Processing quantification

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Abstract Quantification is abundant in natural language and is one of the most studied topics in generative grammar. Sentences with multiple quantifiers are famously ambiguous with respect to their quantifier scope, representing a type of ambiguity related to, but not necessary the same as, structural ambiguity. Two key questions in the psycholinguistic study of quantification are: (i) how does the human processor assign quantifier scope?; and (ii) how and under what circumstances is this scope assignment reanalyzed? The investigation of these questions lies at the intersection of psycholinguistics and theoretical linguistics. We summarize both strands of research, and discuss experimental data that played an essential role in the (psycho)linguistic theorizing about the topic of processing quantification and quantifier scope.

Keywords:quantification, quantifier scope, processing of quantifier scope, quantifier hierarchy, logical form, discourse representation theory, underspecification theories of scope

1 Introduction: what is quantifier scope?

Sentences with multiple quantifiers (expressions like *every cake*, *each man*, *a boy*) are ambiguous in ways in which sentences with one quantifier are not. Consider (1), for example: (1a) makes a statement about one individual boy, introduced by the quantifier *a boy*; in contrast, (1b) makes a statement about potentially many boys, one for each girl, because the quantifier *a boy* now interacts with the other quantifier in the clause, *each girl*.

(1) a. Mary kissed a boy.
b. Each girl kissed a boy.

We say that (1b) receives two different interpretations depending on which quantifier *takes scope* over the other. If *each girl* takes scope over *a boy*, the resulting interpretation is: each girl is such that she kissed some boy or other; the boys are possibly different from girl to girl. If *a boy* takes scope over *each girl*, the resulting interpretation is: there is one boy such that each girl kissed him; all the girls kissed the same boy.

Sentences like (1) with multiple quantifiers were difficult to formalize: they did not receive a proper account in mathematical logic until Frege (1879).[1] Multiple quantifiers are similarly challenging for theories of human reasoning: it is not obvious how the human mind represents them and their multiplicity of scope (see, e.g., Johnson-Laird et al. 1989).

1 For an introduction to the treatment of multiple quantifiers in mathematical logic and semantics, see Gamut (1991) and Heim & Kratzer (1998) among others.

2 Factors influencing the grammar and processing of quantifier scope

In addition to the intrinsic difficulty of formalizing quantifier scope ambiguities and identifying cognitively plausible ways of representing them, explicitly mapping the cognitive consequences of scopal interactions between multiple quantifiers is non-trivial because of the variety of factors affecting scope.

The factors influencing quantifier scope can be grouped into three classes:

- syntactic information – Ioup (1975), Vanlehn (1978), Micham et al. (1980), Gil (1982), Gillen (1991), Kurtzman & MacDonald (1993), Anderson (2004), Villalta (2003), Radó & Bott (2012)
- linear information – Fodor (1982), Gillen (1991), Kurtzman & MacDonald (1993), AnderBois et al. (2012)
- lexical information – Ioup (1975), Micham et al. (1980), Gillen (1991), Kurtzman & MacDonald (1993), Tunstall (1998), AnderBois et al. (2012), Dwivedi (2013), Brasoveanu & Dotlačil (2015b)

These factors, or closely related ones, have also been identified as crucial scope disambiguation predictors in the computational linguistics literature on quantifier scope (Poesio 1994, Saba & Corriveau 2001, Higgins & Sadock 2003, Srinivasan & Yates 2009, Evang & Bos 2013, Manshadi 2014 among others).[2]

Let us show how the factors influencing quantifier scope are deployed with an example. Consider the sentence in (2), which includes two quantifiers, *a caregiver* and *every night*.

(2) A caregiver comforted Mary every night.

How can the human processor/interpreter identify the scope of these quantifiers? One option is that the interpreter consults syntactic information. Apart from the references discussed above, this position has often been defended in theoretical linguistics work (Reinhart 1983, May 1985, Heim & Kratzer 1998). A common assumption shared by this family of approaches is that scope can be read off the syntactic positions in which the quantifiers appear, e.g., Reinhart argues that a quantifier A scopes over a quantifier B iff A c-commands B. For 'canonical' sentences, i.e., sentences without transformations, we can equivalently make use of the grammatical role hierarchy shown in (3): a quantifier taking a particular role scopes over every argument which appears to the right of that role.

(3) Grammatical-Role/Syntactic hierarchy:
Subject $\gg$ Indirect Object $\gg$ Object...

The hierarchy in (3) says that an indirect-object quantifier has an object quantifier – but not a subject quantifier – in its scope, while a subject quantifier has every argument in its scope. The scope position of a temporal modifier like *every night* in (2) depends on what one thinks about the syntax of such modifiers. In some accounts (e.g., Larson 1988, following McConnell-Ginet 1982), they are below objects in the syntactic structure; in others (e.g., Nilsen 2000), they are higher than objects but below subjects. Either way, it follows that the subject quantifier *a caregiver* has the temporal modifier *every night* in its scope, which yields the following reading: there is one caregiver such that every night, Mary was comforted by that caregiver.

2 The same factors have also been used to explain interactions of scope-bearing elements other than quantifiers, for example, negation and modal verbs. In this chapter, we only focus on quantifier scope. For a discussion on negation, see (Tian and Breheny, this volume; Xiang, this volume).

Another possibility is that linear order resolves scope. In that case, the scope of a quantifier is equivalent to the material that appears to the right of the quantifier.

Finally, it has been argued that the lexical identity of the quantifier influences its scope. Commonly, only the role of determiners is investigated in this approach (but see Dwivedi 2013). For instance, Ioup (1975) postulates a scope hierarchy among quantifiers according to which the distributive quantifiers *each* and *every* should take quantifiers like *most* or indefinites in their scope but not vice versa. Using only this hierarchy, we would conclude that, in (2), the temporal modifier has the subject in its scope, yielding the interpretation that every night, there is a possibly different caregiver who comforted Mary. The lexical role of determiners in determining scope has also been studied in theoretical linguistics: Szabolcsi (1997) contains very detailed and careful discussions and is the classical reference on this topic.

