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At least ignorance inferences come at a processing cost: Support from eye movements*

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Abstract We present results of an eye-tracking reading study that directly probes ignorance effects of the superlative numeral modifier *at least* in embedding and unembedding environments. We find that interpreting a numeral (phrase) modified by *at least* in a context with an ignorant speaker is costlier than in a context with a knowledgeable speaker, regardless of whether *at least* is in an embedding environment or not. In line with online studies testing scalar implicatures using a similar paradigm, this finding is taken to suggest that the observed processing cost is due to the derivation of ignorance interpretations via a pragmatic mechanism. Our results, given the paradigm we employ, further enable us to adjudicate not only between semantic and pragmatic accounts of ignorance, but also among various pragmatic proposals, favouring neo-Gricean accounts that derive ignorance as a quantity implicature (Büring 2008; Cummins & Katsos 2010; Schwarz 2013; Kennedy 2015). We find no evidence indicating that ignorance with *at least* in interaction with a universal modal involves an extra operation, like covert movement.

Keywords: superlative numeral modifiers, ignorance effects, eye-tracking, implicature

1 Introduction

Superlative numeral modifiers like *at least* and *at most*, as opposed to their comparative counterparts *more than* and *less/fewer than*, are known to signal speaker ignorance. For instance, (1) is taken to imply that the speaker is ignorant about the exact number *n* of slides Elena's presentation has. Similarly, (2) suggests that the

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speaker does not know how many children she has, which makes (2) a decidedly odd utterance.

(1) Elena has prepared *at least* 40 slides for her presentation.

(2) # I have *at least* two kids.

Geurts & Nouwen (2007) were the first to point out the epistemic character of superlative modifiers. They proposed to incorporate this epistemic component into the lexical semantics. Not long after, however, a series of proposals argued that the epistemic effects of superlative modifiers were pragmatic rather than semantic in nature (Büring 2008; Cummins & Katsos 2010; Coppock & Brochhagen 2013b; Schwarz 2013; Kennedy 2015, a.o.). Roughly, all these accounts take ignorance to arise as a conversational implicature and they only differ in what the underlying pragmatic mechanism is that is responsible for the epistemic effect.

If the epistemic effects are indeed inferences based on conversational reasoning, then it could be expected that they are defeasible. However, ignorance inferences appear to be hard to cancel:

(3) *At least* 50 people came to the party yesterday. ??Actually, to be precise, there were 53 people at the party.

Thus, although the continuation sentence in (3) is not completely illicit, ignorance inferences seem to do quite bad at what is often thought to be the most common diagnostic of conversational implicatures. Shedding light on this dubious (semantic/pragmatic) status of ignorance effects of superlative modifiers is one of the reasons why, more recently, research on numeral modifiers turned to the collection and study of experimental data. Initially, these experiments probed ignorance effects by comparing statements with modified numerals to some given definite value, provided either as the premise in a reasoning task (Geurts & Nouwen 2007; Geurts, Katsos, Moons & Noordman 2010), as a picture in a truth-value judgment task (Coppock & Brochhagen 2013a), or as part of a short discourse (Cummins & Katsos 2010; McNabb & Penka 2015). Constrasts in responses between superlative and comparative conditions are then attributed to the epistemic effect of superlatives. Coppock & Brochhagen (2013a) show that the contrast found in a reasoning task is absent in a truth-value judgment task and argue that this is because the ignorance component is pragmatic in nature. Cummins & Katsos (2010) come to a similar conclusion by showing that responses in conditions where the context clashes with the ignorance conveyed by a superlative modifier occupy the middle region of a Likert scale, while responses to contradictory and congruent conditions are at the extreme ends of the scale.

None of these experiments directly probed an epistemic component. There are some recent experiments, however, that do incorporate epistemic information in

the experimental setup. McNabb & Penka (2015), for instance, manipulate the speaker's epistemic state in some of their experimental conditions. The goal of their experiment is to find out how ignorance inferences are affected by embedding the superlative quantifier in the scope of a modal. Büring (2008) observed that ignorance effects are optional in embedding environments, as in (4).

(4) The presentation has to be *at least* 40 slides long.

On its most salient reading, (4) does not express any ignorance. It simply conveys that the minimum length of the presentation is 40 slides. However, there is an epistemic reading as well, which conveys that the speaker does not know the exact requirement about the number of slides of the presentation, i.e., she is ignorant about whether the requirement is that $n = 40$ or that $n > 40$. This ambiguity is usually attributed to scope (Büring 2008): ignorance inferences are obviated in the scope of modals, but can reappear if the modified numeral takes scope over the modal.

In McNabb and Penka's experiment, participants had to judge whether an utterance with a superlative modifier embedded under a modal (as in (6)) was compatible with a preceding context that sets up her epistemic state, cf. (5a)/(5b).

