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Priming plural ambiguities

Mora Maldonado, Emmanuel Chemla & Benjamin Spector

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Abstract

Sentences that involve two or more plural expressions, such as numerical expressions, give rise to systematic ambiguities. For example, the sentence *Two boys have three balloons* can either mean that there are two boys who, between them, have three balloons (*cumulative reading*) or that there are two boys who each have three balloons (*distributive reading*). In this paper, we report the results of three experiments which show that the distributive/cumulative ambiguity can give rise to *priming effects*. That is, when subjects perform a sentence-picture matching task which creates a strong bias towards one of the two types of readings, they are more likely to access the very same type of interpretation when subsequently presented with a different sentence-picture pair which does not create the same bias. This finding suggests that the abstract constructs that linguists posit to account for different types of readings describe some real features of mental representations.

Introduction: plural ambiguities and priming effects

Sentences that involve two or more plural expressions, such as numerical expressions, can give rise to multiple readings. For example, a sentence like (1) has at least two different readings, paraphrased in (1a) and (1b). Situations illustrating each reading are depicted in Fig. 1.

- (1) Two boys have three balloons.
 - a. **Cumulative reading:** There are two boys who, between them, have three balloons (Fig. 1a).
 - b. **Distributive reading:** Two boys have *each* three balloons (Fig. 1b).

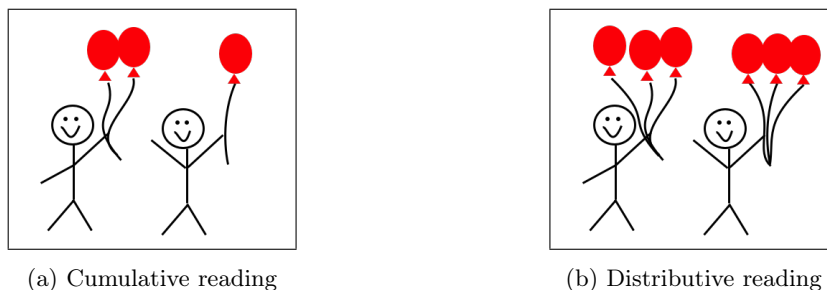


Figure 1: Readings of sentences with plurals

The multiple readings to which plural expressions give rise in natural languages have been extensively studied in theoretical linguistics. Each of the two interpretations mentioned above

for this sentence are assumed to instantiate different types of interpretation rules and possibly different syntactic structures, which play a role in many other sentences and sentence types. These rules and structures are, therefore, of an *abstract and general* nature, and it could be assumed that, when processing such sentences, interpreters access these abstract properties of sentences. The general goal of this paper is to investigate whether abstract semantic properties of these kinds of plural sentence are accessed during sentence comprehension, by means of a *priming paradigm*.

Before providing more details about our goals and methodology, we introduce some formal semantics background regarding the cumulative/distributive ambiguity and present some of the previous psycholinguistic literature on the processing of plural expressions, ambiguities and priming effects.

Formal approaches to distributive and cumulative readings

Formal semantics approaches to the cumulative–distributive contrast are based on the idea that the very same sentence (viewed as a phonological string) corresponds to (at least) two distinct logical forms. A common approach consists of assuming that the distributive interpretation is derived from the cumulative reading through the application of a so-called *distributivity operator*.

Under the *lexical cumulativity hypothesis* (Krifka, 1992; Landman, 2000, see also Kratzer (2007) for relevant discussions), the cumulative reading is in some sense primitive, since it encodes the most basic relation between two pluralities:

(2) Cumulative Interpretation of (1):

There is a plurality made up of two boys, call it X , and a plurality made up of three balloons, call it Y , such that every member of X owns at least one member of Y , and every member of Y is owned by at least one member of X .

In its primary denotation, the predicate ‘have’ denotes a relation between *individuals* (cf. Link, 1983). However, when *have* is used in a sentence (e.g. 1), it receives a more complex meaning, which allows it to denote a relation between *sets of individuals* or *pluralities* (this is the aforementioned *lexical cumulativity hypothesis*). This relation, here represented by HAVE, is defined as follows: A plurality X can be said to HAVE a plurality Y just in case every individual in X is in the HAVE-relation to an individual in Y , and if for every individual in Y , there is an individual in X which is in the HAVE-relation to it.

In contrast with this, the distributive reading of (1) entails that there are two boys who each have three balloons. Following Link (1987) or Champollion (pear), we assume that this second reading is obtained by applying a distributivity operator, noted Δ , to the predicate *have three balloons* (but see Kratzer (2007) for an alternative view based on the star-operator). Under this view, while *have three balloons* is true of a plurality X if the members of X have between them three balloons *in total*, $\Delta(\textit{have three balloons})$ is true of a plurality X only if each atomic member x of X has three balloons in total. When the subject of *have three balloons* is an indefinite numerical phrase such as *two boys*, the resulting meaning is that there are two boys such that each of them has three balloons. To sum up, the cumulative and distributive interpretations of (1) correspond to two distinct Logical Forms (LFs), which we give in (3) in a simplified form:

(3) Two boys have three balloons

a. **LF for the cumulative reading:** [Two boys] [have [three balloons]]

b. **LF for the distributive reading:** [Two boys] [Δ [have [three balloons]]]

We should finally notice that the cumulative interpretation of (1), as defined in (2), is true not only in cumulative situations of the type represented in Fig. 1a, but also in ‘distributive’ situations of the type represented in Fig. 1b: in a distributive situation where the boys have six balloons in total, it is always possible to single out a plurality of exactly three balloons such that the two boys jointly have these three balloons. However, the cumulative reading of sentences such as (1), which can be forced by adding the phrase *between them* (e.g. ‘Two boys have three balloons between them’), tends to be strengthened with the pragmatic inference that the two boys who have three balloons between them do not have *more* than three balloons between them (see Landman (2000) for a discussion of such effects produced by numerals in cumulative sentences). That is, (1) can easily be interpreted with an *exact* meaning, i.e. as conveying that there are two boys who between them have *exactly* three balloons. Under this ‘strengthened’ cumulative reading, sentence (1) is false in the type of situations represented in Fig. 1b. In most of this paper, when we talk about the ‘cumulative’ interpretation, we intend to refer to this strengthened cumulative interpretation; we will discuss the *exact/at least* contrast and its potential implications regarding the interpretation of our results.

Understanding plural ambiguous sentences

In English, plurality can be expressed through a number of means, including the use of plural definites (“the boys”), numerical expressions (“two boys”) and quantificational phrases (“each boy”). Many psycholinguistic approaches to plurality have attempted to define how these different plural expressions are interpreted (Kaup et al., 2002; Patson and Warren, 2010; Patson et al., 2014; Patson, 2014; Sauerland et al., 2005).

In a recent study, Patson et al. (2014) presented participants with a sentence together with a picture, and asked them to judge whether the elements named in the sentence appeared in the image. When the sentences contained numeric expressions (“two boys”), people were faster at making judgments about multiple than about singular referents in the picture. In contrast, no differences in time were found for plural definite descriptions. The authors interpret these results as evidence for the existence of different levels of plural representation: while plural definites are conceptualized in an “underspecified” way (i.e. the numerosity remains unresolved), numerically quantified expressions are interpreted as true pluralities. Specifically, numerals appear to be interpreted as referring to *exact* quantities by both adults and children (Huang et al., 2013; Marty et al., 2013; Patson et al., 2014): ‘two boys’ would refer to a plurality composed by *exactly* two boys. However, this does not necessarily imply that ‘two’-quantified plurals cannot refer to *more than two* entities: weaker, *at least*, readings of numeric expressions, such as the ones proposed by certain accounts of bare numerals, are considered to be available during parsing (Bott and Chemla, 2016). A more extensive theory of how different plural expressions are conceptualized during parsing is provided in Patson (2014).

The study of how these plural expressions interact with each other, giving rise to ambiguities, has been focused on determining whether alternative interpretations (distributive, collective, and cumulative) differ in terms of preference or cognitive cost. Early on, it was observed that adults often prefer collective interpretations of plural ambiguous sentences. Several studies have shown that this pattern is consistent across sentences containing different plural expressions, ranging from numerically quantified phrases (e.g., as in example 1) and plural definites, to personal pronouns and coordinate noun phrases (Brooks and Braine, 1996; Dotlacil, 2010; Kaup et al., 2002; Musolino, 2009; Syrett and Musolino, 2013; Ussery, 1998). This evidence suggests that interpretative differences among plural expressions (such as the ones described above, Patson, 2014) directly favor particular interpretations of ambiguous sentences.