As has been known at least since Montague (1973), considering only one hierarchy is not sufficient to derive all the available interpretations for sentences with multiple quantifiers. For example, in (2), *every night* is an adjunct following the rest of the clause. Thus, from the perspective of several hierarchies, it should not be able to take scope over the subject or the object. But although this reading is dispreferred, it is possible to understand (2) as introducing multiple caregivers into discourse, one per night – a reading in which the indefinite *a caregiver* is interpreted in the scope of the distributive quantifier *every night* (Ioup 1975, Gil 1982, Tunstall 1998, Anderson 2004, AnderBois et al. 2012, Dotlačil & Brasoveanu 2015 a.o.).

The presence of two readings for (2) could be explained by assuming that one hierarchy, e.g., linear order, establishes the preferred interpretation, and another hierarchy, e.g., quantifier hierarchy, establishes a dispreferred, but possible, interpretation. However, it is common to explain both readings using just one hierarchy type. Then, two readings are derived by postulating that any hierarchy must have a certain amount of flexibility in it. For instance, much of the linguistic literature on the syntax and semantics of quantifier scope postulates that, in a range of cases, Adjuncts can be promoted to the first position in the hierarchy, thereby taking scope over Subjects. This promotion is labeled *inverse scope* because the covert scope representation is the inverse of the overt/'surface' one.

(4) Marked hierarchy for a particular instantiation of inverse scope:
Adjunct $\gg$ Subject $\gg$ Object $\gg \ldots$

A similar point has been made about direct object quantifiers: they can take inverse scope over subject quantifiers but as for adjuncts, this is a marked option. For example, the sentence in (5) below has an unmarked surface-scope reading according to which a single boy climbed every tree, and a marked inverse-scope reading in which the direct object quantifier takes wide scope to the effect that for every tree, some boy or other (possibly different from tree to tree) climbed it.

(5) A boy climbed every tree.

(6) Marked hierarchy for another instantiation of inverse scope:
Object $\gg$ Subject $\gg$ Adjunct $\gg \ldots$

3 The difficulty of processing inverse scope: empirical findings

Suppose that (2) above is followed by another sentence that starts either as shown in (7a), or as in (7b). Previous psycholinguistic research has established that (7b) leads to processing difficulties compared to (7a). The same point can be made about the sentence in (5) above and the two possible continuations in (8a) and (8b) below: according to the same kind of processing difficulty measures, (8b) is hard relative to (8a).

(7) a. The caregiver ... [easy]
b. The caregivers ... [hard]

(8) a. The boy ... [easy]
b. The boys ... [hard]

The behavioral measures showing that plural continuations yield more processing difficulty than singular continuations include: preference for singular continuations in forced choice or Likert-scale judgment tasks; increased reading times for plural continuations in self-paced reading studies (Tunstall 1998, Anderson 2004); and more regressions and increased reading times for plural continuations in eye-tracking studies (Filik et al. 2004, Paterson et al. 2008, Dotlačil & Brasoveanu 2015). We turn now to reviewing these experimental findings in some detail.

Tunstall (1998: Chapter 3) reports the results of a word-by-word self-paced reading task coupled with a stops-making-sense judgment task with a design based on Kurtzman & MacDonald (1993). The items consisted of a dative sentence with a universal and an indefinite in direct object and indirect object positions, followed by a continuation sentence intended to be consistent only with one possible scoping of the previous sentence. An example item is provided in (9) below (see Tunstall 1998: 64, example (12)).

(9) a. Kelly showed a photo to every critic last month.
i. The photo was of a run-down building.
ii. The photos were of a run-down building.
b. Kelly showed every photo to a critic last month.
i. The critic was from a major gallery.
ii. The critics were from a major gallery.

The condition in (9a) has an indefinite in direct object position and a universal in indirect object position. The condition in (9b) switches the two determiners (universal in direct object position, indefinite in indirect object position) while keeping everything else in the sentence the same. The continuations contain a definite in subject position that is always anaphoric to the indefinite NP in the previous sentence. The plural number morphology on this anaphoric definite in (9a-ii) and (9b-ii) disambiguates the quantifier scoping in the preceding sentence: it is compatible only with a narrow-scope indefinite, which is the inverse-scope reading of (9a) and the surface-scope reading of (9b).

In the critical 3-word region consisting of the definite and the verb in the continuation sentence, Tunstall (1998: 66 et seqq.) found that number had a reliable effect in the *a-every* quantifier order ((9a) above), with plural taking longer than singular. This was as predicted by Tunstall's Principle of Scope Interpretation (PSI; Tunstall 1998: 56, (5)), which hypothesizes that quantifier scope is read off the LF of a sentence, and the default scoping is based on the LF structure that is minimally different from its S(urface)-structure (for reasons of general processing economy). In contrast, number did not have a significant effect in the *every-a* quantifier order ((9b) above), which Tunstall attributes to the fact that the singular continuation is in fact compatible with the universal taking scope over the indefinite – we just happen to choose the same critic over and over again for every photo (her Vagueness Principle, (16) on p. 71).

Anderson (2004: Chapter 2) reports the results of several off-line (questionnaire) and real-time (self-paced reading) studies showing that inverse scope is costly, both for sentences in isolation and for sentences occurring in a context that supports the inverse-scope interpretation. An example item used in a questionnaire study is provided below (from Anderson 2004: 32, (47)): participants were shown a sentence like (10) (the subject was always an *a*-indefinite and the object an *every*-universal) and were asked to choose the paraphrase that corresponded to their initial interpretation out of two possible paraphrases (10a) and (10b).