(5) 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:

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

Strikingly, however, McNabb & Penka (2015) found no differences between the two contexts. In a different setup, Westera & Brasoveanu (2014) do find a difference between two kinds of contexts. In their study, consisting of two experiments that each combined an offline and an online task, they varied the question under discussion between a precise one (e.g., a *how many* question) and an imprecise one. They found that participants are more likely to interpret modified numerals as conveying ignorance in the precise context. (Strikingly, Westera and Brasoveanu found no difference in this effect between comparative and superlative modifiers in the overall analysis of either of their offline tasks.) The online part of their experiment, which consisted of self-paced reading, showed that in such precise contexts there was a slowdown at and just after the numeral, compared to the self-paced reading in the imprecise context. Westera and Brasoveanu take these results to confirm the offline data, linking the increase in reading times in the precise contexts to the increase of ignorance readings in these conditions. They attribute the increased reading times to the costly online calculation of pragmatic ignorance inferences or to the relevant

silent intonational effects during reading depending on the context. Unfortunately, a second online task, which contained more clear-cut precise/imprecise contexts, provided no significant effect whatsoever.

As such, there is so far no conclusive direct evidence of ignorance effects with modified numerals. The present paper sets out to remedy this. We report on an eye-tracking reading experiment with a paradigm that has effectively been used in experimental studies on scalar implicature. The aim of this paper is twofold: i) to directly measure what happens in real time when interpreting superlative numeral modifiers in ignorance contexts and gain insight into the nature of ignorance effects, ii) to detect traces of wide-scope ignorance interpretations of superlative modifiers in interaction with universal modals.

The next section (Section 2) presents our study, where we also also discuss the predictions that the existing accounts of ignorance effects with modified numerals make given our design. Section 3 summarises our findings and concludes.

2 Current study: Insight into the nature of ignorance inferences with *at least*

The current study was conducted in Dutch and consists of an acceptability pretest experiment and an eye-tracking reading experiment.

2.1 Design

We aimed to directly measure what happens in real time when interpreting both unembedded and embedded occurrences of the superlative modifier *at least* in a context with a –knowledgeable speaker as opposed to a context with a +knowledgeable speaker. To this end, we included two manipulations: (i) we manipulated the speaker's epistemic state set up by the context preceding the target sentence with *at least* in a way similar to that in McNabb & Penka's (2015) second experiment, i.e., +knowledgeable vs. –knowledgeable speaker, see (8a-b), (ii) to test the hypothesis that ignorance effects for superlative modifiers in embedded positions are due to wide scope, we manipulated the main verb of the target sentence, i.e., modal (*moeten* 'must' / *willen* 'want to') vs. non-modal (*hebben* 'to have' / *zijn* 'to be'), see (9).

(7) **Introductory context**

Sophie is een kunstschaatsster en erg fanatiek. Afgelopen weekend
Sophie is a figure-skater and very dedicated last weekend
ging ze proberen zo intensief mogelijk te trainen.
went she try as intensively possible to train

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

(8) a. **+knowledgeable speaker context:**

Ik kan je melden hoeveel omdat ik gisteren met haar gepraat
I can you report how much because I yesterday with her talked
heb.
have

'I can tell you how much because I talked to her yesterday.'

b. **–knowledgeable speaker context:**

Ik weet niet helemaal zeker hoeveel exact, maar dit is mijn idee:
I know not completely sure how much exactly but this is my idea

'I'm not sure how much exactly, but this is what I think:'

(9) **Target sentence:**

Sophie *heeft* / *wilde* minstens zeven uur op het ijs geoefend / oefenen.
Sophie has / wanted at least seven hours on the ice practiced / practice

'Sophie practiced / wanted to practice at least seven hours on the ice.'

As is obvious, a –knowledgeable speaker context like (8b) forces an ignorance interpretation of the target sentence, which is compatible with the core meaning of *minstens* 'at least' ($n \geq 7$ in (9)) and with the relevant ignorance inference (i.e., *the speaker doesn't know whether* (□) $n = 7$ or (□) $n > 7$).[1] On the other hand, a +knowledgeable speaker context as in (8a) is compatible with the core meaning of *at least*, but at odds with the ignorance inference. This context manipulation was inspired by Breheny, Katsos & Williams's (2006) main manipulation in their self-paced reading experiments on scalar expressions. They measured reading times of the scalar expressions *or* and *some* in a context triggering the relevant scalar implicature, which was compatible both with the semantics of the scalar and with the scalar implicature, and in a context that did not trigger that implicature, but was compatible with the semantics of the scalar. They found longer reading times at the region of the scalar expression in the implicature-triggering context condition, which they interpreted as an indication of online scalar implicature generation. A similar effect was found by Panizza, Chierchia & Clifton (2009), who tested the interpretation of bare numerals (lower-bounded vs. upper-bounded) with an eye-tracking reading task with a similar context manipulation: the context that biased an upper-bounded interpretation (upward entailing context) exhibited a slowdown at the region of the numeral, which the authors take to suggest that the upper-bounded

1 Note that the speaker in –knowledgeable speaker contexts is set up so as to have partial knowledge of the *n* in question rather than total ignorance, cf. *I'm not sure how much exactly* in (8b). The idea was to avoid an extremely odd situation of a totally ignorant speaker uttering some number or another.

interpretation of numerals is due to the computation of a scalar implicature that happens online and is costly.[2]