Furthermore, adult preference seems to correlate with the cost associated with each reading

(i.e. dispreferred readings are also slower or more costly). For instance, Frazier et al. (1999) used temporally ambiguous sentences (e.g. "Mary and Paul won 100 dollars each/together") to investigate the dynamics of ambiguity resolution during online processing (see also Brasoveanu and Dotlačil, 2015). These experiments aimed to determine whether people make semantic commitments before disambiguation (e.g., location of 'each'/'together'). The authors found a slowdown in reading times (similar to garden-path effects) when sentences were disambiguated towards a distributive reading (but not towards a collective interpretation). These results suggest an early collective interpretation of the predicate, which may be guiding the slowdown in distributive sentences.

Little attention has been paid in the psycholinguistic literature to the mechanisms that allow the derivation of each of these possible interpretations to begin with. In this paper, we will tackle this issue with a *priming paradigm*. Our main goal is to seek behavioural evidence in favor or against the possibility that very abstract constructs of the kind that theoretical linguists posit are active in the actual process of interpreting plural ambiguous sentences.

Priming studies

Psychologists have demonstrated that the processing of one stimulus can be influenced by previous exposure to similar stimuli (Meyer and Schvaneveldt, 1971). This influence, known as a *priming effect*, can reflect the processes that underlie human behaviour, since, for a priming effect to exist, the relevant representations, operations or features shared between the stimuli would have to remain psychologically active across time.

In the current study, we will present a structural priming paradigm. Structural priming effects occur when the activation of one linguistic structure influences the processing of the same structure on a subsequent trial (Bock, 1986; see review in Pickering and Ferreira 2008). These effects have been traditionally attested in language production, across different syntactic structures (e.g., passive/active sentences, double object constructions, among others; Pickering and Ferreira, 2008). Many of these studies have shown that syntactic priming interacts with preference patterns, giving rise to *inverse-preference effects*: less preferred or less frequent constructions exhibit stronger priming effects than more preferred ones compared to a neutral baseline (Bock and Loebell, 1990; Ferreira and Bock, 2006; Hartsuiker and Kolk, 1998; Scheepers, 2003, among others). For example, while English active sentences do not seem to give rise to priming, less frequent passive structures are known to produce strong priming effects (Bock, 1986). This inverse-preference effect has been interpreted as reflecting that priming corresponds to an attempt to minimize prediction error (Chang et al., 2006; Jaeger and Snider, 2013). Since dispreferred linguistic structures are less expected in the upcoming discourse, they give rise to a larger prediction error when they do arise. The predicted probability of these infrequent structures will then be increased more strongly for subsequent sentences.

More recently, structural priming has also been shown to facilitate sentence comprehension across different syntactic structures (Thothathiri and Snedeker, 2008), and to influence the interpretation of scopally ambiguous sentences (Chemla and Bott, 2015; Feiman and Snedeker, 2016; Raffray and Pickering, 2010). Similar effects were obtained for semantico-pragmatic phenomena, such as scalar implicatures, where enrichment mechanisms are modulated through priming (Bott and Chemla, 2013,0). No priming study, to our knowledge, has addressed purely semantic contrasts such as the cumulative/distributive ambiguity in comprehension. Our experiments might thus serve to enlarge the range of known linguistic phenomena that display priming effects.

Goals

Our main goal in this paper is to determine whether the cumulative–distributive contrast can give rise to *priming effects*. The underlying question is whether the derivation of, for example, a distributive reading for one sentence at one point in time, biases the interpretation of a subsequent *different* sentence, by increasing the likelihood of a distributive interpretation for the second sentence. Such a finding would confirm that certain *abstract semantic properties*, such as the cumulative–distributive distinction, are fully distinguishable during parsing and can be accessed in certain types of decision tasks.

A secondary goal is the following: if a priming effect is found, we would like to determine whether such a priming effect is *symmetric* or *asymmetric* with respect to the cumulative/distributive contrast. Here, we define the priming effect as *symmetric* if the bias towards the distributive interpretation when subjects are primed with a distributive interpretation and the bias towards the cumulative interpretation when subjects are primed with a cumulative interpretation are equally strong.

According to (3), the cumulative reading is in some sense primitive, and the LF for the distributive reading is obtained from the LF for the cumulative reading by adding the distributivity operator. If the priming effects found (if any) are at least partly triggered by the distributivity operator, we may expect stronger priming effects with distributive primes than with cumulative primes (*asymmetric priming*).

Furthermore, an asymmetric priming could suggest an inverse-preference effect, such as the one described above for syntactic priming. The preferred reading of plural ambiguous sentences could demonstrate less priming with respect to a baseline than the dispreferred one. This possibility could still be related to the LFs in (3): the fact that distributive interpretations might involve more complex representations (i.e. with an extra operator) could affect the preference and, consequently, the strength of the effect.

In the rest of this paper, we present the results of three priming experiments which shed light on these questions.

Experiment 1

We used a sentence-picture matching task (Raffray and Pickering, 2010) where participants had to match a sentence with one of two pictures. The sentences always refer to relations between shapes, but they could be ambiguous (e.g., “Two circles are connected to three squares”) or unambiguous (e.g., “A circle is connected to three squares”), depending on the trial. Experimental trials were *primes*, *baselines* or *targets*. Examples are shown in Fig. 2.

In prime trials, the sentence was ambiguous between a *cumulative* and a *distributive* interpretation (e.g., “Two circles are connected to three squares”). One of the two images corresponded to one of these readings (henceforth called the ‘correct’ picture), while the other was incompatible with both readings (‘foil’ picture, under a *exact* reading of numeric expressions)¹.

Participants thus had no real choice in primes: they had to pick the only image that corresponded to a possible reading of the sentence. There were two types of primes. In *cumulative primes*, the correct image made the cumulative reading true and the distributive false. Participants would access the cumulative reading in order to give an accurate answer. Conversely, in

¹ We assume an *exact* reading of numeric expressions. If *at least* readings are also taken into account, most prime trials would allow for a free choice between the two pictures, depending on whether one chooses the *exact* or the *at least* interpretation for the object numeral. Nonetheless, our results show that participants only accessed the exact reading of numerals in this task (see Discussion).

distributive primes, the correct picture only made the distributive reading true, and participants would click on this picture, accessing to the distributive reading of the sentence.

Baseline trials contained sentences without the relevant ambiguity (e.g., “A circle is connected to three squares”). As in primes, they involved a forced choice: the two pictures were such that one (the correct image) corresponded to the unique meaning of the sentence, while the other one made the sentence false.

In target trials, we again used a sentence ambiguous between a cumulative and a distributive reading, but one of the two images corresponded to the cumulative reading and the other one to the distributive reading. Subjects could then follow their preference; they had a choice. Crucially, target trials could be immediately preceded by primes or by baselines. Whenever a target followed a prime, we expected the response to be influenced by the choice that was forced just before: participants should select the distributive image more often after a distributive prime than after a cumulative prime (and vice versa). In contrast, the baseline-target configuration allowed us to measure the rate of cumulative and distributive readings on targets in the absence of immediate priming (i.e. the baseline preference).

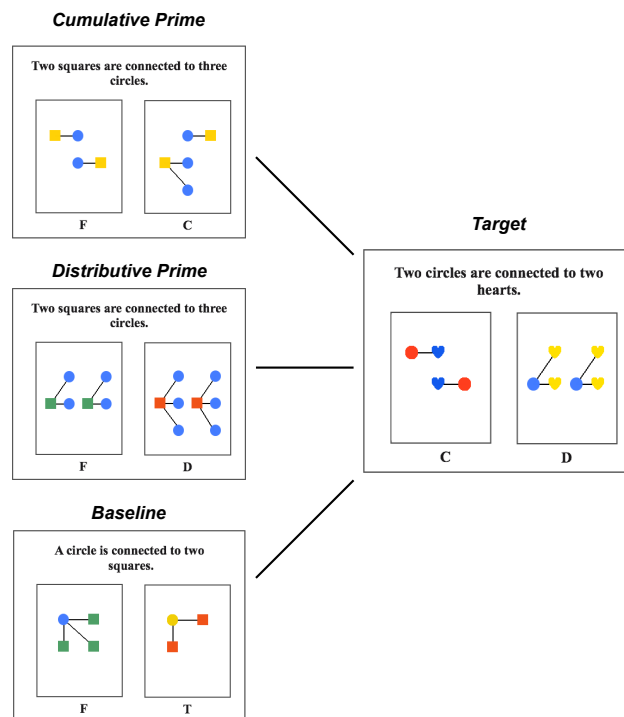


Figure 2: **Schematic representation of the different types of trials in Experiment 1.** Target trials could follow cumulative primes, distributive primes or baselines. Prime and baseline trials were formed by a foil picture (F) and a picture consistent with the sentence (C, D or T, depending on the condition). In target trials the ambiguous sentence was always paired with two consistent pictures (C and D). Image positions (left-right) and numeric expressions in object position (‘two’; ‘three’) were randomized between primes and targets.

