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Structural Priming Across Cognitive Domains: From Simple Arithmetic to Relative-Clause Attachment

Christoph Scheepers[1], Patrick Sturt[2], Catherine J. Martin[1], Andriy Myachykov[1], Kay Teevan[1], and Izabela Viskupova[1]
[1]University of Glasgow and [2]University of Edinburgh

Abstract

In the two experiments reported here, we uncovered evidence for shared structural representations between arithmetic and language. Specifically, we primed subjects using mathematical equations either with or without parenthetical groupings, such as 80 – (9 + 1) × 5 or 80 – 9 + 1 × 5, and then presented a target sentence fragment, such as "The tourist guide mentioned the bells of the church that . . . ," which subjects had to complete. When the mathematical equations were solved correctly, their structure influenced the noun phrase—for example, either "the bells of the church" or "the church," respectively—that subjects chose to attach their sentence completion to. These experiments provide the first demonstration of cross-domain structural priming from mathematics to language. They highlight the importance of global structural representations at a very high level of abstraction and have potentially far-reaching implications regarding the domain generality of structural representations.

Keywords

syntactic priming, relative-clause attachment, arithmetic, psycholinguistics, priming, language, mathematical ability

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The mental representation of language involves a high degree of abstraction. People can produce and understand sentences that they have never encountered or uttered before, and there is no theoretical limit to the number of distinct sentences that they can potentially understand or produce. This indicates that language processing cannot simply proceed via retrieval of fully formed sentences, or sentence meanings, from long-term memory. Instead, there must be some process of abstraction whereby particular sentence tokens are categorized in terms of more general representations. But what is the nature of these abstract representations, and what degree of abstraction do they involve? Answers to these questions are essential for a full understanding of language use and how it relates to other domains of cognition.

In the study reported here, we investigated the degree of abstraction of linguistic representations by testing the domain generality of hierarchical syntactic structure. Specifically, we explored commonalities between the structures of sentences and the structures of mathematical expressions. The latter possess hierarchical structures that resemble sentence structure at a global level of abstraction. We employed a syntactic priming method in which participants were asked to provide written completions to sentence fragments after solving mathematical equations. We showed that the structure of the mathematical equations affected people's syntactic choices in the subsequent sentence completions. This finding provides evidence for domain-general hierarchical representations that must be shared at some level between linguistic and mathematical cognition.

Syntactic priming refers to the facilitation of processing when syntactic structures are repeated over subsequent sentences. When people produce language, they unknowingly reproduce sentence structures that they have recently produced or understood, and when people comprehend language, they find sentences easier to process when their syntactic forms are similar to those in recent input (see Pickering & Ferreira, 2008). Syntactic priming is a useful, implicit method for studying structural representations: If one expression syntactically primes another (relative to an appropriate baseline), then the two expressions must share some aspect of abstract structural representation.

Syntactic priming effects are well documented across a wide range of constructions and languages. Most of this

Corresponding Author:
Christoph Scheepers, University of Glasgow, 58 Hillhead St., Glasgow G12 8QB, United Kingdom
E-mail: christoph.scheepers@glasgow.ac.uk

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evidence is compatible with a view in which local structural units involving the types and orders of immediate phrasal constituents are responsible for these priming effects. Examples include the dative alternation (e.g., Bock, 1986; Pickering & Branigan, 1998) and the active-passive alternation (e.g., Bock, 1986; Bock & Loebell, 1990; for other types of constructions, see, e.g., Cleland & Pickering, 2003; Ferreira, 2003; Griffin & Weinstein-Tull, 2003; Hartsuiker & Westenberg, 2000). More recent studies have also demonstrated syntactic priming for constructions in which the relevant structural alternatives differ in terms of global rather than local composition (e.g., Desmet & Declercq, 2006; Scheepers, 2003), as illustrated in the following example. The sentence "I visited a friend of a colleague who lived in Spain" has two relevant interpretations, known respectively as the high-attachment and low-attachment alternatives. In the high-attachment alternative, the relative clause "who lived in Spain" combines with the complex noun phrase on its left ("a friend of a colleague") to yield an interpretation that implies that the friend lived in Spain. In the low-attachment alternative, the relative clause modifies the most recent (simple) noun phrase "a colleague" to imply that the colleague lived in Spain. Figure 1 shows phrase-structure representations for the two alternatives.