(10) A cashier greeted every customer.
   a. One cashier greeted customers.
   b. Several cashiers greeted customers.

Anderson found that in such out-of-the-blue cases, the paraphrase that is compatible with surface scope (10a) is selected 80% of the time. She then proceeded to embed these doubly-quantified sentences in contexts that would favor one reading or the other, for example (see Anderson 2004: 35 et seqq.):

(11) a. Context supporting surface scope:
   The members of the gourmet club decided to put out a cookbook of their favorite recipes. They wanted the recipes to be easy enough for an inexperienced cook. The president of the club requested that a volunteer test the recipes to make sure that the instructions were correct. After a short discussion, *a member of the club tested every recipe*.
   b. Context supporting inverse scope:
   The members of the gourmet club decided to put out a cookbook of their favorite recipes. They wanted the recipes to be easy enough for an inexperienced cook. Members who nominated recipes were required to test the recipes to make sure that the instructions were correct. *A member of the club tested every recipe*.

Each paragraph was followed by a *how many* comprehension question targeting the indefinite in subject position and asking participants to choose whether *one* vs. *several* entities are contributed by that indefinite, e.g.: *How many members tested recipes?* Participants were asked to identify the answer that matched their first interpretation of the sentence. The surface-scope interpretation was selected 81% of the time in surface-scope biased contexts – not significantly different from the percentage observed for sentences in isolation – but the inverse-scope interpretation was selected 53% of the time in the inverse-scope biased contexts. Thus, we see that the surface-scope biased context does not really boost the already large default preference for surface scope, but the inverse-scope biased contexts do manage to raise the preference for inverse scope from about 20% to about 55%.

Anderson also investigated sentences with a *every*-universal in subject position and an *a*-indefinite in object position, exemplified in (12) below. The paraphrase in (12a) was only compatible with the surface-scope reading, while the paraphrase in (12b) was taken by Anderson to be compatible with the inverse-scope reading.[3] Anderson observed that the interpretation compatible with the inverse-scope reading, (12b), was dispreferred; this was true even in inverse-scope biased contexts (Anderson 2004: 42 et seqq.; judgments on a 5-point Likert scale).

3 Technically speaking, the paraphrase in (12b) is also compatible with the surface-scope reading – see Tunstall's Vagueness Principle mentioned in connection to (9b-ii) above.

(12) Every player rubbed a lucky charm.
  a. Each player rubbed a different charm.
  b. All the players rubbed the same charm.

The same kind of two-quantifier sentences (in both the *a-every* and the *every-a* order) were investigated with self-paced reading tasks involving two-sentence items of the (by now) familiar kind (Anderson 2004: 44 et seqq.): the scopally ambiguous sentence was presented first, followed by a continuation with a definite in subject position anaphoric to the indefinite in the previous sentence. Just as in Tunstall (1998), the plural number marking on the definite disambiguated the scope of the previous indefinite towards narrow scope.

For the *a-every* quantifier order, the plural continuation was read more slowly than the singular continuation, but the effect did not reach significance in any of the individual regions of interest (words in the second sentence). A statistically significant difference between plural and singular was observable only when reading times for the entire continuation sentence were considered: as expected, the plural continuation was slower. For the *every-a* quantifier order, the singular continuation (compatible with inverse scope) was slower than the plural continuation, but the difference was not significant in any region or when the continuation sentence was considered as a whole.

Anderson also let participants read *a-every* sentences without any disambiguating information, as in (13). Each sentence was followed by a comprehension question (13a) with two possible answers (13b). Interestingly, the target sentence was read more slowly if participants in their next step selected the "Several" answer indicating the inverse-scope interpretation.

(13) A paratrooper jumped from every plane.
  a. How many paratroopers jumped from planes?
  b. One vs. Several

The same basic pattern – higher reading times for plural relative to singular continuations in *a-every* sentences – can be observed when sentences and continuations are placed in contexts that support either the surface or the inverse scope reading (Anderson 2004: 57 et seqq.). Importantly, the inverse-scope reading is harder (takes longer) even in contexts that support it (Anderson 2004: 73 et seqq.).

Anderson takes this to support her Processing Scope Economy principle (p. 31, (46)), which conjectures that the human sentence processing mechanism prefers to compute a scope configuration with the simplest syntactic representation (or derivation). As an alternative explanation, Anderson discusses the principle of parsimony (Altmann & Steedman 1988, Crain & Steedman 1985), which states that the interpreter favors a reading that carries fewer unsupported presuppositions. A modified version of that principle, considered by Anderson, would say that the inverse scope of (13) is dispreferred because the interpreter has to accommodate multiple entities (multiple paratroopers) into the discourse model, while the surface scope interpretation has to accommodate only one such paratrooper. This explanation would crucially not work, as it would not explain why the inverse-scope reading is harder even in supporting contexts that introduce multiple entities before the target quantified sentence. Note that Processing Scope Economy is similar to Tunstall's Principle of Scope Interpretation, except it explicitly states that computing a more complex configuration incurs a processing cost.

Turning now to eye-tracking studies, Filik et al. (2004) manipulated quantifier order (*a-every* vs. *every-a*) and grammatical-role order (direct-object vs. indirect-object first) in two-quantifier sentences of roughly the same kind as the ones studied in Tunstall (1998). Following the same pattern, these sentences were followed by continuations containing a singular vs. plural definite in subject position that was anaphoric to the indefinite in the previous sentence. An example item with numbered regions of interest is provided below (see Filik et al. 2004: 955, Table 1); the numbered boundaries indicate where the regions end.