Methods

Participants

Sixty participants (29 women, 31 men) were recruited online using Amazon Mechanical Turk (<https://www.mturk.com>). Nine participants were removed from the analysis because they did

not report English as their native language and a further two were excluded because their mean response times were lower than 1 second. The remaining 49 participants were taken into account for the analysis.

Materials

Each trial consisted of a sentence and two images appearing together on a computer screen. The sentences were automatically generated using one of two frames (Examples 4 and 5) and one of two numeric expressions in object position (a. ‘two’, b. ‘three’).

- (4) Ambiguous sentences (used in primes and targets):
 - a. Two **[shape 1]** are connected to two **[shape 2]**
 - b. Two **[shape 1]** are connected to three **[shape 2]**
- (5) Non-ambiguous sentences (used only in baseline trials)²:
 - a. A **[shape 1]** is connected to two **[shape 2]**
 - b. A **[shape 1]** is connected to three **[shape 2]**

The same predicate ‘be connected to’ was present in all sentences. Shape words were either ‘heart(s)’, ‘square(s)’, ‘circle(s)’, or ‘triangle(s)’, and two different shape words were used in each sentence. Importantly, using different numbers in object position allows for the possibility of an *equal* or *different* combination of numerals in the primes and targets. We generated a list of such sentences with Python, inserting shape words randomly.

Each ambiguous sentence was associated with three images: a foil picture (F) inconsistent with the sentence (i.e. makes all readings of the sentence false), one that made the sentence true under its cumulative reading (C) and another that made the sentence true under its distributive reading (D). For non-ambiguous sentences, there were only two images: a foil picture (F) and a picture that makes the sentence true under its unique interpretation (T; but see fn 2).

Fig. 2 presents examples of the different sentences and their corresponding images for each experimental trial (extended version provided in Appendix: Fig. A.1).

Primes trials were formed by an ambiguous sentence (e.g. 4) presented with a foil picture (F) and a picture consistent with the sentence under one of its readings (i.e. ‘correct’ picture). While in cumulative primes (Fig. 2; upper-left) the correct picture only made the cumulative reading of the sentence true (C picture), in distributive primes (Fig. 2; middle-left), the correct image was consistent with the distributive interpretation (D picture). Baseline trials (Fig. 2; lower-left) involved a non-ambiguous sentence (e.g. 5) together with a foil picture (F) and a consistent picture, which corresponds to the unique meaning of the sentence (T picture). Lastly, target trials (Fig. 2; right) presented an ambiguous sentence (as primes, e.g. 4) with two consistent images: one image that matches the cumulative reading (C) and another one that matches the distributive reading (D).

We also include filler trials. They were just like prime trials except that the two pictures involved different visual arrangements (see Fig. 3).

² These sentences may have more than one interpretation due to potential scope ambiguities. Sentence (5) may have an inverse-scope distributive reading equivalent to ‘there are two squares such that for each of them a circle is connected to it’. This reading is also true in the situation depicted by the target image (cf. Fig. 2), and when accessed it could bias participants towards a “distributive” response. If that were the case, these trials would not be acting as baselines. This potential confound is addressed in Experiment 2.

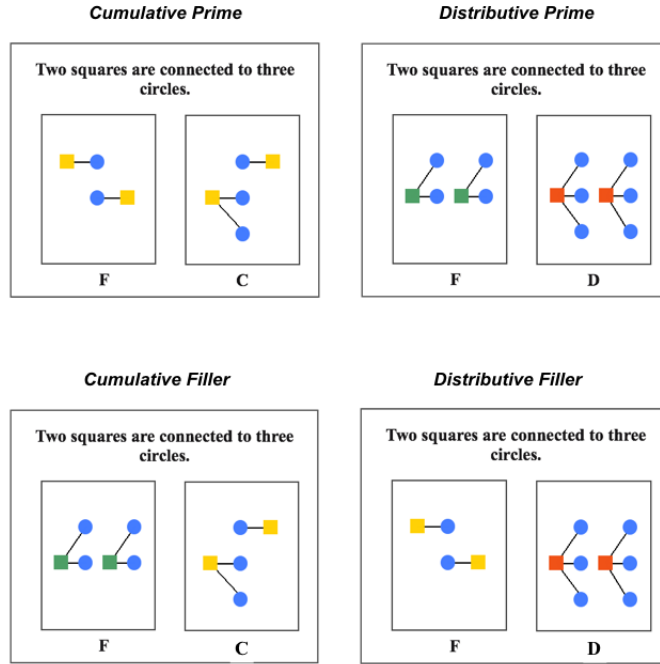


Figure 3: **Fillers and primes in Experiment 1.**

Design

Experimental trials were organized in triplets: each target trial was preceded either by two baselines or by two distributive primes or by two cumulative primes of the same type. Two primes were used instead of one to boost the priming effect and make target trials appear further away from primes associated with a previous target trial.

Each of the trials in a triplet used a different sentence. The two prime/baseline trials always used the same numerals, but with different shapes, word, colors, and different positions on the screen for the correct image. Half of the target trials used the same numerals as their corresponding primes, and the other half used different numerals. In target trials, the position of the image corresponding to the primed reading was either that of the correct image in the first prime or in the second prime.

Target trials therefore appeared in three conditions (cumulative, distributive and baseline), depending on the type of primes in their triplet; four possible number combinations between primes/baselines and targets; and four possible combinations of target image position on the screen.

We crossed these three factors to obtain 48 triplets: 3 (conditions) \times 4 (numeral combinations) \times 4 (image positions). Consequently, the total number of experimental trials was 144. There were a further 48 filler trials randomly inserted between experimental triplets. The total number of trials was 192.

Procedure

Participants were instructed to select the picture that "makes the sentence true". In cases where both pictures could match the sentence, they were instructed to provide their spontaneous preference. At the beginning of the experiment, they were given an example with a baseline sentence (e.g., "A heart is connected to two squares").

The experiment was implemented using the Ibex Farm online platform. All participants saw

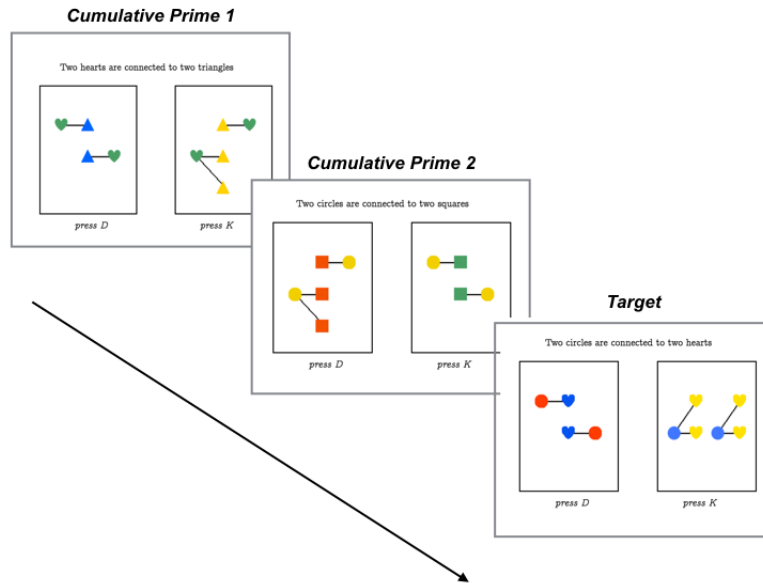


Figure 4: **Example of the procedure (Cumulative triplet)**. Immediately after a response to a given trial, the next trial (sentence and pictures) would appear on the screen, whether within or in between triplets. Experimental triplets were thus not identifiable as such.

the same set of trials. Experimental triplets and individual fillers were administered in random order to each participant. The presentation paradigm is exemplified in Fig. 4.