2.2 Predictions

Given the findings discussed in the previous section as well as similar findings arising from different experimental setups, like those in Bott & Noveck 2004 and Huang & Snedeker 2009, among others, we assume that an interpretation due to the derivation of a pragmatic inference arises by taking the context into account, happens online, and incurs a processing cost. Thus, if ignorance is a pragmatic inference, it is expected to (only) arise in –knowledgeable speaker contexts and to manifest itself in a processing penalty on the region of the numeral modifier or of the modified numeral as a whole. If, in contrast, ignorance is a semantic inference, it should arise across the board and only cause a slowdown in the +knowledgeability speaker contexts when hitting the numeral modifier or later due to the resulting contradiction (i.e., between the speaker's epistemic state set up by *at least* and that set up by the context).

In the next sections, we provide an overview of the predictions the existing accounts of ignorance yield with respect to both unembedded and embedded occurrences of *at least* given our design and by enriching them with the processing assumptions we make.

2.2.1 Predictions regarding the speaker's epistemic state

Büring (2008), Cummins & Katsos (2010), Schwarz (2013) and Kennedy (2015), who adopt a neo-Gricean account, derive ignorance effects as Quantity implicatures. According to these accounts, in the –knowledgeable speaker condition that forces an ignorance interpretation, an ignorance implicature is expected to arise, while no such implicature should arise in the +knowledgeable speaker condition, which involves a context that is in conflict with an ignorance interpretation. It is further predicted that the –knowledgeable speaker contexts will exhibit a slowdown at the region where an ignorance interpretation is triggered (i.e., main effect of the –knowledgeable speaker condition).

Coppock & Brochhagen's (2013b) pragmatic account predicts the same as the neo-Gricean camp with respect to the –knowledgeability contexts. They propose an alternative-introducing semantics for *at least*, or else possibility-introducing

2 The effect in question was found in first-pass measures, e.g., in regression path duration and conditioned regression path duration. As the continuation of the sentence with the bare numeral constituted an additional manipulation of the experiment affecting second-pass measures, only the results of the first-pass measures are relevant for us here.

in the inquisitive semantics framework they adopt, and derive ignorance via the independently motivated conversational maxim of Interactive Sincerity. In their account, a speaker that utters *at least* draws attention to multiple possibilities. According to their maxim, if a speaker draws attention to multiple possibilities, it is required that she does not know which of the possibilities in question holds. Thus, it is also predicted that in the +knowledgeable speaker condition the target sentence with *at least* will be incompatible with the preceding context that reveals that the speaker knows which of the possibilities holds, cf. *I can tell you how much* in (8a). If we assume that violating the maxim in question is costlier than obeying it, a slowdown when reading the modified numeral in the +knowledgeable speaker condition would further be predicted (i.e., main effect of the +knowledgeable speaker condition).

Moving to more semantic accounts of ignorance effects, Spychalska (2015), who makes a distinction between truth- and assertibility conditions, takes ignorance to be part of the assertibility conditions of superlative modifiers. While, roughly speaking, *at least n* is false if the quantity under discussion is smaller than *n* and true if it is exactly *n* or greater, the assertibility conditions for *at least n* require that the speaker considers it possible that the quantity in question is *n* and considers it possible that it is greater than *n*. Both the truth- and the assertibility conditions are met in the –knowledgeability contexts, whereas this is not the case for the assertibility conditions in the +knowledgeability contexts. The speaker's epistemic state as defined by these specific contexts contradicts the speaker's beliefs as defined by the assertibility conditions of *at least* in the target sentence, which always follows (i.e., main effect of the +knowledgeable speaker condition). Again, similarly to Coppock & Brochhagen's (2013b) predictions, if a contradiction of the assertibility conditions is taxing, a slowdown at the region of the modified numeral is expected in the +knowledgeability contexts.

Lastly, according to an analysis like that by Geurts & Nouwen (2007), who assume an epistemic modal component in the truth-conditions of *at least* to account for the ignorance implication, the following are predicted: (i) compatibility of the target sentence with a preceding –knowledgeability context, and (ii) incompatibility of the target sentence with a preceding +knowledgeability context, because of the contradiction between the epistemic state of the speaker in that context and the epistemic state of the speaker signalled by the truth-conditions of *at least* (main effect of the +knowledgeable speaker condition). This incompatibility might be reflected in longer reading times in the –knowledgeability vs. +knowledgeability contexts. The exact same predictions hold for Nouwen's (2010) account, which assumes that unembedded occurrences of *at least* are licensed by a silent existential modal operator, which is responsible for the ignorance implication.