(14) a. Direct object first, *a-every*:
The celebrity gave$|_1$ an in depth interview to every reporter from the newspaper, but$|_2$ the interview(s) was/were$|_3$ not very$|_4$ interesting.$|_5$

b. Direct object first, *every-a*:
The celebrity gave$|_1$ every in depth interview to a reporter from the newspaper, but$|_2$ the reporter(s) was/were$|_3$ not very$|_4$ interested.$|_5$

c. Indirect object first, *a-every*:
The celebrity gave$|_1$ a reporter from the newspaper every in depth interview, but$|_2$ the reporter(s) was/were$|_3$ not very$|_4$ interested.$|_5$

d. Indirect object first, *every-a*:
The celebrity gave$|_1$ every reporter from the newspaper an in depth interview, but$|_2$ the interview(s) was/were$|_3$ not very$|_4$ interesting.$|_5$

In region 2, which contains the two interacting quantifiers, there was an interaction of quantifier order and grammatical-role order, with longer total reading times for *every-a* than for *a-every* when the direct object was first, and for *a-every* than for *every-a* when the indirect object was first. Upon closer inspection, the interaction for direct-object-first stimuli was due to first-pass times (reading time until exiting the region for the first time), while the interaction for indirect-object-first sentences was due to second-pass times (defined as total times minus first-pass times). It is important to note that these findings do not indicate any processing cost of scope since they did not interact with the scope-disambiguating continuation.

In region 3 (the anaphoric definite), plurals took longer than singulars overall but, unexpectedly, there were no effects related to quantifier scope. Filik et al. (2004: 958) conjecture that this might be due to the ‘normal reading’ task, which does not encourage participants to evaluate the two scopal readings as deeply as the tasks in Tunstall (1998) – or Anderson (2004), we might add (Anderson 2004 and Filik et al. 2004 were completed at about the same time, and they do not seem aware of each other).

Paterson et al. (2008) investigate the same kind of discourses as Filik et al. (2004) except they use the universal quantifier *each* rather than *every*. They conjecture that the milder lexical bias for wide scope and distributive interpretations associated with *every* – as opposed to *each* – was the reason for the lack of quantifier-scope effects in region 3 of Filik et al.’s items.

The results for region 2 in Paterson et al. (2008) were similar to the ones in Filik et al. (2004): total reading times were higher for *each-a* than for *a-each* when the direct object was first, and for *a-each* than for *each-a* when the indirect object was first. And just like in Filik et al. (2004), there were no quantifier-scope effects in region 3.

To sum up, the self-paced reading studies of Tunstall (1998) and Anderson (2004) see that plural continuations increase reading measures when they disambiguate towards inverse scope (of *a-every* sentences). In contrast, the eye-tracking studies of Filik et al. (2004) and Paterson et al. (2008) observe that plural continuations always increase reading measures, irrespective of scope disambiguation.

A different way of disambiguating scope is used in Bott & Schlotterbeck (2015), who report an eye-tracking study investigating scope ambiguities in German. They consider sentences with the marked Accusative-Nominative word order, exemplified in (15) below. The sentence-initial Accusative argument consists of a quantifier that either includes the bound possessive pronoun *seiner* (15a, 15c) or does not (15b, 15d).[4] The Nominative argument is either a quantifier (*exactly one teacher*, (15a, 15b)) or a definite noun phrase (*the new teacher*, (15c, 15d)).

(15) a. Jeden seiner Schüler$|_1$ lobte$|_2$ genau ein Lehrer$|_3$ voller$|_4$
Each of-his pupils-acc$|_1$ praised$|_2$ exactly one teacher-nom$|_3$ full-of$|_4$
Wohlwollen.$|_5$
goodwill$|_5$
'Exactly one teacher praised each of his pupils full of goodwill.'

b. Jeden dieser Schüler$|_1$ lobte$|_2$ genau ein Lehrer$|_3$ voller$|_4$
Each of-these pupils-acc$|_1$ praised$|_2$ exactly one teacher-nom$|_3$ full-of$|_4$
Wohlwollen.$|_5$
goodwill$|_5$
'Exactly one teacher praised each of these pupils full of goodwill.'

c. Jeden seiner Schüler$|_1$ lobte$|_2$ der neue Lehrer$|_3$ voller$|_4$
Each of-his pupils-acc$|_1$ praised$|_2$ the new teacher-nom$|_3$ full-of$|_4$
Wohlwollen.$|_5$
goodwill$|_5$
'The new teacher praised each of his pupils full of goodwill.'

d. Jeden dieser Schüler$|_1$ lobte$|_2$ der neue Lehrer$|_3$ voller$|_4$
Each of-these pupils-acc$|_1$ praised$|_2$ the new teacher-nom$|_3$ full-of$|_4$
Wohlwollen.$|_5$
goodwill$|_5$
'The new teacher praised each of these pupils full of goodwill.'

Since binding is parasitic on scope, the presence of the bound pronoun *seiner* in (15a) requires the Accusative quantifier to be interpreted in the scope of the Nominative quantifier. That is, (15a) is only compatible with the inverse-scope reading.[5] But the inverse-scope configuration is not required in the other three conditions: it is not needed in (15b,15d) because these sentences have no pronouns, and it is not needed in (15c) because coreference is sufficient in this case.