Results

Data treatment

Accuracy was analyzed for prime and baseline trials. Targets were preceded by two primes or baselines. When participants responded incorrectly to primes, we could not be sure that they had derived the expected interpretation. Thus, targets were discarded as soon as one of the two preceding primes was inaccurate (following the procedure in Raffray and Pickering, 2010). The remaining target responses were coded as 1 when the selected picture corresponded to the distributive interpretation, and as 0 when they matched the cumulative reading. Therefore, the dependent measure in targets was the proportion of distributive choices.

In Experiment 1, the accuracy for baseline trials and both types of primes was higher than 97%. Less than 3% of target responses were removed because of incorrect prime responses. Detailed results for primes, baselines and fillers are provided in the Appendix (Tables A.1, A.3 and A.4).

Analyses procedure

All analyses were carried out in the R programming language and environment (R Core Team, 2014), using the lme4 software package (Bates et al., 2014). The data and analysis script is available online at <http://semanticsarchive.net/Archive/ThhYTBi0/primingplurals.html>. The responses were analyzed by modeling response-type likelihood using logit mixed-effect models (Jaeger, 2008). We included random slopes and intercepts for subjects (within-subject factors,

conditions) and random intercepts for items (between-items factors, conditions), following recommendations from Barr et al. (2013). The p -values were obtained by a χ^2 likelihood ratio test comparing our model with a simpler one in which the relevant predictor was removed. This type of analysis has been previously used to test similar priming effects (Chemla and Bott, 2015; Raffray and Pickering, 2010, among others).

The p -values are reported without correction for multiple comparisons, but the reader can see that Bonferroni corrections will not affect any relevant inference (i.e. when a p -value is lower than the .05 threshold, it is very far from this threshold).

Analyses

Fig. 5a shows the mean percentage of distributive responses, i.e. the proportion of target trials in which the distributive image was selected per condition. Figs. 6a and 6b break this down depending on whether or not the numeral combination was the same in primes and target. Raw means for these conditions are provided in the Appendix (Table A.1).

We fit a model with a *condition* factor (3 levels: distributive, cumulative, baseline), a *numeric combination* factor (2 levels: same and different than primes/baselines) and their interaction as predictors.

Overall, the proportion of distributive choices in target trials varies significantly across the three conditions (cumulative, distributive and baseline). This is shown by comparing a full model and one which drops the condition factor from the predictors: $\chi^2(1) = 14.9, p < .001$ (Result 1).

The proportion of distributive choices in target trials is significantly higher in the distributive condition than in the cumulative condition. The analysis is the same as above but restricted to the cumulative and distributive conditions: $\chi^2(1) = 11.6, p < .001$ (Result 2).

The proportion of distributive choices in target trials is significantly higher in the distributive condition than in the baseline: $\chi^2(1) = 10, p = .0015$ (Result 3).

The proportion of distributive choices in target trials is not significantly lower in the cumulative condition than in the baseline: $\chi^2(1) = 1.19, p = .27$ (Result 4).

The difference between baseline and cumulative conditions is significantly different from the one between baseline and distributive conditions. This is demonstrated by comparing a model which includes two independent predictors, a coefficient for the cumulative condition and another one for the distributive condition, to a model with a single (numerical) predictor whose value is 1 for cumulative and -1 for distributive conditions (and 0 for baselines). The model comparison shows that it is significantly better to include a *different* coefficient for each potential priming condition ($\chi^2(1) = 8.82, p = .012$), which indicates that the effects of distributive and cumulative primes on target trials are best modelled as having different magnitudes (Result 5).

We did not detect an interaction between Condition and Numeric combinations (same or different): $\chi^2(1) = 2, p = .36$ (Result 6)³.

³Posthoc analyses in each subgroup of data suggest however that the overall effect of condition is significant when the triplets share the numeric combination ($\chi^2(1) = 10.42, p = .005$), but only marginally so when primes and targets do not share numeric expressions ($\chi^2(1) = 5.2, p = .07$). Given the lack of interaction (Result 6) and the decrease of statistical power, it is difficult to interpret these results.

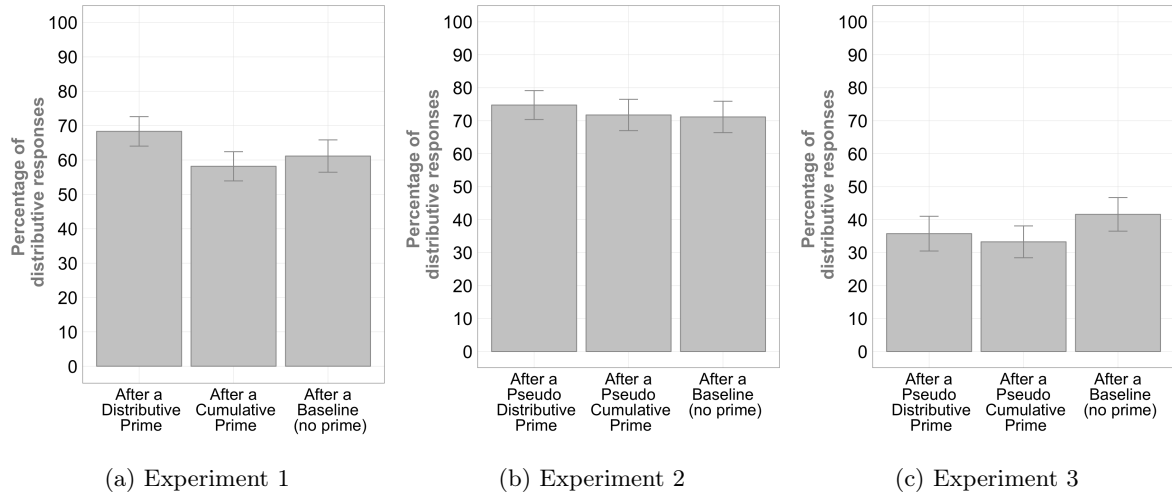


Figure 5: **Target responses.** (a) Mean percentage of distributive responses to targets in Experiment 1 (all numeral combinations); (b) Mean percentage of distributive responses to targets in Experiment 2; (c) Mean percentage of distributive responses to targets in Experiment 3.

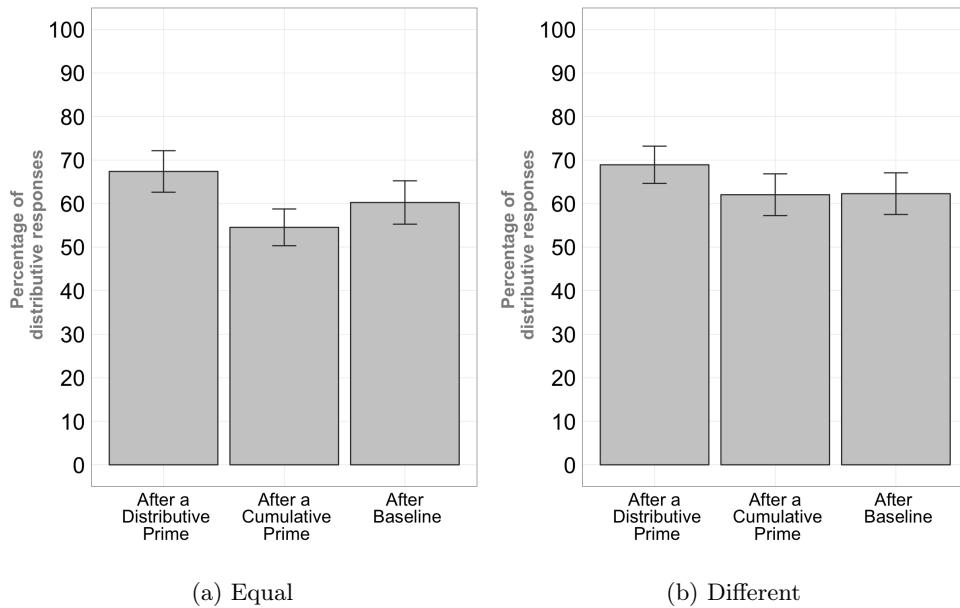


Figure 6: **Target responses per numeral combination (Experiment 1).** (a) Mean percentage of distributive responses when object numeric expressions in primes and targets are the same ('two'-'two' or 'three'-'three'). (b) Mean percentage of distributive responses when the numerals in primes and targets are different ('two'-'three' or 'three'-'two').

