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Hierarchical structure priming from mathematics to two- and three-site relative clause attachment

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ABSTRACT

A number of recent studies found evidence for shared structural representations across different cognitive domains such as mathematics, music, and language. For instance, Scheepers et al. (2011) showed that English speakers' choices of relative clause (RC) attachments in partial sentences like *The tourist guide mentioned the bells of the church that …* can be influenced by the structure of previously solved prime equations such as *80–(9 + 1) × 5* (making *high* RC-attachments more likely) versus *80–9 + 1 × 5* (making *low* RC-attachments more likely). Using the same sentence completion task, Experiment 1 of the present paper fully replicated this cross-domain structural priming effect in Russian, a morphologically rich language. More interestingly, Experiment 2 extended this finding to more complex *three-site* attachment configurations and showed that, relative to a structurally neutral baseline prime condition, N1-, N2-, and N3-attachments of RCs in Russian were equally susceptible to structural priming from mathematical equations such as *18+(7+(3 + 11)) × 2*, *18 + 7+(3 + 11) × 2*, and *18 + 7 + 3 + 11 × 2*, respectively. The latter suggests that cross-domain structural priming from mathematics to language must rely on detailed, domain-general representations of hierarchical structure.

1. Introduction

Every language provides its speakers with a flexible inventory of generative syntactic rules, often allowing them to express the same meaning in different ways. Psycholinguistic theories aim at understanding universal and language-specific principles of syntactic knowledge, including the speaker's ability to select among available structural configurations. Considering that it is impossible to store all such configurations in long-term memory, many theories assume the existence of an abstract incremental production system that allows construction of specific sentences by accessing more abstract and generalized representations stored in memory. Importantly, recent studies suggest that these generalized representations may not only underlie linguistic structural knowledge but also support structural knowledge pertaining to other domains, such as music and mathematics (see Myachykov, Chapman, & Fischer, 2017, for a review).

Of particular interest to the present research are studies that used a structural priming methodology (see Branigan & Pickering, 2017, for a recent review) to provide behavioral evidence for shared structural representations between language and other cognitive domains (e.g. Scheepers et al., 2011, Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016). In Scheepers et al. (2011), for example, participants solved mathematical prime equations with different parenthetical groupings (e.g., *80–(9 + 1) × 5* vs. *80–9 + 1 × 5*) before performing a sentence completion task in subsequent target trials with sentence fragments of the form *The tourist guide mentioned the bells of the church that …*. Crucially, the target sentence fragments ended in a relative pronoun (e.g., *that*) which could syntactically attach either *high* to the entire complex object noun phrase (*the bells of the church*) or *low* to the most recent NP within the object noun phrase (*the church*). It was found that, relative to a syntactically neutral baseline prime condition, high-attachment target completions were more likely after equations of the form *80–(9 + 1) × 5* (where the final multiplication operator applies to a complex term on its left) whereas low-attachment target completions were (at least numerically) more likely after solving prime equations of the form *80–9 + 1 × 5* (where the final multiplication operator applies to the most recent number on its left). Indeed, this cross-domain structural priming effect was the first behavioural demonstration of

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shared abstract hierarchical structure representations between mathematics and language, aspects of which have since been replicated in other domains, tasks, languages, and types of constructions (e.g., Sammler, Novembre, Koelsch, & Keller, 2013; Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016; Van de Cavey, Severens, & Hartsuiker, 2017; Pozniak, Hemforth, & Scheepers, 2018; Zeng, Mao, & Liu, 2018).

The attachment of relative clause (RC) modifiers, as investigated in the target trials of Scheepers et al. (2011), is a particularly useful testbed for studying cross-domain structural priming because it represents an example of a recursively generated hierarchical structure ambiguity where at least two distinct interpretations of the same sentence are simultaneously available (see also, e.g., Cuetos & Mitchell, 1988; De Vincenzi & Job, 1995; Hemforth et al., 2015; Desmet & Declercq, 2006; Scheepers, 2003). Due to the recursive nature of modifiers in linguistic expressions (a feature that is indeed analogous to the recursive expansion of operations in a mathematical expression), it is possible to investigate RC-attachment priming in even more complex hierarchical structure assemblies.

To date, research on cross-domain structural priming has exclusively focused on two-site attachment configurations as in (1a) below, where the critical relative pronoun (and subsequent RC) is preceded by two potential host-NP sites for attachment. A major aim of the present paper is to move beyond this restriction and investigate structural priming from mathematical expressions to linguistic configurations where an attachment-ambiguous RC is preceded by *three* potential host-NPs for attachment, as in (1b).

(1) a. *I met* [$_{\text{NP1}}$ *the daughter of* [$_{\text{NP2}}$ *a colleague*]] *who…*
b. *I met* [$_{\text{NP1}}$ *the daughter of* [$_{\text{NP2}}$ *a colleague of* [$_{\text{NP3}}$ *a friend*]]] *who…*

Structures like (1b) have indeed received much attention in the psycholinguistic literature on sentence comprehension (e.g., Gibson, Pearlmutter, Canseco-González, & Hickok, 1996; Gibson, Schütze, & Salomon, 1996; Hemforth, Konieczny, & Scheepers, 2000); perhaps the most generalizable finding is that N2-attachment of an RC (e.g., to [$_{\text{NP2}}$ *a colleague of a friend*] in 1b) is the least accessible option available to readers/listeners in various languages. In the present context of cross-domain structural priming, the main motivation behind moving from *two-* to *three*-site attachment configurations is not so much to learn more about general attachment preferences for RCs, but to gain more insights into the amount of structural detail that is being maintained between mathematical prime expressions on the one hand and linguistic target expressions on the other.

Indeed, it is conceivable that what is being primed in studies such as Scheepers et al. (2011) is the applicability of a general *locality* principle (e.g., Gibson, 1998; see also general discussion in Desmet & Declercq, 2006) whereby the final RC in a sentence such as (1a,b) would be preferentially attached to the most recent attachment host-NP on its left. After encountering high-attachment prime equations of the form $80–(9 + 1) \times 5$, participants in the Scheepers et al. (2011) study might have been more likely to give *non-local* RC-attachments more consideration in the target trials (thus leading to more high-attachment sentence completions) because this type of equation enforces non-local integration of the final multiplication element into the overall structure. Under such an account, high-attachment equations not so much encourage high RC-attachments in the linguistic target trials, but rather *discourage low RC-attachments*. Two additional observations in Scheepers et al. (2011) may be taken as further support for such a view: The first is that low RC-attachments were generally preferred (as is typical for English) and the second that, relative to a syntactically neutral baseline-prime condition, high-attachment prime equations (e.g., $80–(9 + 1) \times 5$) were notably more effective than low-attachment prime equations (e.g., $80–9 + 1 \times 5$) in eliciting changes to the proportions of low RC-attachments in the target trials. The authors interpreted the latter as a potential 'inverse preference' effect, which has previously also been found for priming of other kinds of structural alternations such as PO/DO dative constructions or active/passive sentences (cf. Pickering & Ferreira, 2008). However, it could equally plausibly indicate a *non-locality priming* effect that is specific to recursively generated (RC-) modifier-attachment configurations.

An important implication of the *non-locality priming* hypothesis is that participants may actually not retain much structural detail from the prime equations when making RC-attachment decisions in the linguistic target trials. Specifically, they might only (implicitly) pay attention to whether the final element – i.e., the multiplication/division operator in the equations and the relative pronoun in the linguistic materials, respectively – should combine with "something simple" on its left or not (i.e., a plain number or a simple NP, respectively). Under this view, any mathematical prime that would discourage simple local integration would be expected to lead to a reduction in the likelihood of low RC-attachments in the linguistic target trials, but importantly, without necessarily being predictive of *the specific kind* of non-local RC-attachment in the target when considering three-site attachment configurations like (1b). Moving from two- to three-site attachment configurations in the linguistic target trials would therefore be informative as to how much structural information is carried over from mathematical primes to linguistic target expressions in cross-domain structural priming.

To make this more concrete, consider mathematical equations of the form (e.g.) $A + (B + (C + D)) \times E$ versus $A + B + (C + D) \times E$ as primes for linguistic targets like (1b), repeated here as (2).