In line with previous observations that inverse scope is associated with processing cost, Bott & Schlotterbeck (2015) observe an interaction between the presence/absence of the pronoun and the type of Nominative noun phrase (quantificational vs. referential) in the early reading measures for regions 3 and 5, and the late reading measures for regions 1–3. As expected, the pronoun *seiner* is associated with increased reading times only when it has to be bound by the Nominative quantifier.[6]

Notably, Bott & Schlotterbeck (2015) provide evidence that the parser has difficulties with inverse-scope readings even in *every-a* sentences. The fact that previous studies did not uncover this cost is probably due to the way scope disambiguation was performed in those studies. While Bott & Schlotterbeck (2015) use bound readings to force inverse-scope interpretations, previous studies use singular vs. plural continuations, which is less illuminating since the singular continuation is technically speaking compatible with both the surface-scope

4 Bott & Schlotterbeck establish in one of their pretests that the pronoun *seiner* is interpreted as bound in (15a).
5 This is confirmed by the results of another pretest reported in the paper.
6 The same effect is also observed in region 4 in a self-paced reading study reported in the same paper.

and the inverse-scope reading. In other words, there is no way to unambiguously force the inverse-scope reading for *every-a* sentences when using singular vs. plural continuations.

From the studies discussed so far, it might seem that what the processor finds costly is to interpret the scope of quantifiers in a way that goes against their linear order. There is at least one construction that clearly argues against this position. When one quantifier is embedded inside another one, as in (16), people prefer to interpret the sentence as if the quantifier introduced later, *every city*, scopes above the earlier one, *someone*. Such cases are known as 'inverse linking'. Inverse linking has been shown (for German) to be associated with processing difficulties precisely when quantifier scope matches linear order (Bott & Radó 2009).

(16) Someone from every city despises it.

All the studies discussed so far focused on the interaction of two quantifiers. There is at least one study, that of Dotlačil & Brasoveanu (2015), which investigated the processing of quantifier scope in sentences with three quantifiers and four possible continuations using eye tracking and self-paced reading. An example is given below:

(17) A caregiver comforted a child every night.
   a. The **caregiver** [SG] wanted the **child** [SG] to get some rest.
   b. The **caregivers** [PL] wanted the **child** [SG] to get some rest.
   c. The **caregiver** [SG] wanted the **children** [PL] to get some rest.
   d. The **caregivers** [PL] wanted the **children** [PL] to get some rest.

There were four regions of interest in the continuation sentence, delimited as follows:

(18) The caregiver(s) wanted$|_1$ the child(ren)$|_2$ to get$|_3$ some rest.$|_4$

Dotlačil & Brasoveanu report that, in their eye-tracking study, plural subjects were associated with increased reading-time measures, as expected given the results in Filik et al. (2004), Paterson et al. (2008). The higher cost of plural subjects was observable in region 1 (the subject definite) and spilled over into region 2 (the object definite) and region 4 (the wrap-up region). The processing cost of plural objects was observable in regions 2 and 3.

Interestingly, the results reveal that in several regions and measures, the cost of plural morphology is not additive: the condition with two plurals is at most as costly as the conditions with a single plural argument. This is visible as a negative interaction term when both the subject and the object were plural. The negative interaction term is statistically significant in region 2 (probability of regression and rereading), region 3 (first-pass times), and region 4 (probability of regression and rereading).

The eye-tracking results were further confirmed by a self-paced reading study, which also added another manipulation: letting the sentences in (17a-17d) play a scope disambiguating role – if the sentences followed a multiple-quantifier sentence like (17) – or not – if the sentences appeared out of the blue. The study revealed the same negative interaction as the eye-tracking experiment, i.e., facilitation when both subject and object were plural, but crucially only when the plural morphology played a scope-disambiguating role.

This completes our overview of the empirical results about processing quantifier scope. With this summary in place, we now turn to a brief discussion of the theories put forth to explain these results.

4 Processing theories of quantifier scope

This section discusses and evluates the major processing theories of scope that we already informally introduced when we discussed the empirical results in the literature.

4.1 Underspecification theories vs. hierarchy-based accounts

As we already mentioned, it has been repeatedly established that in a sentence with two or more scopally interacting quantifiers, the inverse-scope interpretation is dispreferred and harder to process (Ioup 1975, Tunstall 1998, Anderson 2004, Reinhart 2006, AnderBois et al. 2012, among many others).

The asymmetry between the processing of surface and inverse scope indicate that underspecification theories of scope on their own are not sufficient to capture the processing behavior exhibited by the human interpreter. In such theories (see Ebert 2005 for a summary and references), one assumes no scopal ordering unless specifically required. If we abbreviate underspecified scope as '$\approx$' (which stands for "$\gg$ or $\ll$"), we can represent the default scope order for a sentence like (5) as shown below:

(19) Subject $\approx$ Object

Thus, by default, any argument can be in the scope of or take scope over any other argument. Underspecification theories (on their own) predict that processing difficulty for surface and inverse scope should be the same: either they are both easy – no scope is processed until needed – or they should both be equally difficult – when scope finally needs to be processed, one scopal relation needs to be added for both the surface and the inverse scope reading.

One way in which underspecification theories of scope might account for the contrast between singular and plural continuations is by attributing the difficulty to 'shallower' processing levels. For example, as Filik et al. (2004) note, the processing cost of plural continuations after *a-every* and *every-a* sentences might arise simply because readers/listeners prefer to match morphological features of the definite to its antecedent noun phrase, which, however, appears in the singular (see also Kemtes & Kemper 1999). The mismatch in number for plural definites adds an extra processing cost visible in increased reaction times.

There are, however, arguments against the hypothesis that inverse-scope difficulties can be reduced to morphological number mismatches. First, it would not explain the findings of several studies discussed in the preceding section that plural continuations are only costly in *a-every* continuations.

Furthermore, a surface-form number matching account makes specific predictions about items like (17) above: we should see independent processing costs when we anaphorically pick up these indefinites with plural definites in a subsequent sentence. For example: (17b) and (17c) should be equally difficult to process, and more difficult than (17a), and (17d) should be more difficult than either (17b) or (17c) – roughly by the same amount as these ones are relative to (17a). However, this pattern has not been observed. In particular, while (17b) and (17c) exhibited an additional processing cost relative to (17a), the combination of two plural arguments in (17d) yielded a negative interaction: if one argument is plural and disambiguates towards inverse scope, it facilitates the inverse-scope interpretation of a subsequent plural argument.

