wired in the lexical entry. If this kind of finding turns out to be robustly supported by future experimental evidence, then it is up to the theoretical frameworks to make sense of this. What could this hard-wiring be? Could it be a form of conventionalisation or fossilization (cf. Aloni and Port, 2015)? Why is there no cross-linguistic variation in what kind of modifiers end up having stronger inferences? That is, why do, crosslinguistically, superlative modifiers express ignorance inferences much more strongly than comparative modifiers do? As we hope such questions and speculations make clear, the challenges we identified for the experimental investigation of numeral modification directly set the agenda of future challenges for pragmatic-semantic theory.

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