Discussion

General summary

First, the high accuracy rate in prime trials indicates that participants can access both cumulative and distributive interpretations. Result 1 establishes that different primes have different effects on participants' responses to target trials, i.e. that some kind of priming effect is operative. More specifically, the rate of distributive interpretations in target trials is higher when the primes are distributive than when they are cumulative (Result 2). It is also higher with distributive trials than in the baseline condition (Result 3). This suggests that abstract semantic properties such as distributivity and cumulativity might be mentally represented (but see alternatives in subsections below). Given the fact that primes and targets were based on different sentences, no priming effect would be expected unless participants were sensitive to some abstract commonalities within each condition. Note that the sentences used different shapes and that we did not find that the presence of a priming effect depended on whether sentences in primes and targets used the same numeric expressions (Result 6).

Result 4 indicates no significant difference between cumulative and baseline conditions: participants' baseline preference is not biased by exposure to a cumulative prime (i.e. cumulative choices do not increase after cumulative primes). This result suggests the possibility of an *asymmetry* between distributive and cumulative conditions, whereby distributive readings would be more primed by distributive primes (relative to the baseline preference) than cumulative readings are primed by cumulative primes.

Result 5 reports an analysis testing whether the difference between cumulative and distributive conditions could be solely due to the directionality of the effect (i.e. going in opposite directions) or whether these effects are also of different magnitudes. The result finds support for a true asymmetry between the effects.

As mentioned in the introduction, this asymmetry is expected if part of the priming effect is specifically driven by the presence of a distributive operator in the LF of sentences. More specifically, the source of the asymmetry might be the following. Schematically, if we refer to the cumulative LF as α , the distributive LF is of the form $\Delta(\alpha)$. A representation such as α might thus prime not only an α target, but also the α portion of a distributive target. On the other hand, a $\Delta(\alpha)$ prime would be expected to give rise to more priming of a $\Delta(\alpha)$ target than a mere α target. Essentially, the distributivity operator Δ may be the locus of the priming effect, and this would thus be active only with distributive primes. However, alternative interpretations of our results are also available and must be considered.

The possible role of *at least* readings

We will start by taking a closer look at the possibility that participants accessed the *at least*-reading of numeric expressions in the object position (readings paraphrasable by, e.g., *Two circles are connected to at least two squares*), and seeing whether taking this possibility into account would alter the interpretation of our results.

As already noted, in most primes, the availability of *at least* readings would have the effect of making both pictures correct for one reading or another of the relevant sentence. This is the case for all primes except cumulative primes based on the 2-3 numeral combination, and baseline associated with sentences of the form *A circle is connected to three squares* (modulo changes in shapes and shape words). The very high accuracy on primes ($\sim 97\%$) suggests that participants always picked an *exact*-reading in prime trials (otherwise the F-picture would have sometimes been chosen). This makes us confident that, in general, the readings accessed were *exactly*-readings, so that our interpretation is not undermined by the potential availability of *at*

least readings.

A detailed description of the trials –displayed in Fig. A.1 (Appendix)– will nonetheless allow us to illustrate the possible role of *at least*-readings in the experiment. On the *at least*-construal, both pictures of distributive primes (D and F) are ‘correct’ choices on some reading of the sentence (the D-picture is correct on both the cumulative and the distributive *at least*-reading, and the F-picture is correct on both readings when the 2-2 numeral combination is used, and only on the cumulative reading when the 2-3 numeral combination is used). The fact that participants behave as if they only accessed the *exact*-reading (they always pick the D-picture) might derive from the participants’ tendency to look for a reason to choose one picture over the other. This would pressure them to select an *exact*-reading, since on an *exact* construal, but not an *at least* construal, only one picture can make the sentence true. Thus, our distributive primes might conceivably favour *exact* distributive readings and if they give rise to a priming effect, we need to assess whether what is primed is really the distributive construal (as we assumed) rather than the *exact* reading. Importantly, priming of the *exact* reading *per se* is not sufficient to explain the increased rate of (exact) distributive choices in targets after (exact) distributive primes. This is because, in target trials, both the D-picture and the C-picture actually make an exact reading true: the D-picture makes the sentence true under the *exact* distributive reading, and the C-picture makes it true under the *exact* cumulative reading. The increased rate of distributive choices (selection of the D-picture) cannot be due to the fact that the *exact* reading of numerals might have been primed. It must specifically be due to a priming of distributive readings. We conclude that the interpretation of our main finding is not undermined by the theoretical availability of *at least* readings: we can view the increased rate of distributive responses after distributive primes (compared to cumulative and baseline conditions) as reflecting a priming of distributive readings.

If the possibility of *at least* readings cannot explain the priming of distributivity that we observed, could it nonetheless explain the asymmetry between distributive and cumulative conditions?

On the *at least* cumulative interpretation, *both* pictures in target trials make the sentence true (even though only the C-picture makes the cumulative reading true under an *exact* construal), while on an *at least* distributive interpretation, only the D-picture makes the sentence true. Therefore, while we can interpret an increase of distributive responses after distributive primes –compared to baseline– as reflecting distributive priming, it is less clear that we should expect an increase of cumulative responses (choices of C-picture) after cumulative primes, since even the choice of the D-picture is compatible with a cumulative construal (under the *at least* reading). This might be sufficient to explain the absence of a significant increase in cumulative responses in the cumulative condition, as compared to baseline (Result 4), and, more importantly, why distributive responses after distributive primes are increased to a greater extent than are cumulative responses after cumulative primes (Result 5). This asymmetry, which we interpreted above as suggesting that the priming effect was specifically tied to the presence of a distributivity operator, might then receive an alternative explanation in terms of *at least* readings. We should note, however, that in cumulative primes based on the ‘two’-object phrase, the *at least* cumulative reading makes both pictures good descriptions of the sentence. The fact that participants virtually always picked the C-picture in such cases means that they always accessed the exact interpretation. This, in our view, makes it less likely that they accessed an *at least*-reading in the subsequent targets. Overall, given that, in all trials where evidence is available, participants seem to have accessed only exact readings, we conclude that the observed asymmetry between distributive and cumulative primes with respect to baselines is unlikely to be due to the availability of *at least* construals; however, such an alternative explanation cannot be entirely ruled out.

Numeral mismatch in sentence-picture pairs

So far, we have examined two possible interpretations of our data, which explain the effect in terms of a particular type of semantic priming. However, our results could also have an alternative explanation that does not involve priming of semantic representations or properties (such as distributivity or *at least* readings), but of specific verification strategies. Indeed, primes and targets in one particular condition share a property which has nothing to do with whether the reading is cumulative or distributive, but rather with the fact that the object numeral appearing in the sentence *matches* (or not) the number of corresponding shapes in the picture.

Distributive primes force a mismatch between the number expressed in the sentence and the one represented in the picture: a sentence such as “Two squares are connected to three circles” will be systematically paired with a picture containing six circles and not three (see Fig. 2). Although participants are indeed forced to access the distributive reading to choose the ‘correct’ picture, they also need to choose between two mismatching sentence-picture pairs. This is not the case for cumulative primes, where there is always a parallel between sentence and picture. Thus, people could be primed to choose (mis)matching pairs in targets because they did so in primes, independently of the underlying semantic representation.

Crucially, such a numeral mismatch effect could also account for the asymmetry between cumulative and distributive primes. Several studies (Patson and Warren, 2010; Patson, 2014, among others) have suggested that numeric expressions are interpreted in a highly specific way, representing the exact quantity of individuals named in the sentence (cf. Introduction). The numeral mismatch in the distributive condition would then require a more complex interpretation of the numeric expression that might not be the one obtained by default. This change (i.e. passing from three to six shapes) could not only require extra cognitive resources but also be specifically primed. The asymmetry between distributive and cumulative effects would be thus the consequence of priming a particular “mismatch” operation.

The results of Experiments 2 and 3, reported below, will appear to be incompatible with such an interpretation.