(2) *I met the daughter of a colleague of a friend who…*

Both types of equations require non-local integration of the final multiplication operation and are therefore expected to prime non-local RC-attachments in (2). Importantly, however, predictions from the *non-locality priming* hypothesis would hardly be more specific than that: Even though $A + (B + (C + D)) \times E$ is in fact structurally more similar to N1-attachment of the RC (*I met* [[*the daughter of* [*a colleague of a friend*]] *who…*]), and $A + B + (C + D) \times E$ more similar to N2-attachment of the RC (*I met the daughter of* [[*a colleague of a friend*] *who…*]), the *non-locality priming* hypothesis would not discriminate further between the two types of 'locality-discouraging' equations. In other words, both types of equations should prime N1- and N2-attachments in (2) about equally strongly when compared to prime equations like $A + B + C + D \times E$, which are likely to support the default low- (N3-) attachment option for the RC in (2) (*I met the daughter of a colleague of* [*a friend who…*]).

Contrasting with this view (see also general discussions in Scheepers, 2003; Scheepers et al., 2011), there is also the possibility that participants actually retain quite detailed hierarchical structure representations of the mathematical primes, leading to more detailed predictions in terms of N1-, N2-, and N3-attachment priming for targets like (2): Relative to a structurally neutral baseline, equations like $A + (B + (C + D)) \times E$ should prime N1-attachments *specifically*; equations like $A + B + (C + D) \times E$ are expected to specifically prime N2-attachments and equations like $A + B + C + D \times E$ should specifically prime N3-attachments, respectively. Adjudicating between these diverging predictions is the primary aim of the research presented in this paper.

In the following, we report two experiments in Russian which used the same experimental paradigm as in Scheepers et al. (2011). Experiment 1 of the present paper is in fact a close replication of the original Scheepers et al. (2011) study, demonstrating that cross-domain structural priming from mathematical expressions to (two-site) RC-attachments in linguistic expressions works for Russian – a language with strong case, gender, and number morphology – in exactly the same way as it does for English. Experiment 2 will then move on to investigate the theoretically more interesting case of structural priming from mathematical expressions to three-site RC-attachments in Russian. Here the rich morphology of the Russian language can be fully exploited to identify N1-, N2-, or N3-attachments of relative clauses in the target trials – something that could not be done as easily in English where such cues are largely missing or remain ambiguous. As previously discussed, the main question of Experiment 2 concerns the amount of structural detail carried over from mathematical equations to linguistic target expressions in the context of cross-domain structural priming.

2. Experiment 1

2.1. Participants

Thirty-six native Russian speakers (18 male, 18 female, mean age = 19.9 years, SD = 1.87 years) participated in the experiment with no monetary compensation. They were all psychology undergraduates at the Higher School of Economics (HSE) in Moscow. The sample size of N = 36 replicates the size per participant sub-sample in Scheepers et al. (2011, Experiment 1), two of which (Business and Maths) showed reliable cross-domain priming effects. In order to ensure that participants correctly solved the mathematical equations, they were given a brief informal reminder of the arithmetic operator-precedence rules before the start of the experiment.

2.2. Materials

Closely mirroring the design in Scheepers et al. (2011), there were 24 sets of items. Each had a target sentence fragment paired with one of three types of priming equations – EQ1 (where a final multiplication or division operator was preceded by an addition or subtraction term in parentheses), EQ2 (same as EQ1, but with parentheses omitted), and BL (neutral baseline without hierarchical grouping of terms). See Table 1 for an example and Appendix A-A for the full set of experimental items. All priming equations were designed to be solvable without a calculator.

Each of the 24 target sentence fragments consisted of a subject NP, a verb, a complex object NP, and a relative pronoun at the end (e.g., the Russian equivalent of *The European Commission has estimated the debt of the organizations that…*), therefore encouraging sentence completion with a relative clause that could either be attached high to the entire complex object NP (*the debt of the organizations*) or low to the most recent NP within the object NP (*the organizations*). For convenience, these attachment alternatives will henceforth be labelled N1- and N2-attachment, respectively.

2.3. Procedure

Using a Latin-square counterbalancing scheme, we composed three master files. Each file contained eight prime-target pairs per condition in a random order, with different item-condition allocations across files. Each master file was seen by 12 participants. In addition, there were 50 structurally unrelated fillers (25 sentence fragments and 25 equations). Four fillers were placed as warming-up trials at the beginning, and each prime-target pair per file was always preceded by at least two fillers. The mathematical and linguistic fillers were randomly inserted such that no regular sequence of equations vs. sentence fragments was detectable. The materials per file were printed on 5 A4 sheets of paper, with an additional instruction cover sheet at the beginning.

Participants were instructed to solve the equations and complete the sentences in the presented order, and at a reasonable pace. Participants did not receive any specific mention regarding the bracketing or the hierarchical nature of the equations. However, they were briefly reminded of the operator precedence rules (multiplication or division before addition or subtraction). In terms of sentence completions, participants were asked to rely on whatever came to their minds first. None of the participants correctly guessed the purpose of the experiment or noted any systematic pairing of trials during post-experimental debriefing. Each individual session lasted approximately 40 min.

Table 1
Example stimuli used in Experiment 1.

BL prime	36 + 6
EQ1 prime	36 − (3 + 2) × 2
EQ2 prime	36 − 3 + 2 × 2
Target	Еврокомиссия подсчитала долги организаций, которые… *The European Commission has estimated the debt of the organizations that…*

2.4. Response annotation

Response coding largely relied on plausibility criteria (e.g., … *the debt of the organizations that had increased dramatically* was coded as N1-attachment; … *the debt of the organizations that had connections to the Mafia* as N2-attachment). To ensure objectivity of response codes, two native Russian speakers (both blind to experimental condition) independently coded the completed sentences from all critical target trials. The annotators provided mismatching codes in only six out of 864 instances, meaning 99.3% inter-annotator agreement in total. Four of the disagreements were due to mistyped codes, leaving only two instances where attachment of the target-RC remained uncertain. The latter instances were removed from data analysis.

2.5. Data analysis

Inferential analyses were based on Generalised Linear Mixed Models (GLMMs) using the `lme4` package (Bates, Maechler, Bolker, & Walker, 2015) in R (R Core Team, 2018). Since the dependent variable was dichotomous (occurrences of N1-attachments out of all available responses), a binary logistic model was specified in the family argument of the `glmer()` function. The fixed effect predictor Prime Type (three levels) was entered into the model in mean-centred form using deviation coding. The BL prime condition served as a comparison baseline, and there were two contrast variables indexing, respectively, the effect of the EQ1 prime condition and the effect of the EQ2 prime condition relative to that baseline. The model comprised the maximal (by-subjects [N = 36] and by-items [N = 24]) random effects structure justified by the design (Barr et al., 2013), including random correlations. The omnibus effect of Prime Type was tested via Likelihood Ratio Chi-Square model comparisons.

2.6. Results and discussion

As indicated in the response annotation section, target responses were easily identifiable as either N1- or N2-attachment. Mathematical accuracy was high (94.6% on average), ranging from 92.4% (EQ2 primes) to 98.3% (BL primes) across conditions. Trials with incorrectly solved mathematical prime equations were removed from subsequent analyses.

Table 2 shows the distribution of N1- and N2-attachment responses by levels of correctly solved Prime Type. Totals are provided in the bottom row of the table. There was a general low (N2-) attachment preference comparable to English, which is reflected in the marginal totals (bottom row) and in the percentages for the BL prime condition. However, in the non-BL conditions, response proportions notably deviated from the general pattern, showing a less pronounced N2-attachment bias after EQ1 primes and a more pronounced N2-attachment bias after EQ2 primes. Indeed, the analysis confirmed a reliable main effect of Prime Type on occurrences of N1-attachments: ${}_{LR}\chi^2 = 10.615$; $df = 2$; $p < .005$.

Table 3 shows the relevant fixed effect parameter estimates (log odds for occurrences of N1-attachments), and Fig. 1 plots corresponding

Table 2
Distribution of responses per prime condition in Experiment 1. Shown are percentages of N1 and N2 target attachments (absolute cell counts in brackets) for trials with correctly solved prime equations.