The two structures are composed of exactly the same set of local structural units. What differs is the global configuration in which these units are arranged. Scheepers (2003) and Desmet and Declercq (2006) showed reliable priming for these types of structures: Exposure to an unambiguous high-attached relative clause increased the probability of producing a high-attached relative clause in a subsequent sentence, and conversely, exposure to an unambiguous low-attached relative clause increased the likelihood of subsequently producing a low-attached relative clause.

Mathematical equations possess hierarchical structures that may resemble the syntactic structures of linguistic expressions, as illustrated in the following examples:

Example 1a: $80 - (9 + 1) \times 5$
Example 1b: $80 - 9 + 1 \times 5$

The two equations obviously differ with respect to the scope of the final multiplication operator, but it is interesting to note that they do so in a way that is analogous to the distinction between high and low attachment of relative clauses. Example 1a is structurally analogous to a high-attached relative-clause sentence because the multiplication operator combines with a complex expression (i.e., 9 + 1) on its left (see Fig. 2, left), just as the relative pronoun in the high-attached clause (Fig. 1, left) combines with a complex noun phrase on its left. In Example 1b, the multiplication operator combines with a single integer immediately to its left (i.e., 1; Fig. 2, right), just as the relative pronoun in the low-attached sentence combines with the most recent simple noun phrase to its left (Fig. 1, right). Thus, at an abstract level, the linguistic and arithmetic examples resemble