Baseline rates and inverse-preference effects

One may ask what our results can say about the relative preference for the different readings and how the current findings compare with the current literature in that respect. Indeed, while most baseline rates reported in the literature have shown a dispreference for distributive readings (Brasoveanu and Dotlačil, 2015; Dotlacil, 2010; Frazier et al., 1999; Syrett and Musolino, 2013, among others), the baseline rate in our experiment appears to *favor* distributive interpretations (Fig. 5a and Table A.1). However, our experiment investigated the contrast between distributive and *cumulative* readings, whereas other studies contrast distributive and *collective* interpretations. To illustrate, the sentence “John and Mary wrote two papers” can have a cumulative interpretation, where John and Mary may have written one paper each, a distributive interpretation, where John and Mary wrote two papers each, and also a collective interpretation, where John and Mary wrote the two papers together. While our experiment speaks to the comparison between the first two readings, other studies have been interested in the last two. Moreover, many of these studies differ from ours in the specific methodology, using different tasks (e.g., truth-judgments; Dotlacil, 2010), or different stimuli (e.g., other types of predicates; Brooks and Braine, 1996), and such experimental factors could influence preferences (Degen, 2013). Crucially, then, experimental designs more similar to ours might offer similar results. This is indeed the case of an early study by Gil (1982). The author compared the availability of distributive and cumulative interpretations in Hebrew and Dutch, using stimuli similar to ours, and found that distributive and cumulative interpretations were equally available.

Hence, our results do not seem to conflict with current knowledge about preferences for distributive readings. Furthermore, we would like to suggest that our findings are actually consistent with the view that there may not be such a thing as a natural derivation rate of distributive readings. We found that the rate of distributive readings could be influenced even within a single experiment from one item to the next, through priming effects, and it is therefore not surprising that the observed rate of distributive reading can vary from one experimental setting to another. One may then ask how fluctuations in baseline rates due to general factors might impact the priming effect: e.g., is the priming effect only present in the specific conditions of the experiments we present, and possibly not in others in which distributive readings would be dispreferred?

As stated in the Introduction, psycholinguistic literature has suggested that baseline rates can indeed influence priming, giving rise to an *inverse-preference pattern* such that structural priming is stronger for dispreferred or infrequent structures (cf. English passive and active sentences; review in Ferreira and Bock, 2006; Pickering and Ferreira, 2008). The inverse-preference pattern leads to the expectation that, in a context where distributive readings are dispreferred, distributive priming should be stronger than cumulative priming. This prediction would hold for experimental setups with low distributive baselines. However, an inverse-preference effect will not arise in experimental settings with a high baseline rate of distributive readings. In the absence of such reverse pattern, the asymmetric priming attested in our experiment has to be seen as an effect that arises *despite* the fact that distributive readings are not dispreferred and not *because* of it. Therefore, the current results may constitute evidence that priming of distributivity could be rather robust to experimental variations.

Visual priming

Finally, an explanation in terms of a *visual* priming effect should be considered. It has been shown that a visual stimulus is more easily processed when it is repeated, changing typical preference patterns and recognition times (non-verbal perceptual priming, Tulving and Schacter 1990, among others). The general similarity between pictures that correspond to the same interpretation might by itself be responsible for a priming effect. This similarity would have to operate at quite an abstract level, independently of the number and type of shapes present in prime and target images (i.e. priming should be driven by more abstract visual commonalities between primes and targets). This interpretation would also need to be quite sophisticated to explain why the priming effect we found is asymmetric. But we cannot rule out that visual priming could contribute to some of our findings. Experiments 2 and 3 were therefore designed to rule out this alternative explanation in a conclusive way.

Experiments 2 and 3: Control experiments

Experiments 2 and 3 aimed to test the presence of purely visual priming effects in participants' performance. In both cases we modified the design of Experiment 1 by replacing some or all of the sentences in prime trials (but not target trials) without changing the pictures, and we made sure that participants would still be forced to pick the very same picture as in Experiment 1. Crucially, though, the choice of the correct picture no longer involved a distributive reading, but some other kind of reading (see below for details). In other words, in both experiments we eliminated the possibility of any distributive priming (by taking distributivity out of the picture), but not that of a visual priming effect (by keeping the pictures exactly the same). Examples of the trials are provided in Fig. 7.

Methods

Participants

A different group of 40 participants (Experiment 2: 20 women, 20 men; Experiment 3: 20 women, 20 men) was tested for each experiment. None of the participants in Experiments 2 and 3 had done Experiment 1. Participants that were not English native speakers were excluded from the analysis (five participants in Experiment 2 and six participants in Experiment 3). A further two participants were excluded from Experiment 2 because their mean response times were below 1 second.

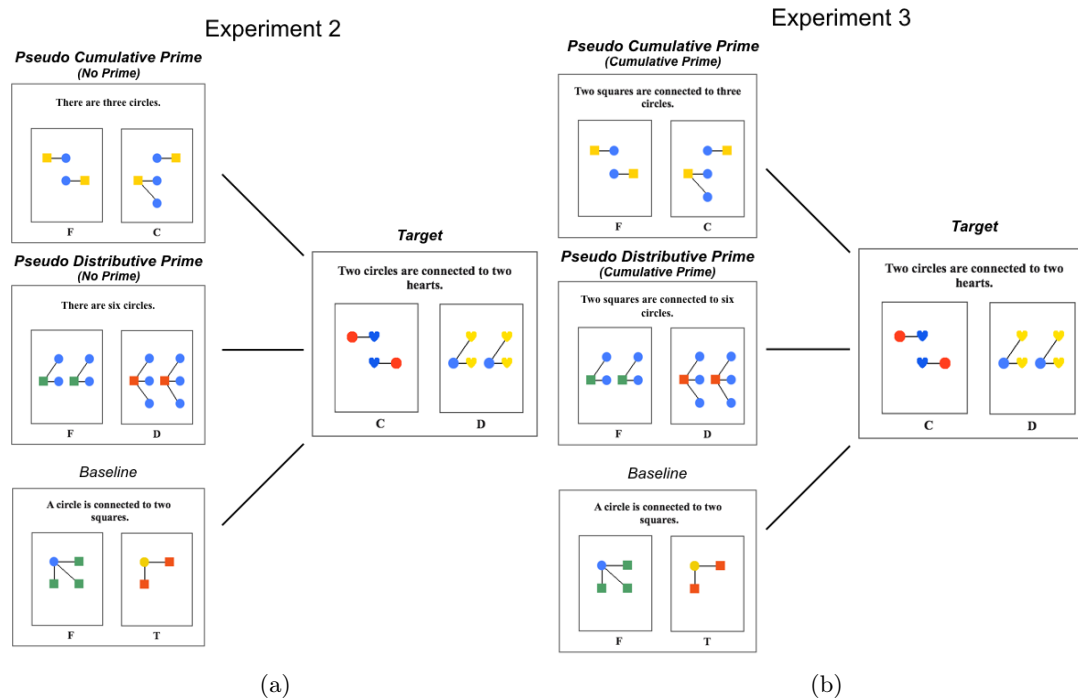


Figure 7: **Illustration of trials in Experiments 2 and 3.** (a) Prime sentences in Experiment 1 (cf. Fig. 2) were replaced by unambiguous sentences in Experiment 2. In *pseudo distributive primes*, what was the distributive picture (D) in Experiment 1 is still the only correct picture, but no longer instantiated a distributive reading (\sim *pseudo cumulative primes*). Targets and baselines were the same as in Experiment 1.; (b) Only distributive primes of Experiment 1 were replaced. Sentences in *pseudo distributive primes* were ambiguous between a cumulative and a distributive reading, but were such that the distributive picture (D) of Experiment 1, while still the correct one, now corresponded to the *cumulative* reading of the sentence. *Pseudo cumulative primes* were similar to cumulative primes in Experiment 1 (same for targets and baselines).

Materials

In Experiment 2, we replaced ambiguous sentences in primes (i.e. former cumulative and distributive primes) with unambiguous sentences, keeping the same images. In each resulting trial, the sentence was true with respect to one image and not the other and, importantly, we made sure that the ‘correct’ image was always the same as in the corresponding trial of Experiment 1. In other words, participants were led to choose the same picture as in Experiment 1, but for a different reason (see Fig. 7a and example sentences in 6).

- (6) Experiment 2
 - a. Pseudo cumulative prime: There are two/three **[shape2]**
 - b. Pseudo distributive prime: There are four/six **[shape2]**

We will call the resulting trials *pseudo distributive* and *pseudo cumulative* primes, depending on the ‘correct’ picture in the trial.