	Target Attachment	
Prime Type	N1	N2
BL	36.4 (103)	63.6 (180)
EQ1	47.0 (126)	53.0 (142)
EQ2	29.7 (79)	70.3 (187)
Total	37.7 (308)	62.3 (509)

Table 3
Binary logistic GLMM parameter estimates and SEs (in log odds units) for occurrences of N1-attachments in Experiment 1. All figures are rounded to the third decimal. The BL Prime condition served as a baseline (intercept), and the remaining two fixed effect parameters (EQ1 and EQ2) index contrasts between that baseline and either of the other two prime conditions.

	Estimate	*SE*	*Z*	*P*
Int. (BL)	−0.642	0.218	−2.948	0.003
EQ1	0.586	0.222	2.637	0.008
EQ2	−0.309	0.225	−1.371	0.170

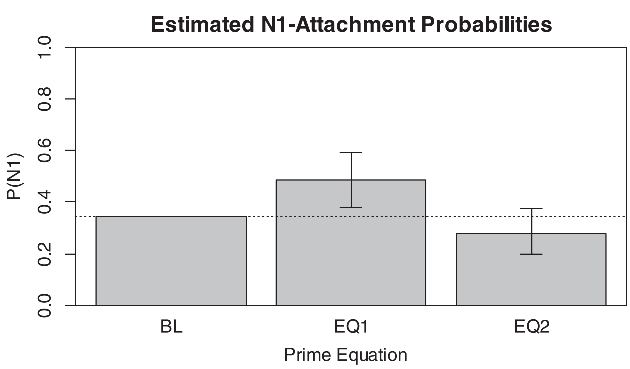

Fig. 1. Probabilities of N1-attachments in the target trials of Experiment 1, as estimated via binary logistic GLMM analyses (see text). Figures are broken down by levels of Prime Type (BL, EQ1, and EQ2). Error bars represent 95% CIs for contrasts with the BL prime condition; the latter is indexed by a horizontal dashed line.

model-estimated probabilities. The significantly negative intercept term in Table 3 confirms a reliable low (N2-)attachment preference in the BL prime condition. Further, it becomes evident that, relative to the baseline, occurrences of N1-attachments reliably increased after EQ1 primes, but only numerically decreased after EQ2 primes (Table 3 and Fig. 1). Overall, these results closely replicate the findings from Scheepers et al. (2011) in English, where it was equally found that low-attachment equations were less effective than high-attachment equations in priming subsequent relative clause attachments. As discussed in the introduction, the latter could either be due to an *inverse preference effect* (whereby priming magnitudes tend to be stronger for primes that go against the baseline preference) or due to a *non-locality priming* effect (whereby primes that discourage local attachments are more effective).

Overall, we can conclude that cross-domain structural priming from mathematical equations to two-site RC-attachments is as detectable in Russian as it has been shown for English. For a more detailed evaluation of obtained effect sizes (also in relation to recent meta-analyses by Mahowald, James, Futrell, & Gibson, 2016), please refer to Appendix B.

3. Experiment 2

The following experiment was designed to investigate cross-domain structural priming in more complex *three-site* attachment configurations where an RC can be attached to one of three potential host-NPs.

Table 4
Example stimuli used in Experiment 2.

BL prime	14 × 3 =
EQ1 prime	18 + (7 + (3 + 11)) × 2 =
EQ2 prime	18 + 7 + (3 + 11) × 2 =
EQ3 prime	18 + 7 + 3 + 11 × 2 =
Target	Мне всегда нравилось варенье бабушки моего друга, котор(…) *I always liked the jam*(neu) *of the grandma*(fem) *of my friend*(masc), *that…*

3.1. Participants

Thirty-six native Russian speakers (18 male, 18 female, mean age = 21.6 years, SD = 2.53 years) participated in the experiment with no monetary compensation. As before, they were all psychology undergraduates from the Higher School of Economics (HSE) in Moscow, but none of them had taken part in Experiment 1. As in the previous experiment, participants were given a brief informal reminder of the arithmetic operator-precedence rules before the experiment started.

3.2. Materials

Thirty-two new sets of items were created, each consisting of a target sentence fragment paired with one of four types of priming equations (see Table 4 and Appendix A-B): BL (structurally neutral baseline), EQ1 (where a final multiplication or division operator was preceded by a complex, ‘double-bracketed’ addition or subtraction term), EQ2 (where the final multiplication or division operator was preceded ‘single-bracketed’ addition or subtraction term), and EQ3 (same as before, but excluding any parentheses). Compared to Experiment 1, each priming equation (except BL) therefore received an additional addition or subtraction term, and the complex object noun phrases in the target sentence fragments comprised an additional noun each (Table 4).

Thus, there were *three* potential attachment sites for the RC in the target fragments: N1, N2, and N3. Contrasting with Experiment 1 (where target attachments were determined semantically), each of the three attachment host NPs per target fragment in Experiment 2 was marked by a different gender (feminine, masculine, neutral), with different gender-marking sequences across items. For relative pronouns, which are also gender marked in Russian, the corresponding endings were removed, so that during sentence completion, participants would indicate their choice of attachment by specifying the gender marking of the relative pronoun.

3.3. Procedure

Using Latin square counterbalancing, the 32 item sets were allotted to four master files comprising 8 items per condition per file. Each file was seen by 9 participants. In addition to the experimental items, 66 structurally unrelated fillers (33 sentence fragments and 33 equations) were inserted in the same way as in the Experiment 1. Materials were printed on 6 A4 sheets of paper per questionnaire, and there was also always an additional cover sheet with instructions. An individual session lasted approximately 60 min with the same experimental task as in Experiment 1. Experimental instructions were identical to the ones used in Experiment 1. As in the previous experiment, none of the participants noted any systematic pairing of trials during debriefing.

3.4. Data analysis

As there were now three response categories (N1-, N2-, and N3-attachment), we performed three separate binary logistic GLMM analyses, i.e. one per response category. Hence, we decomposed a *multinomial* analysis problem into three *binary* ones by coding the dependent variable as 1 = N1-attachment (vs. 0 = rest), 1 = N2-attachment (vs. 0 = rest), and 1 = N3-attachment (vs. 0 = rest) for the first, second, and third analysis, respectively. This not only allowed for more direct comparisons with Experiment 1, but also simplified the analysis (note that multinomial effects would still need to be followed-up by binary comparisons).

As before, the predictor Prime Type (now comprising four levels) was entered into the models in mean-centred form (deviation coding), with the BL prime condition serving as a comparison baseline. In each analysis, we employed the maximal (by-subject [N = 36] and by-item [N = 32]) random effects structure justified by the design, including random correlation terms. Again, omnibus effects of Prime Type were established via likelihood ratio Chi-Square model comparisons.

3.5. Results and discussion

Mathematical accuracy was high on average (93.1%), ranging from 88.2% (EQ3 primes) to 98.3% (BL primes) across conditions. Trials with incorrectly solved mathematical primes were removed from subsequent analyses. Unidentifiable target attachments were virtually non-existent because attachment host NPs were always distinguished via morphological gender and participants had to provide explicit morphological gender-marking on the relative pronoun in their sentence completions.

Table 5 shows the distribution of N1-, N2-, and N3-attachment responses by levels of correctly solved type of prime. Totals are provided in the bottom row of the table. In general, N2-attachments were the most preferred response option, followed by N3-attachments, and lastly, N1-attachments. This is reflected in the marginal totals (bottom row of the table) whose percentages came close to those in the BL prime condition. However, in the non-baseline prime conditions (EQ1, EQ2, and EQ3), response proportions clearly deviated from the general distribution. Binary logistic GLMM analyses corroborated this observation by registering reliable main effects of Prime Type on occurrences of N1-attachments vs. rest (${}_{LR}\chi^2 = 28.423$; $df = 3$; $p < .001$), N2-attachments vs. rest (${}_{LR}\chi^2 = 39.822$; $df = 3$; $p < .001$), and N3-attachments vs. rest (${}_{LR}\chi^2 = 42.999$; $df = 3$; $p < .001$).