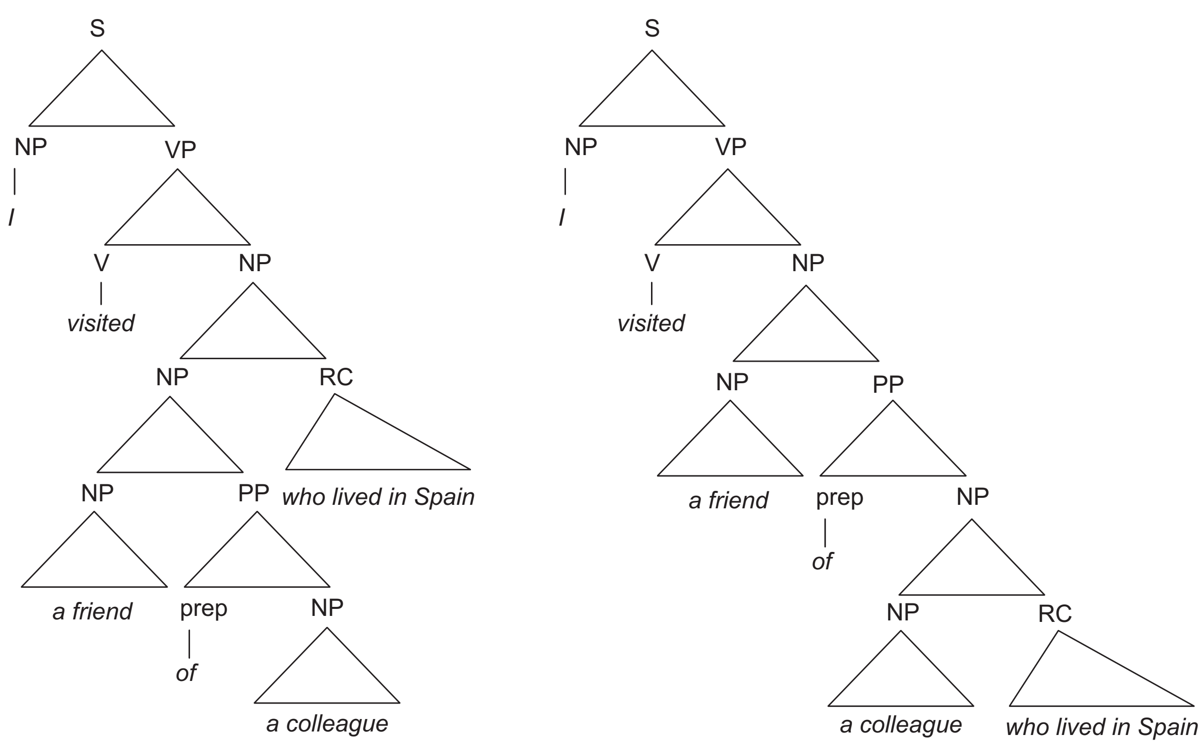

Fig. 1. Example hierarchical phrase structures showing the high-attachment interpretation (left) and low-attachment interpretation (right) of the relative clause in the sentence "I visited a friend of a colleague who lived in Spain." The two interpretations differ in whether the relative clause "who lived in Spain" refers to "a friend of a colleague" (high attachment) or "a colleague" (low attachment). S = sentence, NP = noun phrase, VP = verb phrase, V = verb, RC = relative clause, PP = prepositional phrase, prep = preposition.

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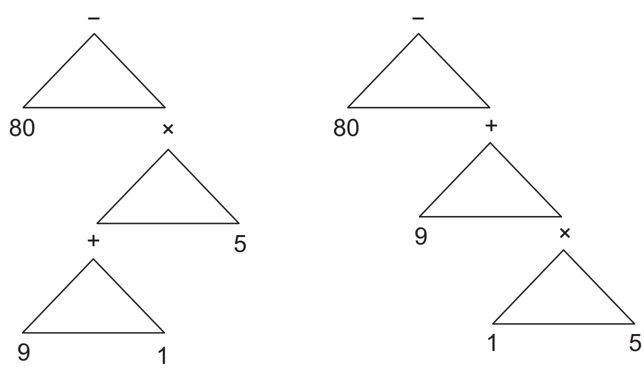

Fig. 2. Hierarchical structure representations of two simple mathematical expressions: 80 − (9 + 1) × 5 (left) and 80 − 9 + 1 × 5 (right).

each other in terms of the overall shape of the relevant hierarchical structures, although both are very different in terms of semantic content and local structure.

In two experiments, we investigated the effect of structural priming from simple equations, such as those in Examples 1a and 1b, on relative-clause attachment in subsequent sentences. We focused on such priming because its discovery would indicate the existence of highly abstract, domain-general structural representations for the generation of global syntactic configurations. Indeed, previous studies have already uncovered a potential link between linguistic cognition and other cognitive domains involving structured representations. For example, linguistic cognition appears to share structural processing resources in the brain with musical cognition (see, e.g., Patel, 2003), mathematical cognition (see, e.g., Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999), and sequential processing (Lelekov, Franck, Dominey, & Georgieff, 2000). There is also behavioral evidence showing that concurrent mathematical tasks interfere with the processing of linguistic structures that have high memory demands (Fedorenko, Gibson, & Rhode, 2007). Given these findings, priming from mathematics to language was not unexpected.

Experiment 1

Method

Participants. The participant sample comprised 108 native English speakers, who were divided into three subsamples. Thirty-six participants were psychology undergraduates at the University of Edinburgh. They were prescreened for mathematical knowledge and, if necessary, given a refresher course before they took part in the experiment proper. Another 36 participants were business undergraduates at the University of Glasgow. The third sample consisted of 36 University of Glasgow undergraduates from mathematical disciplines (29 math students, 6 physics students, and 1 informatics student). Neither the business sample nor the math sample received mathematical training prior to participating.

Design and materials. Twenty-four sets of materials were created (Table 1; see Stimuli in the Supplemental Material available online for a full list). Each set consisted of a target sentence fragment, which was paired with one of three types of priming equations: either a high-attachment equation, a low-attachment equation, or a baseline equation.