2.2.2 Predictions regarding *at least* in embedding environments

Most of the above-mentioned accounts derive a wide-scope ignorance interpretation of *at least* when it interacts with universal modals (cf. *must / want to* in target sentence (9) in modal condition). For instance, an ignorance interpretation would come about (i) when *at least n* outscopes the universal modal (Büring 2008; Kennedy 2015), or, as in Coppock & Brochhagen 2013b, (ii) when *at least*, which quantifies over alternatives/possibilities in that framework, is interpreted above the universal modal, resulting in a speaker's epistemic state that consists of more than one possibility as far as the lower bound of the relevant range is concerned, or (iii) when the epistemic modal quantifier introduced by *at least* takes scope over a universal deontic modal, as in the semantic approach in Geurts & Nouwen 2007. Those accounts also derive a narrow-scope authoritative/+knowledgeability reading, where *at least n* is interpreted in the scope of the universal modal, e.g., in the modal version of (9), *the speaker knows the exact desire of Sophie's, i.e., that Sophie would be satisfied with a 7-hour-long training and would be satisfied with a 8-hour-long training and . . . with a 9-hour-long training, etc.*.

In our design, –knowledgeability contexts are expected to favour a wide-scope ignorance reading of the following target sentence in the modal condition (e.g., *the speaker does not know the exact desire of Sophie's, i.e., whether she wanted to train for 7 hours or whether she wanted to train for 8 hours, etc.*), while +knowledgeability contexts are expected to favour the narrow-scope reading (authoritative/+knowledgeability reading) of the target sentence in the modal condition. We predict that a wide-scope ignorance interpretation of *at least* will be reflected in longer reading times at the region of the modified numeral in the embedding environments preceded by a –knowledgeability context (i.e., an interaction between the modal condition and the –knowledgeable speaker condition). We base this on the assumption that covert quantifier movement is costly (Hackl, Koster-Hale & Varvoutis 2012, but see Jacobson & Gibson 2014; Szabolcsi 2014 for discussion).

2.3 Pretest

2.3.1 Method

We first carried out a pretest to examine the acceptability and coherence of the items to be used in the eye-tracking experiment. It was created in Ibex and hosted on Ibex farm (Drummond 2007). Sixteen native speakers of Dutch (11 female, mean age: 29.69, age range: 20–63) filled in the online questionnaire voluntarily.

The pretest questionnaire consisted of two practice items, forty experimental items, and thirty-two filler items. Each experimental item appeared in four conditions ($\pm$ SPEAKER'S KNOWLEDGEABILITY $\times$ $\pm$ MODAL, cf. (8-9)). Experimental items

were rotated through lists, so that each participant saw one condition per item. Each list was randomly assigned to participants.

Participants were given texts like the one composed of (7-9) and had to assess how compatible the target sentence was with the preceding context. They did so on a Likert scale from 1 to 7, where 1 stands for "the sentence does not fit the preceding contex" and 7 for "the sentence fits well the preceding context".

2.3.2 Results & discussion

As the coherence ratings obtained were ordinal data, we statistically analyse them with ordered probit models using the `ordinal` package (Christensen 2015) in R. The model included two predictors, SPEAKER'S KNOWLEDGEABILITY and MODAL, each factor of which had two levels, i.e., +KNOWLEDGEABILITY / –KNOWLEDGEABILITY and +MODAL / –MODAL, respectively. +KNOWLEDGEABILITY and –MODAL were the reference levels. The model also included random intercepts for participants and items.

Our analysis revealed a highly significant positive main effect of SPEAKER'S KOWLEDGEABILITY ($\beta = -.726$, $SE = .121$, $p < .0001$), indicating that participants judged the target sentence with *at least* as less compatible with the preceding context, when that was uttered by a –knowledgeable speaker than when it was uttered by a +knowledgeable speaker (see relevant scores in boxplot in Figure 1). This was the case regardless of the type of the main verb used in the target sentence, as no other effect was found to be significant.

Quite surprisingly, interpreters seem to like *at least* less in its "natural habitat" than in a +knowledgeable speaker context. This result brings to mind findings from the garden path literature, where it has been shown that the taxing processing operations that take place in garden path sentences make subjects perform poorly on acceptability judgement or question answering tasks (e.g., MacDonald, Just & Carpenter 1992). In this light, carrying out an eye-tracking reading experiment would certainly be in order, to shed light on our intriguing pretest finding and investigate what exactly causes the problem or what the problem/difficulty exactly is.

Before moving to the presentation of our eye-tracking experiment, we would like to already evaluate part of the predictions of the theoretical accounts given the results of the pretest. The higher coherence rates in the case of the –knowledgeability contexts as opposed to +knowledgeability contexts go against Geurts & Nouwen's (2007), Nouwen's (2010), Coppock & Brochhagen's (2013b), and Spychalska's (2015) accounts. That is, those accounts by virtue of a semantic encoding — in one way or another — of the epistemic component of *at least* predict that the target sentence with *at least* should be judged as more compatible with a preceding –knowledgeability context than with a +knowledgeability context.

