Bidirectional syntactic priming across cognitive domains: From arithmetic to language and back

Christoph Scheepers[1] and Patrick Sturt[2]

[1]Institute of Neuroscience and Psychology, University of Glasgow

[2]Psychology, University of Edinburgh

Address for correspondence:

Dr. Christoph Scheepers

Institute of Neuroscience and Psychology

University of Glasgow

58 Hillhead Street

Glasgow G12 8QB

United Kingdom

Tel.: +44 (0)141 330 3606,   Fax: +44 (0)141 330 4606

Email: Christoph.Scheepers@glasgow.ac.uk

ABSTRACT

Scheepers et al. (2011) showed that the structure of a correctly solved mathematical equation affects how people subsequently complete sentences containing high vs. low relative-clause attachment ambiguities. Here we investigated whether such effects generalise to different structures and tasks, and importantly, whether they also hold in the reverse direction (i.e., from linguistic to mathematical processing). In a questionnaire-based experiment, participants had to solve structurally left- or right-branching equations (e.g., 5 × 2 + 7 versus 5 + 2 × 7) and to provide sensicality ratings for structurally left- or right-branching adjective-noun-noun compounds (e.g., *alien monster movie* versus *lengthy monster movie*). In the first version of the experiment, the equations were used as primes and the linguistic expressions as targets (investigating structural priming from maths to language). In the second version, the order was reversed (language-to-maths priming). Both versions of the experiment showed clear structural priming effects, conceptually replicating and extending the findings from Scheepers et al. (2011). Most crucially, the observed bi-directionality of cross-domain structural priming strongly supports the notion of shared syntactic representations (or recursive procedures to generate and parse them) between arithmetic and language.

Keywords: Priming, syntax, arithmetic, language, domain-generality.

INTRODUCTION

Any theory of cognition must account for shared representations across cognitive domains. This is particularly clear within language processing, where utterances often include both linguistic and non-linguistic components. These must be integrated somehow during language comprehension in order for communication to be successful. For example, a verb may select for a gesture as an argument (e.g. "*John just went* [speaker shrugs shoulders]"), or a piece of music (e.g. "*Beethoven's Ode to Joy goes* [speaker hums musical phrase]"). In order to integrate linguistic and non-linguistic information in this way, we must presumably have access to some level of mental representation that is abstract enough to apply to both linguistic and non-linguistic domains.

In this paper, we consider the cross-domain representation of *structural* information between language and mathematics. Mathematical and linguistic expressions share several common properties: for example, they both exhibit recursive syntactic structure that can be interpreted *compositionally*, meaning that the interpretation of a complex expression is a function of the interpretation of its constituent parts. Again, the fact that we can integrate linguistic and mathematical expressions within the same utterance suggests that mental representations must be abstract enough to apply to both domains. For example, on hearing or reading the sentence "*Peggy doesn't believe that 2 + 2 = 4*", a speaker of English will conclude that there is something unusual about Peggy. In order to reach this conclusion, the comprehender needs to evaluate the mathematical expression, and to integrate this information into the structure and meaning of the overall sentence, implying some shared representation, or cross-talk, between the two cognitive domains involved.

The question of how such shared representations might be implemented in the brain has received some attention in the recent neuroimaging literature. However, there is as yet no consensus about the answer to this question. In an fMRI study, Fedorenko, Behr, and

Kanwisher (2011) found little or no response by functionally localized language regions to sequential mathematical tasks such as summing four consecutive numbers. However, there is evidence suggesting that tasks involving *hierarchically* structured mathematical expressions do recruit brain regions that are shared, or adjacent to those involved in analogous linguistic tasks (Friederici et al., 2011; Makuuchi, Bahlmann, & Friederici, 2012). Finally, Varley et al. (2005) showed that patients with severe agrammatic aphasia can nevertheless perform well at various mathematical tasks. This latter finding suggests that any potentially shared representations must be at some separate, domain-general level that is independently accessible by mathematics and language.