The priming equations were designed to be solvable without a calculator. They always resulted in a nonnegative integer, as did the subterms they were composed of. The baseline equations always comprised a single operator between two numbers and were assumed to be neutral in terms of hierarchical structuring. High-attachment and low-attachment priming equations consisted of four numbers and three arithmetic operators. The first two operators always denoted addition or subtraction and the third always multiplication or division. The only difference between high-attachment and low-attachment equations was that in the former, the multiplication or division operator was preceded by a term in parentheses (i.e., the third operator had to be applied to the result of the preceding addition or subtraction term), whereas in low-attachment equations, the parentheses were omitted (i.e., the third operator took precedence over the preceding addition or subtraction term). Although it would have been possible to also employ parentheses in the low-attachment equations, for example, 90 – 5 + (15/5), their omission was deemed informative as to whether priming relies on the presence of a visual cue: If both high-attachment equations (with parentheses) and low-attachment equations (without parentheses) elicit reliable priming effects in comparison with baseline equations, then priming cannot exclusively rely on the presence of a visual cue but must to some extent be driven by the abstract hierarchical structure of the equations.

The target sentence fragment (e.g., "The tourist guide mentioned the bells of the church that . . .") consisted of a subject noun phrase followed by a verb and a complex object noun phrase with a prepositional-phrase modifier. The fragments always ended in a relative pronoun ("that" or "who"), encouraging the generation of a sentence-final relative clause that could either attach high to the whole preceding object noun phrase (e.g., "the bells of the church") or low to the most recent noun phrase within the object noun phrase (e.g., "the church"). The critical host noun phrases were either both animate (e.g., "students," "piano teacher") or both inanimate (e.g., "bells," "church") and differed in number marking such

Table 1. Example Stimuli Used in Experiment 1

Category	Sample item
High-attachment equation	90 − (5 + 15)/5
Low-attachment equation	90 − 5 + 15/5
Baseline equation	5 + 15
Target sentence fragment	The tourist guide mentioned the bells of the church that . . .

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that the high-attachment host noun phrase was plural in half of the items and singular in the other half. Contrasting number marking in this way aided later response annotation; for example, in "the bells of the church that was very old" and "the bells of the church that were very old," relative-clause attachment was determined by assessing whether the verb was singular or plural.

Procedure. Each of the 24 items was split into three prime-target pairs to form the high-attachment, low-attachment, and baseline conditions. These prime-target pairs were then allotted to three master files such that each pair appeared once per file, but in different conditions across files (Latin-square design). There were 8 items per condition per file, together with 51 structurally unrelated fillers (sentence fragments and equations). Twelve different questionnaire booklets were generated from each file. Items were presented in a different quasi-random order in each booklet, subject to the constraint that there were 5 fillers at the beginning and that each prime-target pair was preceded by at least 2 fillers. The fillers were randomly inserted such that no regular sequencing of equations and sentence fragments was detectable. Each equation or sentence fragment was printed in a single line, followed by two carriage returns and a solid line that marked the area where a handwritten response (i.e., a number or a sentence completion) had to be provided. Participants were tested in individual sessions (~45 min each), in which they were asked to solve the equations and complete the sentences in the order in which they appeared in the booklet (i.e., without skipping any items or going back to earlier items) and to work through the booklet at a reasonable pace. No details about the actual priming manipulations were revealed until debriefing at the close of each session.[1]

A pilot run on a number of psychology students (whose data were not analyzed further) revealed that many of them were unable to solve the priming equations correctly because of lack of knowledge of the appropriate operator-precedence rules (multiplication or division before addition or subtraction). The 36 psychology participants in the main experiment therefore underwent an arithmetic prescreening and training procedure before the experiment. They were asked to solve three different equations (two of which were similar in composition to the low-attachment priming equations) on a sheet of paper. If their responses indicated insufficient knowledge of the operator-precedence rules (which was the case for about 60% of these participants), they were explicitly reminded of the rules and shown how to solve the equations correctly. Otherwise, they went straight into the main experiment without a reminder of the rules. Business and math participants were not subjected to this prescreening and training procedure, as it was hoped that they were more likely to know the appropriate rules.

Response coding. Responses were annotated for type of target completion and whether the preceding priming equation was solved correctly. Target completions were coded as high attachment, low attachment, or unclassifiable. In order to be classified as high attachment or low attachment, the relative clause needed to be an unambiguous modifier of the relevant (high or low) host noun phrase. As explained earlier, this could often be determined via the number features of the verb in the completed relative clause because the critical host noun phrases always differed in number. In other cases, classifications were based on plausibility criteria (e.g., "the bells of the church that stood near the town hall" was coded as low attachment, and "the bells of the church that chimed out loudly" was coded as high attachment).