Table 6 shows fixed effect parameter estimates from each of the three GLMMs (one per target category), and Fig. 2 plots corresponding model-estimated probabilities. As can be seen, the results again show very clear evidence for cross-domain structural priming: Relative to the BL prime condition, EQ1-prime equations reliably increased the likelihood of N1-attachments in the subsequent target trials; correspondingly, EQ2-prime equations significantly increased the likelihood of N2-attachments and EQ3-prime equations the likelihood of N3-attachments.

As would be expected, each of these effects was complemented with decreases (relative to the baseline) in likelihoods of the corresponding 'rest' categories (cf. Fig. 2): following EQ1 primes, significantly more N1-attachments (top panel) were complemented with significantly fewer N2-attachments (middle panel) and numerically fewer N3-attachments (bottom panel); following EQ2 primes, significantly more N2-attachments (middle panel) were complemented with reliably fewer N1-attachments (top panel) and reliably fewer N3-attachments (bottom panel); and lastly, following EQ3 primes, significantly more N3-attachments (bottom panel) were complemented with numerically fewer N1-attachments (top panel) and significantly fewer N2-Attachments (middle panel).

Table 5
Distribution of responses per prime condition in Experiment 2. Shown are percentages of N1, N2, and N3 target attachments (absolute cell counts in brackets) for trials with correctly solved prime equations.

	Target Attachment		
Prime Type	N1	N2	N3
BL	27.6 (78)	41.0 (116)	31.4 (89)
EQ1	41.2 (110)	32.2 (86)	26.6 (71)
EQ2	16.0 (43)	64.3 (173)	19.9 (53)
EQ3	18.1 (46)	27.2 (69)	54.7 (139)
Total	25.8 (277)	41.4 (444)	32.8 (352)

Table 6
Binary logistic GLMM parameter estimates, broken down by target response category (N1-, N2-, and N3-attachment). Estimates and SEs are in log odds units. All figures are rounded to the third decimal. The BL Prime condition served as a baseline (intercept), and the remaining three fixed effect parameters (EQ1, EQ2, and EQ3) index contrasts between that baseline and each of the other three prime conditions.

	Estimate	*SE*	*Z*	*P*
N1-Attachment (vs. Rest)				
Int. (BL)	−1.329	0.169	−7.850	< 0.001
EQ1	0.871	0.279	3.123	0.002
EQ2	−0.664	0.300	−2.211	0.027
EQ3	−0.493	0.347	−1.419	0.156
N2-Attachment (vs. Rest)				
Int. (BL)	−0.438	0.156	−2.807	0.005
EQ1	−0.425	0.210	−2.019	0.043
EQ2	1.128	0.235	4.798	< 0.001
EQ3	−0.611	0.222	−2.755	0.006
N3-Attachment (vs. Rest)				
Int. (BL)	−0.967	0.170	−5.697	< 0.001
EQ1	−0.408	0.275	−1.484	0.138
EQ2	−0.863	0.297	−2.908	0.004
EQ3	1.130	0.207	5.458	< 0.001

These results go beyond both Experiment 1 and the previous studies discussed in the introduction. Specifically, Experiment 2 demonstrates that three-site RC-attachment is no less susceptible to cross-domain structural priming than the syntactically simpler case of attaching a relative clause to one of two available host-NPs. Most notably, the present experiment shows that the different types of prime equations have very *specific* effects on RC-attachment decisions in the target trials, such that prime equations like $A + (B + (C + D)) \times E$ (EQ1) make N1-atachments more likely, prime equations like $A + B + (C + D) \times E$ (EQ2) make N2-attachments more likely, and prime equations like $A + B + C + D \times E$ (EQ3) make N3-attachments more likely, respectively. In other words, contrasting with the *non-locality priming* hypothesis discussed in the introduction, we found that cross-domain structural priming from mathematical equations to RC-attachments in complex NPs must rely on relatively detailed representations of recursively generated hierarchical structure, and not just on the general distinction between *local* vs. *non-local* constituent attachments. Interestingly, distributions of complementary 'rest' categories (as described earlier) appeared to suggest that priming occurred primarily at the expense of structural alternatives that were within one position (in either direction) from the primed RC-attachment. In other words, *locality* might account for at least *some* aspects of the data in Experiment 2. However, closer examination in Appendix C actually reveals that the corresponding differences in effect magnitude were hardly compelling enough to warrant further theoretical elaboration at this point.

Another noteworthy finding was that N2-attachments were generally preferred (see in particular Table 5), whereas previous comprehension studies on three-site RC-attachment configurations have suggested that N2-attachment is in fact the *least accessible* option available

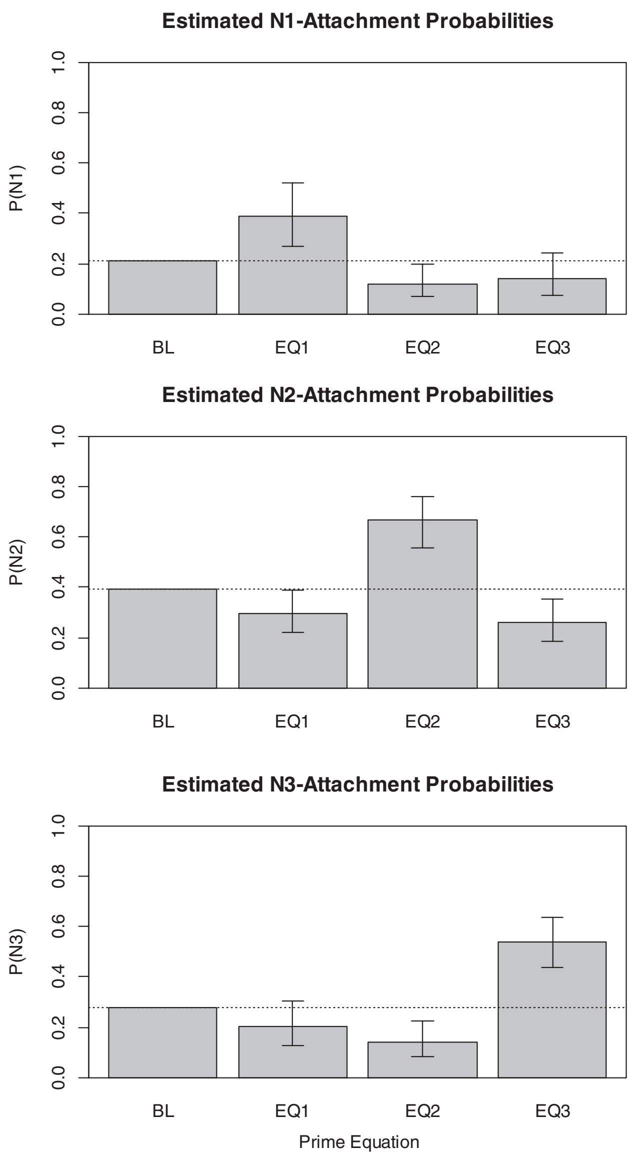

Fig. 2. Probabilities of N1-attachments (top panel), N2-attachments (middle panel), and N3-attachments (bottom panel) in the target trials of Experiment 2, as estimated via binary logistic GLMM analyses (see text). Figures are broken down by levels of Prime Type (BL, EQ1, EQ2, and EQ3). Error bars represent 95% CIs for contrasts with the BL prime condition; the latter is indexed by a horizontal dashed line in each panel.

to readers of various languages (e.g., Gibson et al., 1996; Gibson, Schuetze, & Salomon, 1996; Hemforth et al., 2000). At present, we have to remain agnostic about potential reasons for our contrasting findings, e.g., whether they are specific to Russian, whether they are due to the experimental task (sentence completion rather than comprehension), or whether they are due to our particular set of materials (the vast majority of our items comprised *animate* N2 host-NPs, whereas N1 and N3 host-NPs were more variable in this regard), among other potential factors which remain to be elucidated in future studies. However, we believe that in order to arrive at valid conclusions about cross-domain structural priming, baseline attachment preferences are indeed of secondary theoretical importance, particularly when the experimental design itself includes a syntactically neutral baseline prime condition, as was the case for the studies presented here.

4. General discussion

Previous structural priming studies have found evidence for shared structural representations across different cognitive domains such as mathematics, music, and language (e.g., Scheepers et al., 2011, Scheepers & Sturt, 2014; Van de Cavey & Hartsuiker, 2016; Zeng et al., 2018). The work presented in this paper makes two important novel contributions to our current understanding of the mechanisms underlying cross-domain structural priming from (specifically) mathematical equations to linguistic expressions.