In Experiment 2, we do not expect any priming effect, since the sentences are unambiguous and the relevant trials do not instantiate cumulative or distributive readings. What we now call a pseudo distributive prime (respectively pseudo cumulative prime) is a trial (in a triplet) obtained from a distributive (respectively cumulative) prime from Experiment 1 in the way just described. Baselines and targets were identical to the ones in Experiment 1 (see Fig. 7a). The use of the same non-ambiguous sentences across experiments served to validate the baselines in Experiment 1 (cf. Footnote 2): in Experiment 2, responses in all target trials can now all serve as baselines, whatever the condition is.

In Experiment 3, only the sentences of the distributive primes of Experiment 1 were changed, giving rise to *pseudo distributive primes*. The new sentences were also ambiguous between a cumulative and a distributive reading, but now only the *cumulative* reading corresponded to one of the two images, and furthermore, this ‘correct’ image was the same as in the corresponding *distributive* prime in Experiment 1. In other words, the pictures that instantiated the distributive reading of the associated sentence in Experiment 1 primes now instantiates the cumulative reading of another sentence, generating only cumulative primes (see Fig. 7b and example sentences in 7).

- (7) Experiment 3
 - a. Pseudo cumulative prime: Two **[shape1]** are connected to two/three **[shape2]**
 - b. Pseudo distributive prime: Two **[shape1]** are connected to four/six **[shape2]**

Although Experiment 3 has *only* cumulative primes, for the ease of comprehension we will distinguish ‘pseudo distributive’ primes from ‘cumulative’ primes: a pseudo distributive prime in Experiment 3 is a trial that was obtained from a distributive prime of Experiment 1 in the way just described, and a pseudo cumulative prime of Experiment 3 is a trial that is identical to a cumulative prime of Experiment 1.

Design and procedure

The design for Experiments 2 and 3 was similar to that of Experiment 1. There were the same number of conditions (cumulative, distributive and baseline) and therefore items. The stimuli were obtained by minimally modifying the material from Experiment 1 as described above.

As in Experiment 1, a single list of trials was used for each experiment, following the procedure exemplified in Fig. 4. This list was then administered to each participant in a random order using Ibx Farm.

Results

Responses were analyzed as in Experiment 1. The accuracy in (pseudo) primes was above 93% for both Experiments 2 ($M=94.9$) and 3 ($M=93.4$). Complete data for all the trials can be found in Tables A.3 and A.4 (Appendix). As in Experiment 1, the dependent variable was the response given in target trials (choice between the distributive and cumulative pictures). Figures 7a and 7b show the rate of distributive responses in targets for each condition in both Experiment 2 and Experiment 3.

The overall analysis revealed no significant difference between conditions (3 levels: distributive, cumulative and baseline) in Experiment 2 ($\chi^2(1) = 1.21, p = .54$). However, a main effect of Condition was found in Experiment 3 ($\chi^2(1) = 9.43, p = .0089$). Further analyses revealed that this effect is driven by the baseline, which has a significantly higher proportion of distributive choices than both cumulative and distributive conditions ($\chi^2(1) = 7.80, p = .005$, and $\chi^2(1) = 5.65, p = .017$). No statistical difference in the proportion of distributive choices was found between cumulative and distributive conditions ($\chi^2(1) < 1, p = .69$).

These results suggest that the priming effect found in Experiment 1 is not driven solely by visual priming, or else the results would not have been altered in these new control experiments (especially Experiment 2). A more direct test of the hypothesis is obtained by directly comparing the control experiments to the original experiment. A significant interaction is obtained between Experiment and Condition, both when comparing Experiments 1 and 2 ($\chi^2(1) = 6.66, p = .035$) and when comparing Experiments 1 and 3 ($\chi^2(1) = 19.8, p < .001$).

Discussion

As expected, the pattern of results found in Experiment 1 was not reproduced in Experiments 2 and 3. Crucially, the difference between cumulative and distributive conditions was significantly reduced. The specific effect of Condition found in Experiment 1 was altered in both Experiments 2 and 3, which shows that the priming in Experiment 1 was not a purely visual effect –the effect disappears when priming sentences are changed, while keeping everything else constant, including the ‘correct’ pictures in the (pseudo) primes.

It is important to note that in Experiment 2, all conditions give rise to a similar quantity of distributive responses, showing that our baseline items in Experiment 1 (which were not changed in Experiment 2) were appropriate. Such results not only alleviate the potential problem noted in Footnote 2 (i.e. potential ambiguity of baseline sentences is not at play), but also support the idea that asymmetric results in Experiment 1 cannot be explained in terms of an inverse-preference effect. An inverse-preference pattern would explain the results of Experiment 1 if distributive readings were dispreferred in *complete* absence of priming. Since in Experiment 2 participants prefer distributive readings across the board (as in baselines of Experiment 1), an interpretation in these terms proves not to be on the right track.

Strikingly, in Experiment 3, the overall rate of distributive responses is much lower than in Experiment 2. In fact, *posthoc* analyses reveal a main effect of Experiment between Exp 2 and Exp 3 ($\chi^2(1) = 23.0, p < .001$): the repeated use of trials that force a cumulative reading in Experiment 3 results in a general increase of cumulative responses in targets, compared with Experiment 2. On top of this *global* bias –which can be seen as adaptation, learning or even long-lasting priming (Fine et al., 2013; Kuperberg and Jaeger, 2016; Pickering and Ferreira, 2008)–, Experiment 3 also displays a *trial-to-trial* cumulative priming. Indeed, the rate of distributive responses was lower in the cumulative and (fake) distributive conditions than in baselines, which means that primes that force a cumulative reading (which in Experiment 3 are all the primes) yield an increase of cumulative choices in targets.

These results allow us to rule out the alternative interpretation based on a numeral mismatching effect. Unlike Experiment 1, Experiments 2 and 3 always present “matching” (pseudo) primes: the number of shapes in the pictures matches the number appearing in the sentence in all prime trials (cf. Fig. 7). If the match/mismatch interpretation is correct, we would then expect a strong preference for matching responses across the board in these experiments, that is a preference for cumulative responses. However, the rate of cumulative responses does not increase from Exp 1 to Exp 2 (in fact it non-significantly decreases: $\chi^2(1) = 3.35, p = .067$). It does increase in Exp 3, but this is arguably because then all primes are genuine cumulative

primes (not only matching primes).

The fact that cumulative readings influence preference patterns in targets (cf. Experiment 3) appears to conflict with our suggestion that the priming effect detected in Experiment 1 was asymmetric, i.e. that distributive priming is stronger than cumulative priming, if there were cumulative priming at all. There is, however, no real contradiction. If we assume that distributive priming is, all else being equal, stronger than cumulative priming (specifically in the case of *trial-to-trial* priming effects, i.e. effects of a trial on the next trial), but that cumulative priming nevertheless exists, we expect an overall increase of cumulative responses when we replace all (pseudo) primes with cumulative primes (Experiment 3 vs. Experiment 2). In Experiment 3, the fact that we observe a significant difference between targets after primes (pseudo distributive and pseudo cumulative) and after baselines is not unexpected given that there were in total many more cumulative trials in Experiment 3 than in Experiment 1, and no genuine distributive primes getting in the way.

Our results are therefore consistent with the view that a) there is an asymmetry of strength in *trial-to-trial* priming between cumulative and distributive primes (i.e. distributive primes have a stronger influence than cumulative primes on the targets that immediately follow them), and b) the presence of cumulative primes throughout an experiment affects the *global* rate of cumulative responses. Overall, the results of Experiments 2 and 3 are therefore not inconsistent with the conclusion from Experiment 1 that distributive priming is stronger than local cumulative priming. Note that Experiment 1 is the only one with a direct bearing on the existence of such an asymmetry.

General Discussion

Experiment 1 provided evidence that the cumulative vs. distributive ambiguity can give rise to a priming effect. Experiments 2 and 3 strengthened this interpretation by ruling out the possibility that our results in Experiment 1 were entirely driven by visual priming. Furthermore, these control experiments also allowed us to exclude an alternative interpretation in terms of a numeral matching priming, since such effect would not explain the difference in target responses between Experiments 2 and 3.