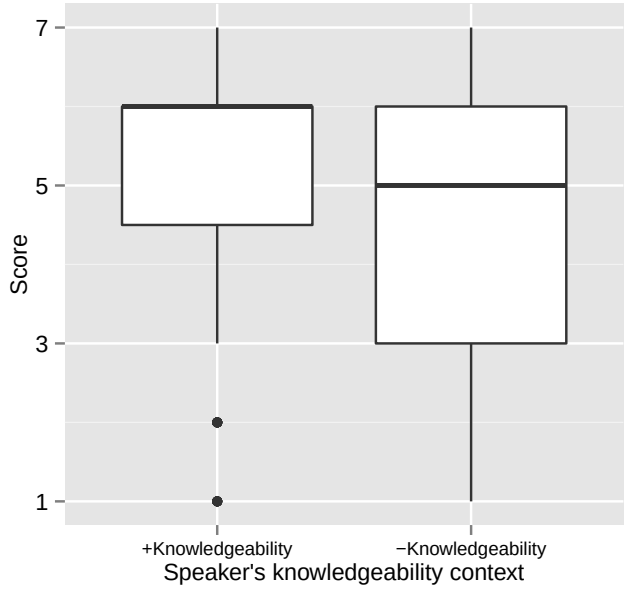

Figure 1 Pretest: Boxplot of scores per speaker's knowledgeability condition.

2.4 Eye-tracking reading experiment

In this section, we present our main experiment that uses the eye-tracking reading technique. This is a sensitive method of detecting effects and processes that occur during reading and will help us investigate the real-time interpretation of unembedded and embedded occurrences of *at least* in ± knowledgeability contexts and also clarify the effect of –knowledgeability contexts detected in the pretest experiment.

2.4.1 Participants

Forty native speakers of Dutch participated in the eye-tracking experiment (28 female, mean age: 24.23, age range: 18–65), who where recruited from the UiL OTS participant database.[3] They received 7.5 euro for their participation. All participants had normal or corrected to normal vision and were naive as to the purpose of the study.

3 Three participants were excluded early on, as two of them turned out to have participated in our pretest and the third was falling asleep during the experiment.

2.4.2 Materials

Of the forty test items included in the pretest, thirty-two of them were tested in the experiment, as eight items with the lowest acceptability mean scores overall were excluded. Participants saw 128 trials in total: four practice items, thirty-two test items, and ninety-two filler items. The latter constituted the test items of two separate experiments. Sixty-eight comprehension questions were included too, to control for whether participants pay attention to the texts they are reading. Of the experimental items eighteen had a comprehension question, while the remaining fifty comprehension questions were follow-ups of the filler items. The target sentence in twenty-five of the test items like that composed of (7-9) was not the last sentence of the text, but was followed by another sentence (e.g., (9) was followed by *She has been busy for weeks with a very difficult new exercise*).

As in the pretest, each experimental item appeared in four conditions ($\pm$ SPEAKER'S KNOWLEDGEABILITY $\times$ $\pm$ MODAL). Experimental items were rotated through four lists, so that each participant only saw one condition per item. Every participant saw only one list and the trials of every list were randomly ordered for each participant.

Experimental items extended on five to eight lines and filler items between one and eight lines. Every line included up to sixty-eight characters (including spaces). The target sentence most of the time was kept on one single line, unless it was more than 68 characters long, in which case a line break occurred after at least two words after the numeral modifier. ($\pm$) Knowledgeability context sentences appeared in one or two lines.

2.4.3 Procedure

Participants were seated in a comfortable chair and the distance of their head to the screen was 55–70 cm. Their eye movements were recored by an EyeLink 1000 in remote mode (using a target sticker), sampling at 500Hz. The stimuli were presented on a 17-inch Acer AL1717 monitor and a three-button button box was also provided to participants for answering the comprehension questions or moving on.

Participants first read the instructions, where they were informed that they would be presented with short stories, each consisting in a short paragraph. After the story, a comprehension question about the text just presented would occasionally appear, which they had to answer by using the button box (right button for YES and left button for NO). The third, middle button could be used to go to the next page. After reading the instructions, the calibration procedure with nine fixation points would start. After that, participants would move on to the practice block, where they read four practice items and answered comprehension questions that two of them were

Region 2	**Region 3**	**Region 4**	**Region 5**	**Region 6**	**Region 7**
Sophie	has / wanted to	at least	seven hours	on the ice	practiced / practice

Table 1 Eye-tracking experiment: Regions of target sentence.

associated with. Then the experiment block began. Before the presentation of a stimulus, a fixation point would appear to mark the beginning of the text, in order to help participants find the start of the first sentence and avoid a seeking behaviour that can influence the reading data. Participants were instructed to read at a normal pace, as they would do in their everyday life. The whole experiment lasted approximately 40 minutes.

2.4.4 Results

Subjects answered correctly 87% of the comprehension questions on average and no subject scored lower than 75%. All participants were included in the statistical analyses. Data of two items that contained a typo were excluded from the analyses. These two items were not excluded altogether though, as the typos were noticed early on and were corrected for the most part of the experiment.

The relevant parts of the texts for our manipulations, that is, starting from the speaker's knowledgeability sentence up to the end of the target sentence, were split into regions for the purpose of the analyses. The knowledgeability context sentence as a whole made up Region 1, while the target sentence was broken down into smaller regions as illustrated in Table 1 for (9).[4] For each of those regions we analysed the following seven reading time measures: (i) first pass (i.e., all fixations in a region before exited to any direction), (ii) right bounded (i.e., all fixations in a region before exited to the right), (iii) regression path duration (i.e., all fixations since the first fixation in a region until it is exited to the right), (iv) probability of regression, (v) total reading time (i.e., all fixations in a region), (vi) re-reading time (i.e., all fixations in a region excl. first-pass fixations), and (vii) probability of re-reading.