Whenever a target completion could not be classified as high attachment or low attachment, it was coded as unclassifiable. These cases included fully ambiguous relative-clause attachments, ungrammatical responses, or responses that did not result in a relative clause. Since target-response coding often required the application of plausibility criteria, all categorizations were performed in parallel by two independent annotators blind to condition. Cases of disagreement (~10% of all responses) were reinspected and discussed in order to determine a final classification. Most of these controversial cases were eventually coded as unclassifiable.

Data analysis. Statistical analyses were performed in SPSS PASW 18 software using generalized estimating equations (Hardin & Hilbe, 2003), which provide distribution and link functions for categorical frequencies. As our data were binary, we used a binomial distribution and logit link function (cf. Jaeger, 2008). We report generalized score chi-square statistics from two sets of analyses. One set of analyses treated priming condition as a within-subjects predictor and participant sample as a between-subjects predictor (χ^2_s); the other set of analyses treated both variables as within-items predictors (χ^2_i). For repeated measurements, a compound symmetry covariance structure was assumed (for model coefficients, see GEE_EXP1 in the Supplemental Material).

Results

Correctly solved priming equations. Proportions of correctly solved priming equations varied as a function of participant sample, $\chi^2_s(2) = 11.86$, $p < .005$; $\chi^2_i(2) = 11.29$, $p < .005$. The (untrained) math sample produced the highest percentage of correctly solved equations (M = 93%), followed by the (trained) psychology sample (M = 86%) and the (untrained) business sample (M = 78%). Moreover, there was a main effect of priming condition, $\chi^2_s(2) = 30.64$, $p < .001$; $\chi^2_i(2) = 21.11$, $p < .001$; baseline priming equations were nearly always solved correctly (M = 99%), but high-attachment and low-attachment priming equations were less frequently solved correctly (M = 83% and M = 79%, respectively). The following analyses focused on trials with correctly solved priming equations only.

Mean target-response distributions. Overall, 32% of target completions were classified as high attachment, 50% as low

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attachment, and 18% as unclassifiable; these results are in line with previous findings (e.g., Desmet & Declercq, 2006). Proportions of classifiable completions (i.e., the combined proportions of high-attachment and low-attachment completions) did not vary significantly across participant samples and priming conditions (ps > .1). All subsequent analyses were therefore performed on the proportion of low-attachment completions in relation to all classifiable target completions.

Priming results. Overall, there was a reliable main effect of priming condition on the proportion of low-attachment target completions, $\chi_s^2(2) = 22.62$, $p < .001$; $\chi_i^2(2) = 13.87$, $p < .001$ (Fig. 3). This effect was due to reliably decreased proportions of low-attachment completions in the high-attachment priming condition relative to the baseline priming condition (ps < .001), and to reliably increased proportions of low-attachment completions in the low-attachment priming condition relative to the baseline priming condition (ps < .05). The main effect of sample was not reliable (ps > .1), and the Sample × Priming Condition interaction was marginal by items only, $\chi_s^2(4) = 6.79$, $p = .15$; $\chi_i^2(4) = 8.35$, $p = .08$.

Testing the effect of priming condition within each sample revealed no reliable priming effect for the (trained) psychology sample (ps > .25), but a significant priming effect for the (untrained) business sample, $\chi_s^2(2) = 9.41$, $p < .01$; $\chi_i^2(2) = 14.74$, $p < .001$, and for the (untrained) math sample, $\chi_s^2(2) = 12.00$, $p < .005$; $\chi_i^2(2) = 12.80$, $p < .005$. The corresponding 95% confidence intervals in Figure 3 indicate that in relation to baseline priming equations, high-attachment priming equations elicited reliably lower proportions of low-attachment target completions in the business sample (ps < .01) and in the math sample (ps < .001); conversely, low-attachment priming equations elicited reliably higher proportions of low-attachment target completions for the math sample (ps < .05), yet only nonsignificantly more low-attachment completions for the business sample (ps > .1).