In Experiment 1, we also detected an asymmetry between cumulative and distributive primes: while distributive primes give rise to an increase of distributive responses in targets compared to baseline trials, this does not occur (at least not to the same extent) with cumulative primes. Although this might resemble the inverse-preference effects documented in the literature, our results do not allow us to conclude that specific preference patterns are at the origin of the asymmetry (i.e. distributive interpretations are actually *preferred* in baseline targets). Instead, this asymmetry suggests that distributive readings involve a different derivation from cumulative interpretations. This difference might be well explained by the presence of a distributivity operator in the relevant cases, which would be responsible for the priming effect we uncovered. However, distributive interpretations may also require a particular interpretation of numeric expressions or specific attentional resources, not shared by cumulative readings. Any of these might well be at the origin of the asymmetric effect.

Nonetheless, the (partly *posthoc*) comparison of our two control experiments suggests that the repeated exposure to cumulative primes in Experiment 3 –together with an absence of distributive priming– led to a cumulative priming effect. These two findings (the asymmetry between distributive and cumulative priming in Experiment 1, and the evidence that cumulative priming took place in Experiment 3) are compatible with the view that while priming effects specifically linked to distributivity might be stronger, both readings can give rise to detectable priming effects.

To conclude, the fact that the cumulative vs. distributive ambiguity can give rise to priming effects across different sentences suggests that this distinction is at play during parsing. One possible interpretation for the asymmetry detected in Experiment 1 is that part of the priming effect we detected is specifically due to the distributivity operator or whatever mechanism is responsible for distributive readings.

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Appendix

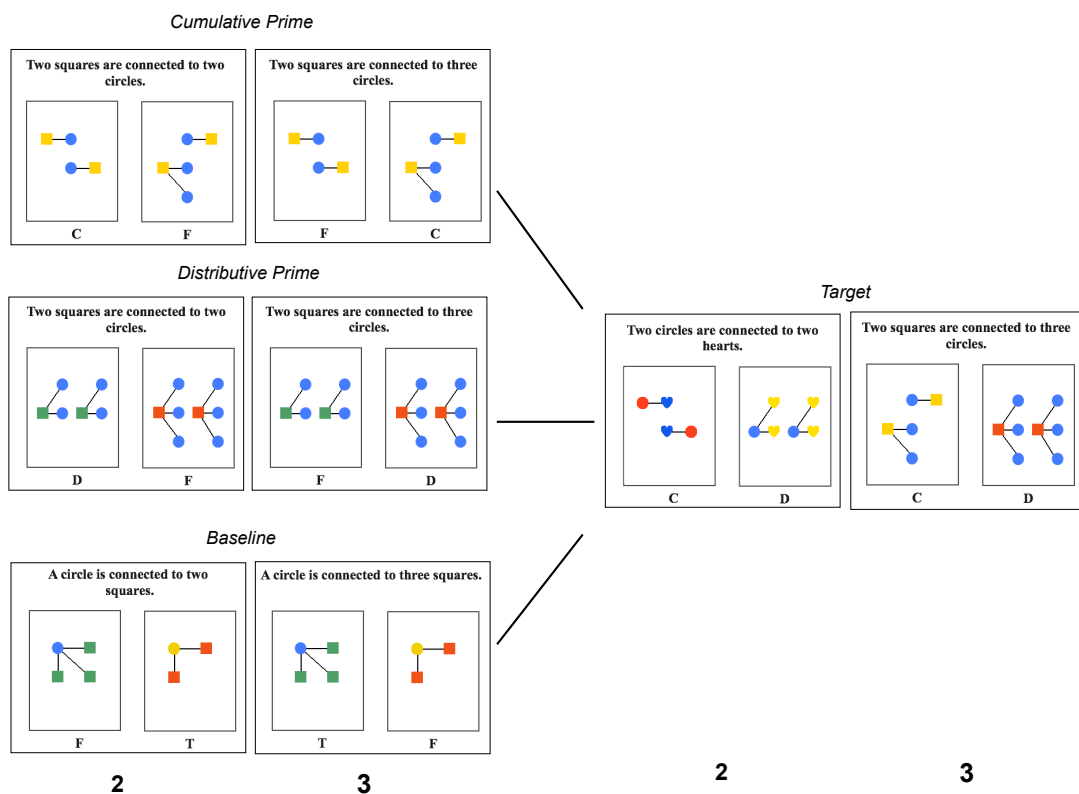


Figure A.1: Detailed description of trials in Experiment 1

Table A.1: Raw means for target trials in Experiment 1, 2 and 3.

	Condition	Mean Distributive Choices	SE
Experiment 1	Baseline	61.15	4.71
	Cumulative	58.17	4.25
	Distributive	68.33	4.29
Experiment 2	Baseline	71.15	4.76
	Cumulative	71.74	4.75
	Distributive	74.75	4.38
Experiment 3	Baseline	41.59	5.10
	Cumulative	33.27	4.83
	Distributive	35.75	5.27

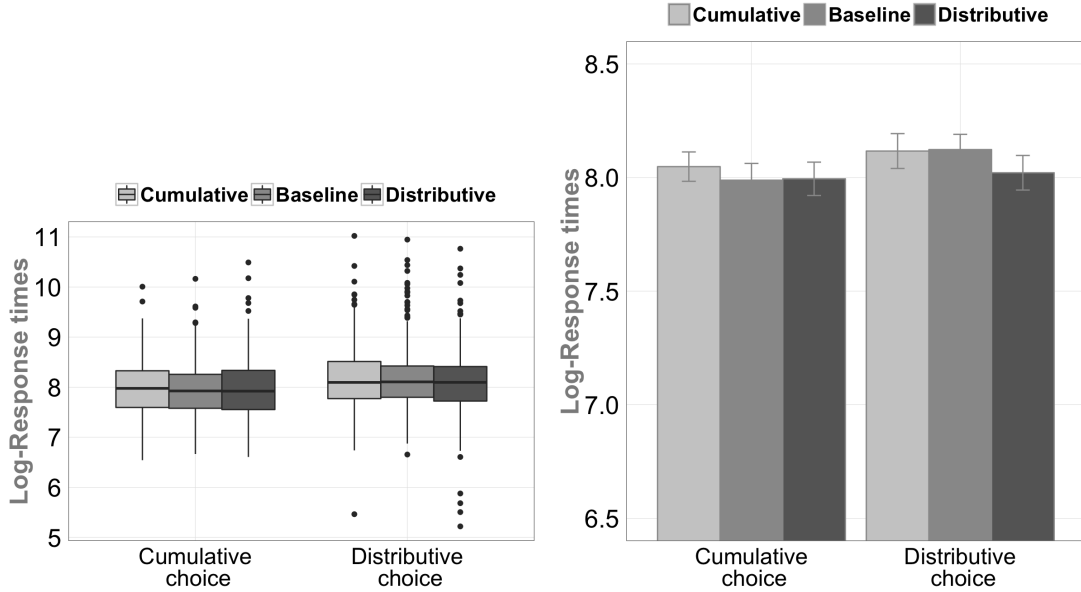


Figure A.2: Response Times (log-transformed) in target trials (Experiment 1). The color code indicates the condition (cumulative, baseline and distributive). Data is factored according to the type of response in targets, distinguishing between distributive and cumulative choices.

Table A.2: Response times for target trials in Experiment 1, 2 and 3.

	Condition	Mean RTs (ms.)	SE
Experiment 1	Cumulative	3922.5	196.8
	Baseline	3897.8	211.7
	Distributive	3882.6	187.8
Experiment 2	Cumulative	3648.0	252.0
	Baseline	3595.7	226.8
	Distributive	3557.6	386.5
Experiment 3	Cumulative	3469.9	330.6
	Baseline	3775.3	459.4
	Distributive	2970.7	211.5

Table A.3: Raw means for prime trials in Experiment 1, 2 and 3.

	Condition	Mean Accuracy (%)	SE
Experiment 1	Baseline	97.51	0.62
	Cumulative	97.32	0.57
	Distributive	97.19	0.53
Experiment 2	Baseline	94.35	1.91
	Cumulative	95.67	1.16
	Distributive	94.86	1.35
Experiment 3	Baseline	94.03	1.39
	Cumulative	93.47	1.59
	Distributive	92.65	1.80

Table A.4: Raw means for filler trials in Experiment 1, 2 and 3.

	Condition	Mean Accuracy (%)	SE
Experiment 1	Cumulative	96.01	0.90
	Distributive	95.66	0.82
Experiment 2	Cumulative	89.20	2.49
	Distributive	90.73	1.97
Experiment 3	Cumulative	92.58	1.92
	Distributive	91.91	2.42