In the current paper, we examine the nature of shared representations across cognitive domains through the use of the structural priming technique, a behavioural method that is widely used within psycholinguistics (see Pickering & Ferreira, 2008, for a review). This technique relies on the general facilitation of processing when linguistic structures are repeated: in language production, speakers unknowingly re-generate sentence structures that they have recently produced or comprehended, and in language comprehension, perceivers find sentence structures easier to process when they are similar to recently encountered ones. For example, right after producing a double object sentence such as *Peter read the girl a book*, people are more likely to produce another sentence with the same double object structure (such as *Mary gave the dog a bone*), relative to a condition where the previously produced sentence had a different structure, such as *Peter read a book to the girl* (e.g., Bock, 1986; Pickering & Branigan, 1998). Structural priming is an excellent *implicit* method for studying the mental representations activated during language use, contrasting with methods that rely on metalinguistic judgement (cf. Pickering & Branigan, 1999). If priming effects are observed between sentences that are similar along some structural dimension, then it follows that this structural dimension is part of the mental representation of those sentences.

The current paper extends previous work by Scheepers et al. (2011), who used structural priming to probe shared structural representations between linguistic and mathematical expressions. They demonstrated that the structure of a mathematical equation that participants had to solve in one trial (the “prime”) affected how participants would complete a partial sentence in the immediately following trial (the “target”). Mathematical prime stimuli were of two types: *high attachment* and *low attachment*, as illustrated in (1):

(1) a. $80 + (9 + 1) \times 5 =$

b. $80 + 9 + 1 \times 5 =$

In the high attachment condition (1a), the final integer “5” combines with a complex expression on its left: (i.e. “9 + 1”), while in the low attachment condition (1b), due to the operator precedence rules, “5” combines with a single integer on its left (i.e. “1”). Thus, the correct answer to the high attachment prime in (1a) is 130, while that of the low attachment prime in (1b) is 94. The target stimuli in Scheepers et al. (2011) were sentence fragments that the participants had to complete, as in (2):

(2) *The tour guide mentioned the bells of the church that …*

The final relative pronoun “*that*” in (2) induces a *relative-clause attachment* ambiguity, a type of ambiguity that has previously been shown to be susceptible to structural priming from one sentence to the next (Desmet & Declerq, 2006; Scheepers, 2003). Due to this ambiguity, (2) allows for either a high attachment of the relative clause, as in “…*the bells of the church that were ringing loudly*”, or a low attachment of the relative clause, as in “…*the bells of the church that was built of brick*”. At an abstract structural level, these two alternatives actually mirror the high and low attachment conditions of the mathematical prime equations in (1): when the relative clause is attached high, it is combined with a complex structure on its left (i.e., *the bells of the church*), while low attachment involves the combination of the relative clause with a simpler noun phrase on its left (*the church*). Scheepers et al. (2011) found that when the mathematical prime had a high-attachment structure (1a), people were more likely to use the high attached structure to complete the target sentence, relative to when the prime equation had a low-attachment structure (1b) and also relative to a structurally neutral baseline prime condition. Thus, the study demonstrated cross-domain structural priming from mathematics to language.

The experiment reported here extends this previous work in theoretically and methodologically important ways. Apart from establishing whether the findings in Scheepers et al. (2011) generalise to other types of linguistic and mathematical stimuli (as well as to other types of linguistic tasks), we test whether the cross-domain priming effect is *bi-directional*. In other words, we test for structural priming not only from the processing of mathematical equations to the processing of linguistic expressions (as in Scheepers et al., 2011), but also in the reverse direction (from language to mathematics) which has never been shown before. If language and mathematics do indeed share abstract mental representations, then bidirectional priming is expected, since there is no reason to assume that language and mathematics should differ in their access to these shared representations. On the other hand, if cross-domain priming is found to be unidirectional (from maths to language only), then this might suggest that one of the two cognitive domains is somehow privileged in its access to the relevant structural representations. For example, the structure of a mathematical equation could generally be more transparent or salient than that of a linguistic expression, mainly because of the potentially more explicit consideration of structuring cues such as parentheses and operator-precedence rules when solving an equation. This would predict that equations are likely to exert a structural influence on subsequent language trials, while the reverse (priming from linguistic to mathematical structure) would not necessarily be expected.