Discussion

Experiment 1 showed that the structure of a correctly solved mathematical equation affected relative-clause attachment in a subsequent sentence-completion trial. The priming effect was reliable for the business and math samples but not for the psychology sample, although the pattern of results was similar. One reason for the lack of a priming effect in the psychology sample might be that many of those participants were explicitly reminded of the operator-precedence rules before the actual experiment. Although the reminder appears to have benefited participants' mathematical performance (the psychology sample slightly outperformed the business sample), it could have triggered a more strategic approach to the task whereby participants actively searched for a multiplication or division operator in an equation first. This could have dampened priming effects that typically rely on a more implicit kind of processing.

Also note that, relative to performance following the baseline equations, priming was weaker after low-attachment than after high-attachment priming equations. This could reflect an *inverse-preference effect* (see Pickering & Ferreira, 2008),

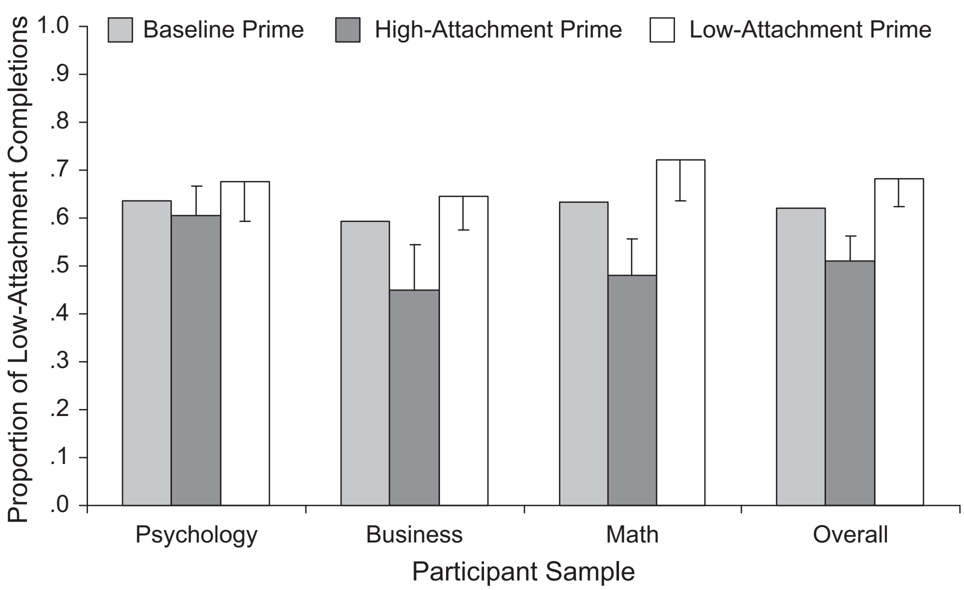

Fig. 3. Results from Experiment 1: mean proportion of low-attachment target completions as a function of participant sample and priming condition. Averaged results for the three groups are also shown. Error bars represent by-subjects 95% confidence intervals for contrasts with the baseline priming condition; these intervals were derived from logit binomial generalized-estimating-equation parameters (see the text).

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whereby priming magnitudes tend to be smaller for generally preferred linguistic structures. Alternatively, weaker low-attachment priming might have resulted from the lack of parentheses in the low-attachment equations (parentheses might function as an additional visual structuring cue, boosting the effect of high-attachment priming equations).

Experiment 2 was designed to investigate these issues. The participants were psychology undergraduates, but unlike the psychology participants in Experiment 1, they did not undergo any mathematical training before taking part. The prime and target stimuli were the same as in Experiment 1, but with one important difference: We added structurally redundant parentheses around the final multiplication or division term in the high-attachment and low-attachment priming equations. If the redundant parentheses help psychology students overcome their difficulty with operator-precedence rules (and, as a crucial point, without introducing training-related strategies), we should find reliable priming effects in those students' results as well. Moreover, if the weaker low-attachment priming effects in Experiment 1 were due to the lack of parentheses in the low-attachment priming equations, we might now find a more symmetrical pattern of high-attachment and low-attachment priming around the baseline. Alternatively, if weaker low-attachment priming is primarily due to an inverse-preference effect, we should find the same asymmetrical pattern as in Experiment 1.