In contrast to underspecification theories, we can straightforwardly make sense of this data in hierarchy-based accounts. These accounts take scope representations to be total orders over the quantifiers in a sentence, which are computed based on some aspect of the (surface) *form* of the sentence (linear order, or c-command, or thematic-roles; see also Sect. 2). In particular, a total order requires *totality* (for any quantifiers Q and Q', either Q scopes over Q' or *vice versa*) and *transitivity* of scope (for any quantifiers Q, Q' and Q'', if Q scopes over Q' and Q' scopes over Q'', then Q scopes over Q'').

Consequently, in a sentence like (17), the subject indefinite *a caregiver* is by default assumed to take scope over the 'object' indefinite *a child*. When this sentence is followed up by the double-plural continuation in (17d), we know that the universal *every night* takes scope over the subject indefinite as soon as we read the plural definite *the caregivers* in the continuation. By totality and transitivity of scope, it follows that the universal *every night* has to also take scope over the object indefinite. We therefore expect the plural subject to make the plural object easier to process, which matches well with the observed negative interaction (see Sayeed 2015 for a formal analysis of this data in event semantics).

Morphological number matching accounts built on top of underspecification theories make the opposite prediction: the two plurals in (17d) should take longer than the single plural in (17b). And 'bare' underspecification accounts (with no surface number-matching requirements) do not distinguish between continuations like (17d) and (17b) since we do the same amount of work in both cases: we need to independently specify the two scopal relations between the universal and each of the two indefinites.

Cases like (17) also provide an argument against accounts in which no scopal representations are retained. For example, let's assume scopal relations are determined by the linear order of the quantifiers (Johnson-Laird et al. 1989), but are not stored as such. Instead, we directly modify the mental model we construct as we interpret a sentence, and that mental model is the only representation we maintain.

Concretely, let's take the interpretation of a sentence to consist of a mental model along the lines of Johnson-Laird (1969). Extending this work, Johnson-Laird et al. (1989) propose that distributive quantifiers add a loop to the mental model, which can be summarized as follows:

i. introduce one element from the domain of the quantifier;
ii. interpret the scope of the quantifier, introducing a single new element for every indefinite;
iii. go back to step (i.);
iv. repeat until all elements in the domain of the distributive quantifier are introduced

Assuming that readers start with the default model created by the linear order of quantifiers and directly modify their mental model only if necessary, they should consider the subject indefinite and the object indefinite in (17) outside the loop of the distributive quantifier. Then, when they read the continuation with a plural subject like (17b), they minimally revise the mental model so that the (discourse) referent contributed by the subject indefinite is inside the loop contributed by the universal quantifier. There is no reason to make additional revisions, so we expect the 'object' indefinite to still outscope the universal because that was the default scope induced by linear order (importantly, linear order is used to construct the original mental model, but it is not invoked later on). The double-plural continuation in (17d) requires two revisions of the default mental model, so if anything, it should be slower / more difficult to process than (17b). This is contrary to the facts.

Thus, the results in Dotlačil & Brasoveanu (2015) are most compatible with the position that a total hierarchy is stored and manipulated when interpreting and revising quantifier scope. Importantly, this finding does not automatically provide an answer to the separate question of processing cost. That is, we now have a good idea about the kind of scopal representations that are built and maintained/updated in discourse, but we have not yet identified the cause for the processing cost associated with inverse scope. This issue is addressed in the following subsection.

4.2 Cost of inverse scope as scope revision

The main idea behind most processing accounts of inverse scope is that the cost associated with it is due to the revision of a mental representation that is constructed 'by default' when a sentence is interpreted. The accounts differ mainly with respect to the nature of this mental representation. Differences can also arise depending on the specification of the revision procedure, but we focus here on the nature of the representation that is manipulated.

The two major choices are (*i*) logical form revision and (*ii*) discourse model revision. We can think of these two classes of mental representations as different stops on the way from the surface form of a sentence to its truth-conditional interpretation. Logical forms are the first stop on the way to truth conditions, which disambiguates between various syntactic structures that are left unspecified by the surface structures. Basically, this is surface structure + quantifying-in / quantifier raising (Montague 1973, May 1985 among many others). Logical forms are very rich representations: they maintain all the surface morpho-syntactic information and add to it additional information necessary to identify a specific set of truth conditions.

Discourse models – specifically, Discourse Representation Structures (DRSs; Kamp 1981, Kamp & Reyle 1993, Kamp 2001) – are further removed from surface syntactic structures. They might retain some of the surface morpho-syntactic information, e.g., person, number and gender information needed for pronoun resolution, or other kinds of form-related features needed for presupposition resolution (e.g., the specific location in the surface syntactic structure where the presupposition was triggered), but many morpho-syntactic features that have no semantic import are not encoded. Discourse models also contain scopal information, but the way that information is encoded might abstract away from many features of the overt syntax that would still be present in logical forms.

In this subsection, we will briefly introduce these two types of processing theories of scope and attempt to empirically distinguish between them.

4.2.1 Logical form revision

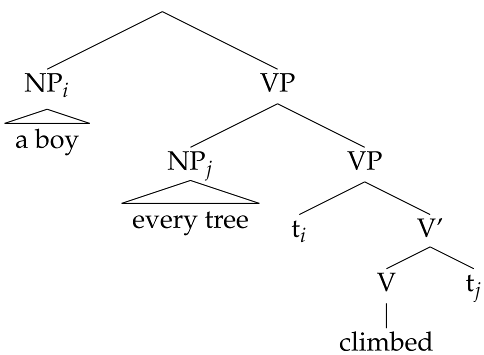
In one of the two classes of accounts we mentioned, processing difficulties associated with inverse scope are the result of reanalyzing a logical-form representation that encodes scope (Kurtzman & MacDonald 1993, Tunstall 1998, Anderson 2004, Pylkkänen & McElree 2006, Hackl et al. 2012).