In the present paper, we use mathematical and linguistic stimuli that are simpler than those of Scheepers et al. (2011). Both the mathematical and the linguistic stimuli possess either a right-branching or a left-branching structure, as illustrated in (3) and in Figure 1:

*** FIGURE 1 ABOUT HERE ***

(3) Mathematical stimuli:

a. *25 – 4 × 3*

b. *25 × 4 – 3*

Linguistic stimuli:

c. *bankrupt coffee dealer*

d. *organic coffee dealer*

The right-branching stimuli have the structure (A (B C)), while left-branching stimuli have the structure ((A B) C). This is achieved through operator precedence rules in the mathematical equations (i.e. multiplication and division take precedence over addition and subtraction), and through plausibility constraints in the linguistic stimuli (e.g., it makes more sense to interpret 3c as "*a coffee dealer who is bankrupt*", as opposed to "*a dealer of bankrupt coffee*"). Note that the mathematical stimuli (3a,b) do not employ any parentheses, and this rules out explanations of any structural priming effect in terms of visual cues. This was not the case in Scheepers et al. (2011), where each experiment involved at least one condition that required parentheses, due to the more complex nature of the stimuli. Another interesting feature of the structures in (3) is that they are potentially more informative as to whether cross-domain structural priming is sensitive to procedural aspects such as the direction of processing. For example, if people prefer to solve mathematical equations in a strictly incremental left-to-right manner—as Scheepers et al. (2011) speculated in the *incremental procedural* account of their data—then this would predict a higher error rate for right-branching (3a) than for left-branching (3b) equations, particularly in participants who are not very confident in the correct use of arithmetic operator-precedence rules. It will be interesting to see whether such procedural biases do indeed exist, and whether they have any modulating influence on the strength of cross-domain priming.

To preview the more detailed descriptions below, the present study comprised two sub-experiments which examined priming from mathematics to language (Experiment A) and from language to mathematics (Experiment B). Each version of the experiment used the same stimuli and tasks, but differed in the relative order in which mathematical and linguistic stimuli were presented. In Experiment A, participants had to solve a mathematical equation (3a,b) and then judge the sensicality of an adjective-noun-noun compound (3c,d), with the sensicality ratings being the main dependent variable. Note that this linguistic task is different from the sentence completion method used in Scheepers et al. (2011): while sentence completion combines elements of language comprehension (reading a sentence fragment) and production (completing the fragment), the present task is primarily based on comprehension only. Our prediction was that sensicality ratings would be higher when the linguistic target is structurally congruent rather than incongruent with the preceding mathematical prime. In Experiment B, participants had to judge the sensicality of an adjective-noun-noun compound (3c,d), and then solve a mathematical equation (3a,b). The main dependent variable in this second version of the experiment was the accuracy of equation solving, and our prediction was that mathematical accuracy would be higher for target equations that were structurally congruent rather than incongruent with the linguistic primes.

It is important to note that structural priming from linguistic processing to mathematical equation solving (Experiment B) is only possible if participants have less than perfect knowledge of the arithmetic operator-precedence rules. On the other hand, priming from mathematics to language (Experiment A) requires very good knowledge of those rules (cf. Scheepers et al., 2011). This meant that participants could not reasonably be allocated *at random* to either version of the experiment, but had to be pre-screened in terms of mathematical ability.