The first is that cross-domain priming of hierarchical structure configurations is largely *language-independent*. Indeed, Experiment 1 almost perfectly replicated the English findings from Scheepers et al. (2011), but in a different language (Russian, which is not closely related to English). While such a finding is perhaps not too surprising (especially when considering that our Russian participants were as mathematically adept as the Business and Maths students in Scheepers et al., 2011), it is nonetheless an important demonstration because it suggests that cross-domain hierarchical structure priming occurs regardless of the specific details of the target language's grammar.

The second, arguably more interesting theoretical contribution stems from Experiment 2 of the present paper, showing that cross-domain hierarchical structure priming also extends to three-site RC-attachment configurations in noun-phrases of even greater syntactic complexity. The latter is indeed the first empirical demonstration of its kind. More specifically, the results from Experiment 2 suggest that cross-domain structural priming of RC-attachments must rely on relatively *detailed* hierarchical structure representations that are being carried over from mathematical prime equations to linguistic expressions in subsequent target trials. At the same time, our data provide little or no support for the hypothesis (see introduction) that cross-domain hierarchical structure priming would rely on the (non-)applicability of a general *locality principle* for the recursive expansion of structure (see also Appendix C). Below, we provide a more mechanistic explanation of the findings from Experiment 2, based on an extended version of the *incremental-procedural* account suggested by Scheepers et al. (2011). At the same time, it is important to stress that the validity of such an account would need to be corroborated further by data from on-line techniques such as eye-tracking, not the least because the present syntactic priming results offer hardly any clues about how the relevant mathematical equations and linguistic expressions are actually being processed in real time.

The *incremental-procedural* account proposes that the processing of mathematical equations, just like the processing of linguistic materials, proceeds incrementally 'from left to right' such that each new element is being integrated into a partial, incrementally updated representation of the entire expression.[1] For instance, when solving an EQ3 prime equation structured like $A + B + C + D \times E$ (cf. Experiment 2), participants would initially calculate the sum $A + B + C + D\ldots$ in a left-to-right fashion; however, this would require a form of reanalysis when encountering the multiplication term ($\times E$) at the end of the equation because the mathematical operator-precedence rules require that the product ($D \times E$) is determined first before combining it with the result of the previous sum ($A + B + C$). By analogy, encountering a relative pronoun (e.g. "that") after having processed a complex noun phrase like NP_1 *-of-* NP_2 *-of-* NP_3 would also require a mild form of structural revision to take place because the relative pronoun (and subsequent RC) needs to be combined with one of the preceding host NPs first before

[1] Scheepers and Sturt (2014) noted that the distribution of mathematical errors in their Experiment 2 could be interpreted as tentative support for left-to-right processing of equations. Specifically, they found that structurally left-branching equations like A × B + C were more likely to be solved correctly than structurally right-branching equations like A + B × C; the latter were often solved in analogy to (A + B) × C.

this NP + relative pronoun combination can be integrated into the overall structure; at this point, there are three possibilities: either the relative pronoun combines with the entire complex object-NP that precedes it, resulting in [[NP_1 *-of-* [NP_2 *-of-* [NP_3]]] *that* …] (N1-attachment), or it combines with second-most complex NP within the preceding object-NP, resulting in [NP_1 *-of-* [[NP_2 *-of-* [NP_3]] *that* …]] (N2-attachment), or it combines with the least complex (and most recent) NP within the preceding object-NP, resulting in [NP_1 *-of-* [NP_2 *-of-* [[NP_3] *that* …]]] (N3-attachment), respectively. The bracketing of the resulting expressions is important here. Specifically, note that the three options differ with respect to the *hierarchical complexity* of the preceding NP that the relative pronoun (and subsequent RC) ultimately combines with: the N1-attachment option implies that the RC combines with a rather complex NP on its left, which itself contains two further NP-embeddings; the N2-attachment option implies that the RC combines with an NP on its left that has one further NP-embedding, and lastly, the N3-attachment option entails that the RC combines with a simple NP on its left without further embeddings. To account for the findings from Experiment 2, we propose that perceivers must in some way keep track of the number of hierarchical embeddings within the constituent on the left that the final element in the (mathematical or linguistic) expression combines with. Thus, after EQ3-type prime equations structured like $A + B + C + D \times E$ (where the final multiplication combines with a simple *number* on its left, i.e. without any further embedded operations), N3-atachments become more likely in the subsequent target trial; after EQ2-type equations like $A + B + (C + D) \times E$ (where the final multiplication combines with the result of *single embedded sum* on its left), N2-attachments become more likely, and lastly, after EQ1-type equations like $A + (B + (C + D)) \times E$ (where the final multiplication applies to the result of a *doubly-embedded sum*), N1-attachments become more likely in the subsequent linguistic target trial.

How do the present (and previous) cross-domain structural priming effects relate to potential neural architectures and mechanisms within the brain? Indeed, the idea that language and other cognitive domains might share aspects of functional, behavioural, and neuroanatomical organization is by no means a new one (e.g., Piaget, 1952), and some available reports indicate at least *some* correspondence between language-related brain circuits and those supporting other cognitive operations (Hauser & Watumull, 2017; Lelekov, Franck, Dominey, & Georgieff, 2000; Makuuchi, Bahlmann, & Friederici, 2012; Nakai & Okanoya, 2018; Patel, 2003). On the other hand, some of the existing neuroimaging literature suggests a substantial degree of independence between the brain networks responsible for (specifically) mathematical and linguistic cognition (e.g., Amalric & Dehaene, 2016; Fedorenko, Behr, & Kanwisher, 2011; Monti, Parsons, & Osherson, 2012). Unfortunately, evidence from cross-domain structural priming does not offer any direct clues in terms of sharing of domain-specific vs. domain-general brain regions. Therefore, informing current neuroscientific debates about the relation between mathematical and linguistic processing is clearly beyond the scope of the present paper. What our data show is an interplay between the hierarchical configurations of mathematical and linguistic expressions traced in the associated *behavior*; i.e., in the likelihood of making specific structural choices. Indeed, the relationship between brain structures supporting a behavioral process and the parameters of that process itself rarely exhibits a one-to-one correspondence (Page, 2006; Whishaw & Kolb, 2010), and more research is necessary to determine the brain mechanisms involved in cross-domain structural priming (e.g., by applying the paradigms used here to neuroimaging designs). A plausible outcome might be that the behavioural effects reported here and elsewhere result from activation of a rather complex neuroanatomical system that includes both independent and overlapping, domain-specific and domain-general neural circuits.

To conclude, the present work strengthens previous evidence for shared structural representations between (seemingly) disparate cognitive domains such as language and mathematics. Specifically, we have shown that cross-domain structural priming from mathematical to linguistic expressions previously shown in English and Dutch occurs in a morphologically rich language such as Russian. More interestingly, our research suggests that – at some abstract, domain-unspecific level – perceivers must *keep track of the number of hierarchical recursive embeddings* within an equation during mathematical problem solving, which they are likely to replicate in a subsequent linguistic target trial that allows for the syntactic integration of a relative clause at different levels of hierarchical embedding within a complex noun phrase (e.g., [NP_1 -of- [NP_2 -of- [NP_3-]]]).

It is important to stress (again) that we do not interpret our data as providing direct support for the idea that linguistic and mathematical processing involve the exact same brain regions. As pointed out above, many neuroscientific reports suggest a substantial degree of independence between the neural networks involved in linguistic and mathematical processing (Amalric & Dehaene, 2016; Fedorenko et al., 2011; Monti et al., 2012), and it has also been shown that people with severe agrammatic aphasia can perform well in tasks involving mathematical problem solving (Varley, Klessinger, Romanowski, & Siegal, 2005). At the same time, the present findings do seem to suggest that potentially separate brain networks for language, mathematics, music, etc., draw upon shared, and presumably independently accessible, domain-general networks for the processing of abstract hierarchical structures. Plausible candidates for such domain-general processing resources may include attention and, specifically in the context of hierarchical RC-attachment configurations, working memory (see, e.g., Swets, Desmet, Hambrick, & Ferreira, 2007; Fedorenko, Gibson, & Rhode, 2007). Indeed, the present and related findings could be interpreted as evidence for mechanisms that are responsible for the recursive chunking and integration of elements in working memory that could also apply to various other domains of human cognition (see also Martins & Fitch, 2014).