Abstracting away from the specifics of the linguistic representations, which vary somewhat from account to account, the strategy employed by this family of approaches goes as follows. Recall the example in (5), namely *A boy climbed every tree*. The processor considers the basic hierarchy 'Subject $\gg$ Object' in (3) by default and builds an initial representation ('logical form') for (5) in which the subject *a boy* scopes over the object *every tree*. When the processor encounters the continuation *The boys ...* in (8b), it has to switch from that default scope representation to the marked hierarchy 'Object $\gg$ Subject' in (6), which allows the subject indefinite to introduce multiple individuals. This reanalysis, as is often the case, incurs processing cost.

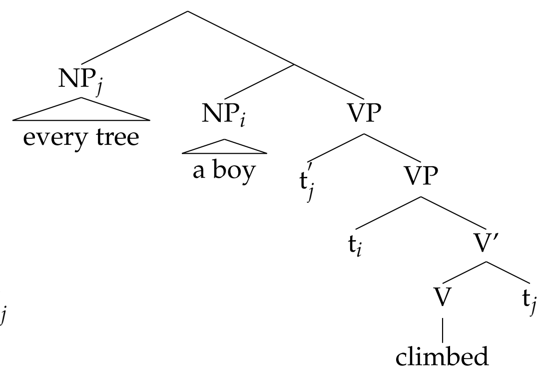
One common way to specify this general strategy is to say that inverse scope requires an extra quantifier raising (QR) operation (Tunstall 1998, Anderson 2004, Pylkkänen & McElree 2006, Reinhart 2006, among others) to derive the requisite logical-form representation. This is shown in (20), modeled after Fox (2000), where quantifiers always adjoin to VP in their original order of c-command, and the inverse-scope interpretation requires an extra movement and adjunction of a quantifier.

(20) A boy climbed every tree.

Surface scope:



Inverse scope:



Another version of this approach appeals to type-shifting instead of QR: an optional type-shifting operator has to be inserted to derive inverse-scope readings (Hendriks 1993). The operator can be reified, i.e., actually inserted, in the logical-form representation, or can have a more ethereal nature and be introduced only during semantic composition. Either way, an extra reanalyzing operation is necessary, which can explain the processing cost of inverse scope.

4.2.2 Discourse model revision

Alternatively, we could explain inverse-scope processing difficulties in terms of changes to the discourse model structure: inverse scope is harder because it requires revising the already built discourse model structure (Fodor 1982; see also Crain & Steedman 1985, Altmann & Steedman 1988).

To see this, consider how sentence (5) is interpreted online. We first hear or read *A boy climbed* . . . , at which point we add a new entity to our discourse model that is a boy and that stands in the climbing relation to whatever direct object we are about to interpret. Then we hear or read the direct object . . . *every tree*.

If we want the direct object quantifier to take wide scope, we need to revise the current discourse structure and introduce a set of boys, each of which is associated with a possibly distinct tree.

Before moving on, we note that in this presentation, we tacitly assume that discourse models are built eagerly and incrementally, i.e., they are basically updated after every word. The presented account would also be compatible with the position that the discourse model structure is constrained and specified only when certain semantically coherent 'chunks' (domains) are processed.[7]

We can make the proposal more specific in various ways. Following Johnson-Laird et al. (1989), we can take the object quantifier to add a loop to the mental model. By default, the subject indefinite is interpreted outside this loop, and this assumption has to be revised when the universal in object position takes inverse scope over the subject.

Alternatively, we can take discourse / mental models to be nothing other than the Discourse Representation Structures (DRSs) that are building blocks of meaning in Discourse Representation Theory (DRT; Kamp 1981, Kamp & Reyle 1993). Using DRT as the basic framework is perhaps the best way to conceptualize this line of approaches since, as a representational theory of meaning and interpretation, DRT far outstrips any other mental-model based approach in formal explicitness and sophistication, as well as empirical success.

In DRT, quantifiers are taken to introduce conditions with a specific structure (duplex conditions) to the current DRS. A universal in object position introduces a duplex condition in the current / main DRS – crucially, after the subject indefinite already introduced a discourse referent in the same DRS. The discourse referent introduced by the subject is therefore outside the duplex condition contributed by the universal, i.e., outside its scope. The inverse-scope reading requires a revision of the main / current DRS to the effect that the discourse referent contributed by the subject indefinite (and whatever other conditions the indefinite contributed to the main DRS) be moved inside the duplex condition contributed by the universal. This change requires additional cognitive operations, yielding the additional processing cost associated with inverse scope.

4.3 Distinguishing between logical-form and discourse-model theories

The empirical results discussed in Sect. 3 are compatible with approaches in which the cost is driven by changes in LF. In fact, several accounts explicitly adopt that position, albeit with slight modifications (Tunstall 1998, Anderson 2004, Bott & Schlotterbeck 2015: a.o.). They are also compatible with discourse-model revisions. For example, the most robust result, namely the processing cost tied to the inverse scope of *a-every* sentences, can be derived because it requires a change in the constructed DRT, as we just discussed. Inverse-scope also requires a change in the number of valuations associated with the discourse referent contributed by the indefinite (one vs. many).

Brasoveanu & Dotlačil (2015a) consider a new type of evidence that can distinguish between logical-form and discourse-model approaches. This evidence is provided by the interaction between quantifiers and adjectives of comparison (AOCs) like *same* and *different*. Consider the sentence in (21) below.