Experiment 2

Method

Participants. Twenty-seven native English speakers took part in Experiment 2. They were all undergraduates studying psychology at the University of Glasgow. Unlike the psychology participants in Experiment 1, they received no mathematical training.

Design, procedure, and data analysis. Experiment 2 was identical to Experiment 1 in design, procedure, and analysis (see GEE_EXP2 in the Supplemental Material for GEE coefficients), except that we added structurally redundant parentheses around the final multiplication or division term in the high-attachment and low-attachment priming equations (these parentheses are marked in red in Stimuli in the Supplemental Material, though they appeared in black in the actual experiment). For example, one equation in the high-attachment priming condition read 90 – ((5 + 15)/5), and one equation in the low-attachment priming condition read 90 – 5 + (15/5).

Results and discussion

Correctly solved priming equations. Compared with the mathematically trained psychology sample in Experiment 1 (which showed a mean accuracy of 86%), the psychology students in Experiment 2 solved a higher percentage of equations correctly (M = 94%); this was apparently a result of the redundant parentheses in the equations. There was still a significant effect of priming condition, $\chi_s^2(2) = 9.83$; $p < .01$; $\chi_i^2(2) = 9.01$; $p < .02$; baseline priming equations were nearly always solved correctly (mean accuracy = 99%), whereas high-attachment and low-attachment priming equations were less frequently solved correctly (mean accuracy = 94% and 89%, respectively). All further analyses focused on trials with correctly solved priming equations only.

General target-response distributions. Overall, 30% of target completions were classified as high attachment, 48% as low attachment, and 21% as unclassifiable. Proportions of classifiable completions (i.e., the combined proportions of high-attachment and low-attachment completions) did not vary across priming condition (ps > .5). All subsequent analyses were performed on the proportion of low-attachment completions in relation to all classifiable target completions.

Priming results. As Figure 4 shows, proportions of low-attachment target completions were significantly affected by priming condition, $\chi_s^2(2) = 11.30$; $p < .004$; $\chi_i^2(2) = 12.56$; $p < .002$. Compared with the baseline priming condition, there were reliably fewer low-attachment target completions in the high-attachment priming condition (ps < .04) and marginally more low-attachment target completions in the low-attachment priming condition (p = .064 by subjects, p = .106 by items).

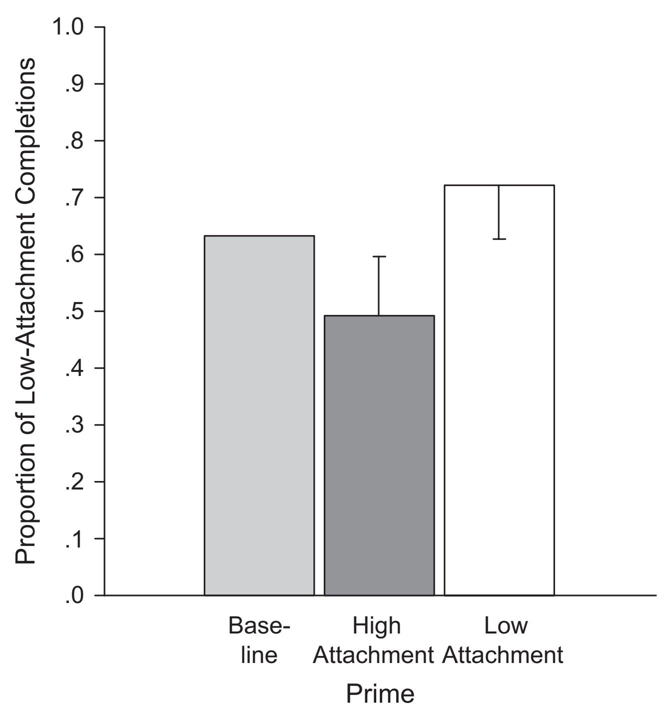

Fig. 4. Results from Experiment 2: mean proportion of low-attachment target completions as a function of priming condition. Error bars represent by-subjects 95% confidence intervals for contrasts with the baseline priming condition; these intervals were derived from logit binomial generalized-estimating-equation parameters (see the text).