Another important point in evaluating the partially conflicting findings from the neuroimaging literature appears to be that mathematical tasks vary greatly across studies, ranging from solving computation problems of a relatively ‘flat’, sequential nature (e.g., Fedorenko et al., 2011) to problems that involve more complex hierarchical embeddings (e.g. Makuuchi et al., 2012; Nakai & Okanoya, 2018; Dehaene et al., 2015). In other words, some of the contradicting findings may be a reflection of using different classes of mathematical problems that could have diverging behavioural and neural organizations.

We nevertheless remain cautious about architectural implications of our research, and conclude that while our data suggest that language and mathematics share aspects of recursive hierarchical structure processing, they do not offer direct evidence regarding the brain networks involved in enabling this sharing of structural information. Our findings could indicate an overlap in domain-specific brain regions or – perhaps more plausibly – an interface based on sharing of domain-general resources such as attention and working memory.

Author notes

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Appendix A

(A) Priming materials for Experiment 1. Primes are provided in the format EQ1 | EQ2 | BL. The term *relPro* at the end of the English gloss per target fragment stands for relative pronoun and is translated as either *that* or *who*, dependent on attachment and context.

Item 01	
Primes:	2 + (8 − 4)/2 = | 2 + 8 − 4/2 = | 48/8 =
Target:	Во дворе на дереве висел ботинок соседа, который…
	On the tree in the yard there was hanging the shoe of the neighbour, *relPro*…
Item 02	
Primes:	60 − (6 + 4) × 5 = | 60 − 6 + 4 × 5 = | 14 + 54 =
Target:	На фестивале победил фильм режиссера, который…
	At the festival won the movie of the director, *relPro*…
Item 03	
Primes:	16 + (7 − 3) × 3 = | 16 + 7 − 3 × 3 = | 31 + 16 =
Target:	Коллекционер решил продать фотографии государственных деятелей, которые… The collector decided to sell the photographs of statesman, *relPro*…
Item 04	
Primes:	59 − (36 − 24)/3 = | 59 − 36 − 24/3 = | 36 × 2 =
Target:	Вражеское войско атаковало замок принца, который…
	The enemy army attacked the castle of the prince, *relPro*…
Item 05	
Primes:	26 + (8 + 6)/2 = | 26 + 8 + 6/2 = | 26/2 =
Target:	Студенты приняли участие в эксперименте психолога, который…
	The students took part in the experiment of the psychologist, *relPro*…
Item 06	
Primes:	32 + (24 − 4) × 2 = | 32 + 24 − 4 × 2 = | 56 − 23 =
Target:	Президент был вынужден вернуть подарок посла, который…
	The president was obliged to return the present of the ambassador, *relPro*…
Item 07	
Primes:	54 − (20 + 10)/5 = | 54 − 20 + 10/5 = | 20 × 3 =
Target:	Археологи нашли ружья французских солдат, которые…
	The archeologists have found the guns of the French soldiers, *relPro*…
Item 08	
Primes:	9 + (12 − 4) × 3 = | 9 + 12 − 4 × 3 = | 9 + 58 =
Target:	Полицейские не заметили побега преступника, который…
	The police didn't notice the prison break of the criminal, *relPro*…
Item 09	
Primes:	72 − (8 − 5) × 4 = | 72 − 8 − 5 × 4 = | 72/8 =
Target:	По легенде в старинном замке живет призрак графа, который…
	The legend tells that in the old castle lives the ghost of the count, *relPro*…
Item 10	
Primes:	13 + (22 − 4)/2 = | 13 + 22 − 4/2 = | 14 − 9 =
Target:	Туристы случайно нашли вход в гробницу императрицы, которая…
	The tourist found by accident the entrance to the tomb of the queen, *relPro*…
Item 11	
Primes:	4 + (6 + 3) × 2 = | 4 + 6 + 3 × 2 = | 12 × 6 =
Target:	На аукционе были выставлены драгоценности актрис, которые…
	At the auction were exhibited the jewelry of the actresses, *relPro*…
Item 12	
Primes:	85 − (27 − 9)/3 = | 85 − 27 − 9/3 = | 85/5 =
Target:	СМИ сообщили о взрыве дома, который…
	Mass media reported about the explosion of the house, *relPro*…
Item 13	
Primes:	19 + (8 + 3) × 3 = | 19 + 8 + 3 × 3 = | 27 + 15 =
Target:	Компания обещала в течение года вернуть деньги инвесторам, которые…
	The company promised to return in a year the money of the investors, *relPro*…
Item 14	
Primes:	98 − (44 − 22)/2 = | 98 − 44 − 22/2 = | 98 − 44 =
Target:	Денис все утро не мог найти адрес магазина, который…
	All morning Denis was looking for the address of the shop, *relPro*…
Item 15	
Primes:	5 + (17 − 1) × 4 = | 5 + 17 − 1 × 4 = | 17 × 4 =
Target:	Белый дом был вынужден отказать в визите премьеру-министру, который…
	The White House had to refuse the visit of the prime minister, *relPro*…
Item 16	
Primes:	34 − (6 + 16)/2 = | 34 − 6 + 16/2 = | 34/2 =
Target:	В выставочном зале были представлены медали спортсменов, которые…
	In the exhibition hall were demonstrated the medals of the athletes, *relPro*…
Item 17	
Primes:	10 + (13 − 5) × 3 = | 10 + 13 − 5 × 3 = | 23 + 16 =
Target:	Ураган уничтожил урожай фермера, который… /
	The hurricane destroyed the harvest of the farmer, *relPro*…
Item 18	
Primes:	67 − (40 − 24)/8 = | 67 − 40 − 24/8 = | 27/3 =
Target:	Я так и не решилась распечатать посылку незнакомки, которая…
	I couldn't open the parcel of the stranger, *relPro*…
Item 19	
Primes:	29 + (17 − 1) × 4 = | 29 + 17 − 1 × 4 = | 13 × 3 =

Target: Нина старательно украшала подарок другу, который…
Nina was diligently decorating the present to the friend, *relPro*…

Item 20
Primes: $6 + (25 + 5)/5 =$ | $6 + 25 + 5/5 =$ | $31 - 6 =$
Target: Еврокомиссия подсчитала долги организаций, которые…
The European Commission has estimated the debt of the organisations, *relPro*…

Item 21
Primes: $84 - (14 + 4) \times 7 =$ | $84 - 14 + 4 \times 7 =$ | $28 + 15 =$
Target: Меня до глубины души поразил рассказ проповедника, который…
I was profoundly impressed by the story of the preacher, *relPro*…

Item 22
Primes: $12 + (23 + 5) \times 3 =$ | $12 + 23 + 5 \times 3 =$ | $23 - 12 =$
Target: В заброшенном доме были обнаружены письма революционеров, которые…
In the abandoned house were found the letters of the revolutionaries, *relPro*…

Item 23
Primes: $64 - (18 - 6)/3 =$ | $64 - 18 - 6/3 =$ | $64/8 =$
Target: Для побега мальчику нужно было украсть метлу ведьмы, которая…
To escape the boy has to steal the broom of the witch, *relPro*…

Item 24
Primes: $20 + (35 - 7) \times 2 =$ | $20 + 35 - 7 \times 2 =$ | $14 \times 5 =$
Target: В пыльном подвале брат нашел портрет рыцаря, который…
In the dusty basement my brother has found the portrait of the knight, *relPro*…

(B) Priming materials for Experiment 2. Primes are provided in the format EQ1 | EQ2 | EQ3 | BL. The term *relPro* at the end of the English gloss per target fragment stands for relative pronoun and is translated as either *that* or *who*, dependent on attachment and context.