(21) The same student saw every movie.

7 This is what Bott & Schlotterbeck (2015) argue for. They base their argument on sentences in which a lexical verb either appears between two quantifiers (QVQ) or follows them (QQV). If inverse scope is costly and calculated right away, we should observe processing cost on the second quantifier irrespective of the verb. If only particular chunks receive scope interpretations – more concretely, propositions – inverse scope would be calculated on the second quantifier in the QVQ condition, but delayed until the lexical verb appears in the QQV condition, delaying the cost in the latter case. The evidence is equivocal. In their self-paced reading study, Bott and Schlotterbeck report that inverse scope is costly on (the spillover of) the second quantifier only in the QVQ condition. However, the interaction term showing this is only marginally significant in the ANOVA analysis by items. The follow-up eye-tracking study does not replicate the effect, not even marginally so. Rather, readers slow down on the second quantifier in both QVQ and QQV orders.

The AOC *same* has the so-called sentence-internal reading here, i.e., one and the same student saw all the movies. This reading is only possible if *same* is interpreted in the scope of a semantically plural noun phrase that distributes over it (Carlson 1987; see also (Syrett, this volume) for a discussion on distributivity). Semantically plural noun phrases include morphologically singular and distributive universal quantifiers like *every movie*, but also morphologically plural noun phrases like *all the movies*.

Sentence-internal *same* has the potential to distinguish between logical-form and discourse-model theories. This is because *same* in the sentence-internal reading requires inverse scope in sentences like (21) but no revision of the discourse model structure is necessary when a quantifier takes inverse scope over *same*. The universal *every movie* scopes and distributes over *same* to license its sentence-internal reading, but the model will contain only one student both before and after the processing of *every movie*.[8]

The self-paced reading study in Brasoveanu & Dotlačil (2015a) considered four different quantifiers that either preceded *same*, as in (22a) below, or followed it, as in (22b). The quantifiers had to license the sentence-internal reading, otherwise the sentence would be infelicitous.

(22) a. … {all the / each / every / the} researcher(s) learned the same **language spoken in the** eastern Indonesian islands.

b. … the same researcher learned {all the / each / every / the} **language(s) spoken in the** eastern Indonesian islands.

The main regions of interest are the four words that follow the direct object, which is the word *same* in (22a) or the quantificational licensor in (22b). These regions were matched across all conditions and are boldfaced in (22a/22b) below. Several other measures were considered, including reading times for full sentences (since Anderson 2004 observed processing cost in these measures) and answers to comprehension questions.

Interestingly, no effect of inverse scope was detected. This is compatible with discourse-model theories but problematic for the theories that tie cost to logical-form revision. The sentence-internal reading of *same* requires logical-form revision as much as the inverse-scope interpretation of an indefinite. However, these revisions do not change some parameters of the discourse model, unlike indefinites. Specifically, *the same researcher* introduces the same number of discourse referents – or the same number of valuations for the discourse referent it contributes – under both the surface-scope and the inverse-scope reading. One concern about this argument is that it is based on a null effect, so it is in principle possible that the finding is simply due to the lack of power of the reported experiment. This, however, does not seem to be the case – see Brasoveanu & Dotlačil (2015a) for arguments using Monte Carlo simulations that this is very unlikely.

8 Other experimental studies examining scope and AOCs like *same* and *different* are Anderson (2004) and Dwivedi et al. (2010). The former only looked at the interpretation of *different*, which unlike *same* cannot distinguish between different families of approaches to scope processing. The latter examined event-related brain potentials in the processing of sentence-internal *same* and *different*, but considered only surface-scope structures.

5 Conclusion: Bringing it all together

In sections 3 and 4.1, we saw that scope hierarchies – potentially identical to LF structures – are built and maintained/updated when discourses containing sentences with multiple quantifiers are interpreted. In subsections 4.2 and 4.3, we saw that only changes in discourse models (or semantic valuations associated with discourse models) yield processing costs. It might seem that these findings contradict each other, but in fact it is fully coherent to accept both of these experimental conclusions.

Here is one possible way to integrate them into a unified processing theory of scope. Suppose for simplicity that the processor does indeed construct and maintain LF structures as part of its interpretation procedure. LF structures, however, are not the end result of interpretation; they cannot be – we need an actual semantics for them to capture intuitions about entailment, logical equivalence etc. Thus, LFs have to be interpreted relative to a model.

Furthermore, suppose that LF structures are not forgotten as soon as they are interpreted. Instead, they – or similar representations, e.g., DRSs possibly enriched with scope hierarchies – are carried over intra- and cross-sententially and can be modified in light of new discourse information. This makes sense: if scope hierarchies were used to encode quantifier scope in the first place, it is natural that they would be consulted again and updated when revising that quantifier scope.

Now LF modifications/revisions triggered by new discourse information might in turn trigger new, updated discourse model structures (or valuations thereof) – or they might not. The evidence in subsection 4.3 indicates that LF modifications themselves are not costly. The cost only comes about if the LF modifications have consequences for discourse models; for example, if new interpretations are incompatible with previous assumptions about (the number of) discourse referents and/or valuations for these referents.

In sum, what is modified and what is costly for the processor (at least in the range of tasks we examined) might only partially overlap. Some LF-level representation revisions might be cost free as long as they do not have specific kinds of effects on discourse models. This seems to suggest that the representations built by the human processor/interpreter have multiple 'layers' or facets – an LF-like one that is closer to the surface syntactic structure, and a discourse-model one that abstracts away from various surface features. This 'layered' view of semantic processing raises many questions about the exact nature of these representations, as well as about which interpretive subprocesses target which of these 'layers'/facets, and what the temporal unfolding of these subprocesses is.

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