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Thus, structural priming from arithmetic expressions to relative-clause attachment also emerged in psychology students when instead of mathematical training, they were aided by additional redundant parentheses in the priming equations. The fact that the effect of low-attachment priming was still weaker than the effect of high-attachment priming likely resulted from an inverse-preference effect.

General Discussion

Taken together, the results of our two experiments provide striking evidence for a domain-general level of abstraction in the representation of hierarchical structural information. What kind of mechanism could underlie these findings? One possibility is that what is primed is the overall global configuration or shape of the structure. Thus, when participants solve a mathematical equation with a certain structural configuration, a subsequent target sentence will be processed such that its structure is isomorphic with the structure of the equation, at an appropriate level of abstraction. This account assumes that because high-attachment and low-attachment structures are not distinguished by purely local structure, people must retain global structural representations of equations and sentences in working memory. If this *representational* account is correct, it is necessary to determine the level of abstraction at which mathematical and linguistic structures are treated as isomorphic. One question is whether linear order is represented in mathematical expressions: Would the mirror image of a low-attachment priming equation (e.g., 15/5 + 90 – 5 as opposed to 90 – 5 + 15/5) still prime a low-attached relative clause?

Other accounts may rely on the sequence of processing. One possibility is what we call the *incremental-procedural* account, which assumes that the computation of a mathematical expression mostly proceeds from left to right, as in sentence reading. Thus in the low-attached example, 90 – 5 + 15/5, the first three integers would initially be combined to yield a temporary result of 100. This temporary result then needs to be revised because the division operator needs a term on its left, and the precedence rules dictate that it should combine with 15. Sentences containing complex noun phrases and relative clauses are also likely to be processed in such a left-to-right fashion (see, e.g., Sturt & Lombardo, 2005). Thus, a partial interpretation is first computed for “The tourist guide mentioned the bells of the church . . .”; when the following relative pronoun (“that”) is encountered, it triggers structural revision because it needs to combine with a previous expression that has already been incorporated into the partial tree representation. A low- or high-attachment interpretation is then possible, depending on whether the relative pronoun combines with the simpler phrase “the church” or the more complex phrase “the bells of the church.” According to the incremental-procedural account, it is this combinatorial choice that is affected by priming, that is, whether the final element combines with a simple (low attachment) or a more complex (high attachment) constituent on its left.

At a broader level, the different attachment configurations, as well as mathematical structures, concern the chunking of elements in the global hierarchical representation of expressions. Indeed, Swets, Desmet, Hambrick, and Ferreira (2007) reported evidence suggesting that relative-clause attachment relies on domain-general memory resources associated with chunking. Such domain-general resources may also be involved in priming from equations to language.

Ultimately, questions about the mechanism of priming can be answered only with an extended program of research including on-line techniques, such as eye tracking, as well as more conditions than those we were able to include in these experiments. Nevertheless, our findings challenge existing theories of syntactic priming. The results are not easily captured by theories that explain priming solely in terms of local structure (e.g., Pickering & Branigan, 1998) or ordering of symbols (e.g., Chang, Dell, & Bock, 2006). The manipulations in our experiments concerned global structure rather than immediate phrasal constituents. The cross-domain nature of the task also rules out any explanations based on semantic composition or the types of phrasal constituents that are being maintained from prime to target. Finally, although it could be argued that the observed effects were mediated by internal verbalizations of the equations, it is not obvious how such verbalizations would prime relative-clause attachments without taking the appropriate (nonlinguistic) operator-precedence rules into account. Thus, in order to explain our findings, priming theories need to account for the representation of structure not only at the local, but also at the global level, and with a very high degree of abstraction. Therefore, our findings provide a significant contribution to the growing body of evidence for the domain generality of structure.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

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Note

1. Interviews conducted during debriefing confirmed that participants remained unaware of the purpose of the study. None of the participants noted that some of the trials were systematically paired.

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