Item 01
Primes: $18 + (7 + (3 + 11)) \times 2 =$ | $18 + 7 + (3 + 11) \times 2 =$ | $18 + 7 + 3 + 11 \times 2 =$ | $14 \times 3 =$
Target: Мне всегда нравилось варенье бабушки моего друга, котор(…)
I always liked the jam of the granny of my friend, *relPro*…

Item 02
Primes: $15 + (36 + (18 + 27))/9 =$ | $15 + 36 + (18 + 27)/9 =$ | $15 + 36 + 18 + 27/9 =$ | $36/6 =$
Target: Пираты нашли на берегу золото королевы острова, котор(…)
The pirates found by the coast the gold of the queen of the island, *relPro*…

Item 03
Primes: $37 + (22 - (5 + 4)) \times 3 =$ | $37 + 22 - (5 + 4) \times 3 =$ | $37 + 22 - 5 + 4 \times 3 =$ | $17 + 9 =$
Target: Дикие кочевники вытоптали пастбище деревни лорда, котор(…)
The wild nomads trampled down the pasture of the village of the lord, *relPro*…

Item 04
Primes: $21 + (48 - (16 + 24))/8 =$ | $21 + 48 - (16 + 24)/8 =$ | $21 + 48 - 16 + 24/8 =$ | $48 - 19 =$
Target: Правительство не собиралось терпеть восстание противника реформы, котор(…)
The government wasn't going to tolerate the uproar of the opponent of the reform, *relPro*…

Item 05
Primes: $53 - (1 + (4 + 7)) \times 4 =$ | $53 - 1 + (4 + 7) \times 4 =$ | $53 - 1 + 4 + 7 \times 4 =$ | $7 \times 12 =$
Target: На конференции ученые признали лучшим исследование студента лаборатории, котор(…)
At the conference the scientists chose as best the research of the student of the lab, *relPro*…

Item 06
Primes: $86 - (63 - (14 + 42))/7 =$ | $86 - 63 - (14 + 42)/7 =$ | $86 - 63 - 14 + 42/7 =$ | $63/9 =$
Target: На красной дорожке все были поражены подолом платья актрисы, котор(…)
On the red carpet everyone was astonished by the hem of the dress of the actress, *relPro*…

Item 07
Primes: $46 + (14 - (12 - 5)) \times 6 =$ | $46 + 14 - (12 - 5) \times 6 =$ | $46 + 14 - 12 - 5 \times 6 =$ | $23 + 46 =$
Target: Биологи довольно долго изучали строение скелета ехидны, котор(…)
The biologists were studying for quite a long time the structure of the skeleton of the echidna, *relPro*…

Item 08
Primes: $4 + (70 - (60 - 15))/5 =$ | $4 + 70 - (60 - 15)/5 =$ | $4 + 70 - 60 - 15/5 =$ | $80/5 =$
Target: Археологи обнаружили наконечник копья амазонки, котор(…)
The archaeologists have found the tip of the lance of the Amazon, *relPro*…

Item 09
Primes: $47 + (14 + (34 - 22))/2 =$ | $47 + 14 + (34 - 22)/2 =$ | $47 + 14 + 34 - 22/2 =$ | $47 - 19 =$
Target: На переговорах бизнесмен постоянно забывал имя помощницы своего партнера, котор(…)
During the negotiations the businessman constantly forgot the name of the assistant of his partner, *relPro*…

Item 10
Primes: $53 + (20 - (12 + 5)) \times 3 =$ | $53 + 20 - (12 + 5) \times 3 =$ | $53 + 20 - 12 + 5 \times 3 =$ | $12 \times 6 =$
Target: Полицейский внимательно изучил удостоверение водителя машины, котор(…)
The policeman carefully examined the license of the driver of the car, *relPro*…

Item 11
Primes: $16 + (27 + (54 - 36))/9 =$ | $16 + 27 + (54 - 36)/9 =$ | $16 + 27 + 54 - 36/9 =$ | $54 + 7 =$
Target: В Совете Безопасности никто не прислушивался к мнению ветерана войны, котор(…)
Nobody in the Security Council listened to the opinion of the veteran of the war, *relPro*…

Item 12
Primes: $89 - (18 - (13 - 6)) \times 7 =$ | $89 - 18 - (13 - 6) \times 7 =$ | $89 - 18 - 13 - 6 \times 7 =$ | $42/7 =$
Target: Джинн был не в силах исполнитель желание дочери тирана, котор(…)
The genie was unable to fulfill the wish of the daughter of the tyrant, *relPro*…

Item 13
Primes: $31 + (16 + (24 - 8))/4 =$ | $31 + 16 + (24 - 8)/4 =$ | $31 + 16 + 24 - 8/4 =$ | $58 - 24 =$
Target: Странствующий рыцарь не верил в волшебство посоха ведьмы, котор(…)
The knave didn't believe in the magic of the staff of the witch, *relPro*…

Item 14

Primes: $77 - (23 - (4 + 5)) \times 5 =$ | $77 - 23 - (4 + 5) \times 5 =$ | $77 - 23 - 4 + 5 \times 5 =$ | $23 \times 3 =$
Target: В деревне на окраине страны все боятся проклятья призрака графини, котор(…)
In the village on the outskirts of the country everybody is afraid of the curse of the ghost of the countess, *relPro*…

Item 15
Primes: $10 + (6 + (48 - 24))/6 =$ | $10 + 6 + (48 - 24)/6 =$ | $10 + 6 + 48 - 24/6 =$ | $6 + 41 =$
Target: Индейцы верили, что год начинается с рождением бога реки, котор(…)
Indians believed that the year starts with the birth of the god of the river, *relPro*…

Item 16
Primes: $82 - (5 + (5 - 3)) \times 8 =$ | $82 - 5 + (5 - 3) \times 8 =$ | $82 - 5 + 5 - 3 \times 8 =$ | $56/8 =$
Target: Адвокат был вынужден отказаться от дела дочери президента, котор(…)
The advocate was forced to refuse the case of the daughter of the president, *relPro*…

Item 17
Primes: $28 + (45 - (12 - 3))/3 =$ | $28 + 45 - (12 - 3)/3 =$ | $28 + 45 - 12 - 3/3 =$ | $96 - 28 =$
Target: Александр обещал рассмотреть резюме выпускницы университета, котор(…)
Alexander promised to take a look at the CV of the graduating student of the university, *relPro*…

Item 18
Primes: $17 + (11 + (4 + 2)) \times 4 =$ | $17 + 11 + (4 + 2) \times 4 =$ | $17 + 11 + 4 + 2 \times 4 =$ | $17 \times 4 =$
Target: Ежегодный концерт откроет выступление поклонника певицы, котор(…)
The annual concert will be opened with the performance of the admirer of the singer, *relPro*…

Item 19
Primes: $53 - (9 + (36 - 18))/9 =$ | $53 - 9 + (36 - 18)/9 =$ | $53 - 9 + 36 - 18/9 =$ | $7 + 36 =$
Target: В утренних новостях сообщили о крушении самолета принцессы, котор(…)
In the morning news we were informed about the crash of the plane of the princess, *relPro*…

Item 20
Primes: $66 - (17 + (32 - 25)) \times 2 =$ | $66 - 17 + (32 - 25) \times 2 =$ | $66 - 17 + 32 - 25 \times 2 =$ | $32/16 =$
Target: На пороге моей квартиры почему-то лежало кольцо супруги соседа, котор(…)
For some reason on the doorstep of my flat was lying the ring of the wife of my neighbour, *relPro*…

Item 21
Primes: $19 + (20 + (55 - 30))/5 =$ | $19 + 20 + (55 - 30)/5 =$ | $19 + 20 + 55 - 30/5 =$ | $55 - 23 =$
Target: Лилипуты старались обходить стороной королевство врага феи, котор(…)
The Lilliputian tried to bypass the kingdom of the enemy of the fairy, *relPro*…

Item 22
Primes: $6 + (1 + (12 - 2)) \times 8 =$ | $6 + 1 + (12 - 2) \times 8 =$ | $6 + 1 + 12 - 2 \times 8 =$ | $12 \times 7 =$
Target: В финале конкурса представили блюдо повара академии, котор(…)
In the competition final they presented the dish of the cook of the academy, *relPro*…