We conducted mixed-effects linear regression analyses for the log-transformed reading-time data and mixed-effects logistic regression analyses for the categorical regression probability and re-reading probability measures, by using the `lme4` package in `R`. All analyses included two predictors, SPEAKER'S KNOWLEDGEABILITY (+KNOWLEDGEABILITY vs. −KNOWLEDGEABILITY) and MODAL (+MODAL

4 The numeral was grouped together with the noun (Region 5) to comply with the predominant syntactic structure of modified numeral phrases in the literature (Krifka 1999; Geurts & Nouwen 2007).

vs. −MODAL), with +KNOWLEDGEABILITY and −MODAL as the reference levels, respectively. The analyses also included random intercepts for both subjects and items. Finally, observations with residuals over ±2 were removed from the analyses.

Under a neo-Gricean pragmatic analysis in which ignorance inferences are implicatures (Büring 2008; Cummins & Katsos 2010; Schwarz 2013; Kennedy 2015) that have to be computed online and are costly, parallel to scalar implicatures, a positive main effect of SPEAKER'S KNOWLEDGEABILITY is expected. At the other extreme, a clearly semantic account of ignorance, such as Geurts & Nouwen's (2007) and Nouwen's (2010), would be in line with a negative main effect of SPEAKER'S KNOWLEDGEABILITY. The same could hold for hybrid accounts that include a different maxim or condition on the use of *at least* (Coppock & Brochhagen 2013b; Spychalska 2015), assuming that the violation of such a condition would be costly. The statistical analyses revealed a positive main effect of SPEAKER'S KNOWLEDGEABILITY in Region 5 ("seven hours"), which was significant in total reading times ($\beta = .055$, $SE = .024$, $p = .033$) (see Figure 2), and marginal in re-reading probability ($\beta = .347$, $SE = .177$, $p = .050$) and in first-pass reading times ($\beta = .043$, $SE = .025$, $p = .092$). Note that this region is where the interpretation of the whole modified numeral is completed. For this reason, Region 6 ("on the ice") constitutes a spillover region. A positive main effect of SPEAKER'S KNOWLEDGEABILITY was further found in that spillover region in re-reading time ($\beta = .166$, $SE = .054$, $p = .005$). These effects are in line with a neo-Gricean account of ignorance effects of superlative modifiers that derives them by exploiting the maxim of Quantity.

Furthermore, according to an account of ignorance effects with an embedded occurrence of *at least*, whereby ignorance is the result of a wide-scope movement of *at least* with respect to the present universal modal operator (Geurts & Nouwen 2007; Büring 2008; Coppock & Brochhagen 2013b; Kennedy 2015) and that operation is costly, as has been shown for other types of covert movement, a positive interaction effect is expected at *at least* or at spillover regions. No such effect was found, or any other interaction effect whatsoever.

Finally, we found a positive main effect of MODAL in Region 3 ("has/wanted to") up to Region 6 ("on the ice") in various first-pass and second-pass measures (all $p < .05$) as well as in Region 2 ("Sophie") in re-reading probability ($\beta = .378$, $SE = .173$, $p = .029$). This effect became negative in the very last region (Region 7: "practiced/practice") in right-bounded and total reading times ($\beta = -.063$, $SE = .028$, $p = .033$, and $\beta = -.071$, $SE = .029$, $p = .022$, respectively).

2.4.5 Discussion

To start with the least interesting findings as to the purpose of the present study, the effects of MODAL, manifested throughout the target sentence, could most probably be