Item 23
Primes: $76 - (21 - (42 - 28))/7 =$ | $76 - 21 - (42 - 28)/7 =$ | $76 - 21 - 42 - 28/7 =$ | $21 + 65 =$
Target: Старый коллекционер уже полвека хранит украшение жрицы храма, котор(…)
For half a century the old collector is keeping the jewel of the priestess of the temple, *relPro*…

Item 24
Primes: $90 - (18 - (3 + 5)) \times 6 =$ | $90 - 18 - (3 + 5) \times 6 =$ | $90 - 18 - 3 + 5 \times 6 =$ | $72/8 =$
Target: Переводчик долго не решался озвучить послание министра страны, котор(…)
The translator deliberated for a long time whether to read the message of the minister of the country, *relPro*…

Item 25
Primes: $69 - (17 + (8 + 8)) \times 2 =$ | $69 - 17 + (8 + 8) \times 2 =$ | $69 - 17 + 8 + 8 \times 2 =$ | $69 - 25 =$
Target: Электрик приходил утром, чтобы проверить освещение кладовки дома, котор(…)
The electrician came this morning to check the light of the closet of the house, *relPro*…

Item 26
Primes: $33 + (44 - (28 + 8))/4 =$ | $33 + 44 - (28 + 8)/4 =$ | $33 + 44 - 28 + 8/4 =$ | $6 \times 9 =$
Target: Детективы долго расследовали ограбление квартиры журналиста, котор(…)
The detectives investigated for a long time the burglary of the flat of the journalist, *relPro*…

Item 27
Primes: $21 + (17 - (10 - 4)) \times 5 =$ | $21 + 17 - (10 - 4) \times 5 =$ | $21 + 17 - 10 - 4 \times 5 =$ | $17 + 44 =$
Target: В путевых заметках было описано путешествие группы Смирнова, котор(…)
In the travel notes they described the journey of the group of Smirnov, *relPro*…

Item 28
Primes: $3 + (16 + (72 - 48))/8 =$ | $3 + 16 + (72 - 48)/8 =$ | $3 + (16 + 72 - 48/8 =$ | $72/9 =$
Target: Летом на подоконнике можно увидеть кошку хозяина кафе, котор(…)
During summer on the windowsill it is possible to see the cat of the owner of the cafe, *relPro*…

Item 29
Primes: $87 - (29 - (14 + 2)) \times 3 =$ | $87 - 29 - (14 + 2) \times 3 =$ | $87 - 29 - 14 + 2 \times 3 =$ | $40 - 29 =$
Target: В правительстве одобрили строительство музея балерины, котор(…)
The government approved the construction of the museum of the ballet, *relPro*…

Item 30
Primes: $23 + (21 + (7 + 35))/7 =$ | $23 + 21 + (7 + 35)/7 =$ | $23 + 21 + 7 + 35/7 =$ | $42 \times 2 =$
Target: В подвале дома я нашёл ружьё солдата армии, котор(…)
In the basement of my house I found the shotgun of the soldier of the army, *relPro*…

Item 31
Primes: $29 + (7 + (7 - 4)) \times 6 =$ | $29 + 7 + (7 - 4) \times 6 =$ | $29 + 7 + 7 - 4 \times 6 =$ | $36 + 51 =$
Target: В праздник Рождества Христова всех угощали вином крестьянина деревни, котор(…)
At the Christmas festival everyone was treated to the wine of the peasant of the village, *relPro*…

Item 32
Primes: $38 - (27 + (72 - 45))/9 =$ | $38 - 27 + (72 - 45)/9 =$ | $38 - 27 + 72 - 45/9 =$ | $54/6 =$
Target: В своём дневнике психиатр подробно описал безумие пациента клиники, котор(…)
The psychiatrist described in detail in his diary the madness of the patient of the clinic, *relPro*…

Appendix B

Considering the GLMM parameter estimates in Table 3, effect sizes in Experiment 1 (relative to the BL condition) amounted to *log odds* of 0.586 and −0.309, respectively, yielding an overall effect of *log odds* = 0.895 when the baseline is ignored. In their meta-analyses, Mahowald et al. (2016) reported general *odds ratio* effect sizes of 3.26 and 1.67, for priming *with* and *without* lexical overlap, respectively. With an *odds ratio* of roughly *exp* (0.9) = 2.46, our effect therefore falls *in-between* those general benchmarks, i.e., it is stronger than is typical for priming without lexical overlap, but weaker than is typical for *lexically boosted* structural priming.

However, it is important to consider that around 85% of the data included in Mahowald et al. (2016) were actually from studies investigating priming of transitive (active vs. passive) or ditransitive (PO vs. DO) structures, i.e., syntactic alternations that are *very different* from the hierarchical attachment configurations investigated in the present paper (for theoretical discussion, see Desmet & Declercq, 2006; Scheepers, 2003). Hence, it is useful to also make more specific comparisons with previous research on (particularly) RC-attachment priming, both *across* and *within* cognitive domains.

Indeed, results from Experiment 1 agree quite well with previous demonstrations of priming from mathematical equations to RC-attachment. The percentage differences between EQ1 and EQ2 primes in the raw descriptive figures (Table 2) show that our priming effect amounted to a 17.3% shift in N1 vs. N2 responses between the two non-baseline conditions. To compare, the average priming effects in Scheepers et al. (2011) were around 17% (Experiment 1) respectively 22% (Experiment 2) – again, without considering the baseline, and excluding “other” responses. Our Experiment 1 also compares well with previous *within-domain* (language-to-language) demonstrations of RC-attachment priming. For example, in Scheepers (2003)'s Experiment 1, there was 16.6% priming, and in Experiment 2 of the same paper (using improved materials), there was 20.1% priming (ignoring the baseline and excluding “other” responses, as before).

It is indeed quite remarkable that RC-attachment priming does not appear to be notably different *across* than *within* cognitive domains. However, under the assumption that this kind of priming is based on preservation of hierarchical structure rather than preservation of (say) lexical, semantic, or pragmatic aspects, such cross-domain consistency in effect sizes is actually not unexpected.

Appendix C

An anonymous reviewer made a very interesting observation about priming at the expense of complementary alternatives in our Experiment 2, suggesting that the results may not be entirely incompatible with a locality-based principle for at least *some* aspects of our data. Specifically, the reviewer noted that for each type of prime, the corresponding attachment site was primed at the expense of attachment sites that were within one position (in either direction) away from that attachment site. Indeed, this is what the relevant *significant* contrasts with the BL prime condition appear to suggest (see Fig. 2 and Table 6).

However, it is also important to note that proportions of structural alternatives which were *more than one* position away from the primed attachment site were still descriptively below baseline in each case: there were numerically fewer N3-attachments after EQ1 than after BL primes (bottom panel of Fig. 2) and numerically fewer N1-attachments after EQ3 than after BL primes (top panel of Fig. 2). It therefore makes sense to evaluate the available evidence on this matter more carefully, by taking a closer look at the relevant *log odds* parameters in Table 6:

- The BL vs. **EQ1** contrast amounted to *log odds* = −0.425 for the ‘local’ alternative (N2-attachment) compared to *log odds* = −0.408 for the ‘non-local’ alternative (N3-attachment). Only the former was significant, but the latter was in the same direction and differed by only 0.017 *log odds* units.
- The BL vs. **EQ2** contrast amounted to *log odds* = −0.664 for N1-attachments and *log odds* = −0.863 for N3-attachments. Both were significant (and in the same direction) but differed by 0.199 *log odds* units.
- The BL vs. **EQ3** contrast amounted to *log odds* = −0.611 for the ‘local’ alternative (N2-attachment) compared to *log odds* = −0.493 for the ‘non-local’ alternative (N1-attachment). Again, only the former was significant, but the latter was in the same direction and differed by only 0.118 *log odds* units.

Indeed, even the largest of the above differences (0.199) is well within the 95% CI derived from even the smallest *SE* in Table 6 ($0.156 \times 1.96 = 0.306$). We take this to indicate that our data provide only rather faint support, if anything, for a locality-based distribution of non-primed structures. Thus, while we acknowledge that locality might explain interesting (but very subtle) secondary aspects of our data, we maintain that the primary pattern of results – specifically the fact that each type of prime selectively promoted only one type of RC-attachment – clearly points to the preservation of more detailed hierarchical structure representations.

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.03.021.

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