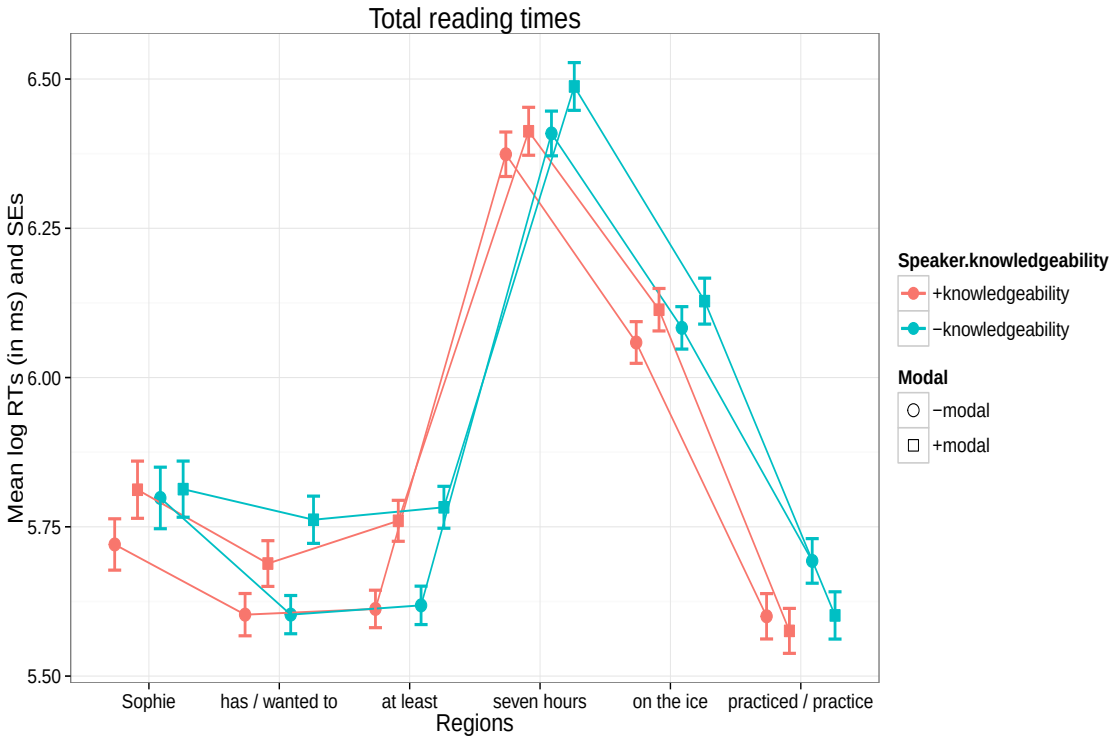

Figure 2 Eye-tracking experiment: Mean log-transformed total reading times (log RTs) and standard errors (SEs) for the regions of the target sentence.

attributed to the different verbal material in Region 3 ("has/wanted to") and Region 7 ("practiced/practice"), and the various aspects that make those verbs differ, e.g., length, frequency, tense, semantics, etc.. Next, the absence of an interaction effect, leads us to conclude that we found no evidence indicating that ignorance triggered by the interaction of *at least* with a universal modal involves an extra process, such as covert movement (wide-scope ignorance). Finally, and most importantly, it seems that the online findings come to confirm our offline data and to show us where exactly the unacceptability for –knowledgeability contexts in the pretest comes from: the region of the modified numeral phrase and the first spillover region cause people difficulties and make them spend more time or re-read those regions. This result lends support to a pragmatic account where ignorance is derived as a scalar implicature and is costly, and is obviously against an account that takes ignorance to be a semantic inference, predicting a similar penalty, though in the +knowledgeability contexts, due to the arising contradiction.

However, there is an alternative explanation of the SPEAKER'S KNOWLEDGEABILITY effects we found. Although we used both low (e.g., *two*, *seven*, *fifteen*) and higher (e.g., *sixty-four*, *four hundred* or *hundred thirty millions*) numbers in our target sentences, we did not systematically control for the roundness or the preciseness of the number. One could expect that the use of *at least* would be incompatible or less acceptable with a non-round or precise number in –knowledgeability contexts, as it would be weird for an ignorant speaker (with partial knowledge of the number at stake) to utter such a number with *at least*. Hence, the effects in the numeral or the next region could be because subjects did not expect that material there or found its use unnatural. In the next section, we report on two additional analyses we performed to investigate the possibility that the SPEAKER'S KNOWLEDGEABILITY effects were confounded by the roundness or the preciseness of the numbers used.

2.4.6 Subsequent analyses

In these analyses, we considered two notions of roundness: one that only takes the number into account and one that considers the preciseness of the number given the granularity level set by the noun, e.g., cf. *to lose at least 2.3 kg* vs. *to lose at least 2.5 kg*, where in the former the number involves a finer granularity and is more precise/unround compared to the latter.

In the first analysis, the notion of roundness was based on Jansen & Pollmann's (2001) definition. Jansen & Pollmann tested in a corpus study in Dutch which numbers appear in approximation contexts following the word *ongeveer* "approximately". Based on their findings, they concluded that a number is round if it belongs to the range 2–9 or if it is divisible by powers of 2, 5 or 10. Given this definition, nineteen of our items contained a round number. ROUNDNESS was added to the model as a predictor, besides SPEAKER'S KNOWLEDGEABILITY and MODAL. +ROUNDNESS, +KNOWLEDGEABILITY and –MODAL were the reference levels. A positive effect of SPEAKER'S KNOWLEDGEABILITY was found in Region 5 ("seven hours"), which was significant in total reading times ($\beta = .054$, $SE = .024$, $p = .037$) and marginally significant in first-pass reading times ($\beta = .046$, $SE = .025$, $p = .075$). Moreover, a positive effect of SPEAKER'S KNOWLEDGEABILITY was attested in the spillover Region 6 ("on the ice") in re-reading times ($\beta = .232$, $SE = .071$, $p = .003$). ROUNDNESS was further found to be significant in Region 5 in various measures (first pass: $\beta = .446$, $SE = .113$, $p < .001$, right-bounded: $\beta = .471$, $SE = .125$, $p =< .001$, regression path duration: $\beta = .490$, $SE = .129$, $p < .001$, total reading time: $\beta = .433$, $SE = .122$, $p = .002$, re-reading time: $\beta = .379$, $SE = .126$, $p < .001$).

In our second analysis, where the second notion of roundness was employed, fifteen of our items turned out to involve a round number. Again, ROUNDNESS

was added to the model as a predictor and the reference levels were +ROUNDNESS, +KNOWLEDGEABILITY and –MODAL. The analysis revealed a positive main effect of SPEAKER'S KNOWLEDGEABILITY in Region 5 ("seven hours") in first-pass and total reading times ($\beta = .078$, $SE = .036$, $p = .039$, and $\beta = .055$, $SE = .024$, $p = .033$, respectively), as well as in spillover Region 6 ("on the ice") in re-reading times ($\beta = .248$, $SE = .078$, $p = .004$). No effects of ROUNDNESS were found.

The new analyses show that the SPEAKER'S KNOWLEDGEABILITY effects attested in the main analyses persist, even when (either notion of) roundness is taken into account. In other words, comprehenders still slow down on a round or imprecise number and the region that follows it when the sentence is uttered by a –knowledgeable vs. a +knowledgeable speaker. Thus, it seems that the roundness of the numbers used in our experiment was not a confounding factor and we can still take our findings to support a scalar implicature status of ignorance with *at least* whose calculation incurs a processing cost, similarly to run-of the-mill quantity implicatures.

3 Conclusion

Aiming to obtain and provide conclusive direct evidence of ignorance effects with numeral modifiers, we investigated how the superlative numeral modifier *at least* is interpreted in –knowledgeable speaker contexts as opposed to +knowledgeable speaker contexts by means of a paradigm that has successfully been used in the experimental research on scalar implicature. We considered both unembedded and embedded occurrences of *at least* when uttered by a +knowledgeable or a –knowledgeable speaker. Employing such a setup and examining what happens in real-time processing of the resulting discourses, further allow us to evaluate the predictions that existing theoretical accounts of ignorance give rise to and differentiate between the various proposals.

We found that comprehenders like an utterance with *at least* more when this follows a +knowledgeable speaker context than when it follows a –knowledgeable speaker context, regardless of whether *at least* appears in the scope of a universal modal or does not. This first finding already invalidates the accounts that assume a clear semantic status for the epistemic effects of superlative modifiers (Geurts & Nouwen 2007; Nouwen 2010) or that pose a maxim/condition on the use of superlative modifiers, requiring that, when a speaker utters them, she has to entertain more than one possibility and should not know which one holds (Coppock & Brochhagen 2013b; Spychalska 2015).[5] All those accounts predict that a sentence with a superlative modifier would be contradictory or infelicitous when uttered by

5 Note that the term *possibility* is used differently in each of these two accounts.

a +knowledgeable speaker, contrary to what the pretest revealed. The eye-tracking reading measures in turn enabled us to pinpoint what has most probably caused comprehenders' dislike of the –knowledgeable speaker condition in the acceptability pretest. We found that the region where the interpretation of the whole modified numeral is completed as well as the one just after cause difficulties to the interpreters and make them slow down in –knowledgeable speaker contexts. After having excluded potential confounding effects of the unroundness of the numbers used in the experimental items, we take the processing cost incurred in these specific regions to be associated with the derivation of an ignorance implicature, similarly to the interpretation of similar findings by studies on scalar implicatures using the same paradigm (Breheny et al. 2006; Panizza et al. 2009). Our online finding is in line with the neo-Gricean pragmatic accounts that derive ignorance as a scalar implicature, but again at odds with Geurts & Nouwen (2007); Nouwen (2010); Coppock & Brochhagen (2013b); Spychalska (2015), who would predict the opposite effect, assuming that the contradiction between the speaker's epistemic state as encoded in the semantics of *at least* or signalled by its use and of that revealed by the +knowledgeability contexts would cause extra processing cost. As to the secondary goal of our study, we found no evidence that the ignorance reading that arises when *at least* is embedded under a universal modal is due to the wide-scope movement of *at least*.

Although the offline findings offered up until now by Geurts & Nouwen (2007), Cummins & Katsos (2010), Geurts et al. (2010), Coppock & Brochhagen (2013a), McNabb & Penka (2015) suggest that ignorance effects are pragmatic in nature and, thus, help us adjudicate between semantic and pragmatic accounts of ignorance, a more direct as well as online investigation enables us to distinguish even further between the various accounts and exclude certain pragmatic proposals whose predictions are not borne out. More importantly, our study can be viewed as providing additional evidence in favour of the claim that the computation of pragmatic inferences by means of the standard neo-Gricean recipe happens online and is costly.

As an outlook for future investigation, it would be interesting to also test comparative modifiers using the same paradigm and even material, and contrast them with superlative modifiers. As is evident from (8a-b), the question under discussion in our experimental items is a precise one (cf. *I can tell you how much / I'm not sure how much exactly*) and according to Westera & Brasoveanu's (2014) predictions and findings no difference between the two types of numeral modifiers is expected in the ignorance-triggering condition (–knowledgeable speaker contexts). On the other hand, according to a well-established claim in the modified numeral literature, ignorance should (more strongly) arise with superlative modifiers and a processing difference should be observed between the two types of numeral modifiers in the ignorance-triggering condition.

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