EXPERIMENT

Participants

Participants were recruited via advertisements on the online Psychology Experiment portal at Glasgow University (ca. 6000 subscriptions). The experiment itself took part in the lab. Participants were tested in individual sessions lasting ca. 20-25 minutes each. At the beginning of each session, participants were assigned to either of two versions of the experiment (A or B) by means of how they solved the following equation, presented to them on a sheet of paper: $3 + 5 \times 2$. If they provided the correct answer "13", they were given an Experiment A questionnaire (maths-to-language priming, for which good arithmetic skills were required); if they demonstrated insufficient knowledge of the operator-precedence rules by replying "16", they took part in Experiment B (language-to-maths priming, for which less than perfect mathematical skills were required). No participant gave a result other than 13 or 16. Thirty-six participants were tested in Experiment A, and another 36 in Experiment B. (Before the participant sample for Experiment A was complete, a further four participants were assigned to Experiment B whose data did not enter subsequent analyses). All participants were native English speakers. They were undergraduates from various departments at Glasgow University. In Experiment A, 8 participants studied computing or engineering, 8 medicine, 8 politics, and 5 psychology (the remaining 7 were from various other disciplines). In Experiment B, 11 participants studied literature, 10 psychology, 4 politics, and 4 history of arts (again, 7 were from various other disciplines). Each participant received £3 for taking part.

Design and Materials

The experiment employed a 2 × 2 within-subjects/within-items design. Twenty-four sets of materials like (3)—repeated here as (4)—were created, each consisting of two differentially structured equations (4a,b) and two differentially structured adjective-noun-noun compounds (4c,d). The full set of experimental materials is provided in the Appendix.

(4) a. *25 – 4 × 3 =*

b. *25 × 4 – 3 =*

c. *bankrupt coffee dealer*

d. *organic coffee dealer*

The equations consisted of three numbers connected with two arithmetic operators. They were designed to be solvable without a calculator and always resulted in a non-negative integer. In the *right-branching* version of the equations, an initial addition or subtraction operator was always followed by a multiplication or division operator (4a). In the *left-branching* version of the equations (4b), the order of the operators was reversed (multiplication or division followed by addition or subtraction). Thus, in the right-branching equations (4a), the first operation had to be applied to the result of the second operation, and vice versa in the left-branching equations (4b). Each operator combination ({+,×}, {+,/}, {–,×}, {–,/}) appeared an equal number of times across items. Care was taken to ensure that the equations were easily solvable not only in their *correct* structuring (i.e., in accordance with the arithmetic operator-precedence rules) but also in their *incorrect* structuring (i.e., violating the operator-precedence rules). The latter was important because the equations were not only used as primes (Experiment A) but also as targets (Experiment B).

The adjective-noun-noun compounds also came in two versions per item, differing only in the initial adjective which semantically encouraged either a right-branching (4c) or a left-branching (4d) structure (cf. Figure 1). The relevant semantic restrictions were pre-tested in a questionnaire study in which 40 native English speakers (different from those in the main experiment) rated paraphrases such as (5) on a five-point scale ranging from 1 ("*makes no sense*") to 5 ("*makes perfect sense*").

(5) a. *a coffee dealer who is bankrupt*

b. *a dealer of bankrupt coffee*

c. *a coffee dealer who is organic*

d. *a dealer of organic coffee*

The paraphrases in (5a,b) were designed to test the right- versus left-branching interpretation of the expressions in (4c), and correspondingly, (5c,d) tested the right- versus left-branching interpretation of the expressions in (4d). As expected, (5a) paraphrases (M = 4.32) were judged to make more sense than (5b) paraphrases (M = 2.21), with a difference of 2.11 ± 0.29 (95% CI) scale points by items. Conversely, (5c) paraphrases (M = 2.15) were judged to make 2.21 ± 0.23 scale points less sense than (5d) paraphrases (M = 4.36). This supports the notion of a right-branching bias for (4c), and of a left-branching bias for (4d), respectively.

Ninety-six pairings of equations and adjective-noun-noun compounds were created, such that each of the 24 items had two structurally congruent conditions (e.g., 4a paired with 4c; 4b paired with 4d) and two structurally incongruent conditions (e.g., 4a paired with 4d; 4b paired with 4c). The 96 stimulus pairs were allotted to four master files using a Latin square. Each master file contained six items per condition. Item-condition combinations were fully counterbalanced across files. In addition to the experimental materials, each file contained 25 filler equations (e.g., *13 + (20 – 1) – 8 =*) and 26 filler linguistic expressions (e.g., *a tree and a picnic in the park*) to distract from the structures of interest.

The materials in each master file were placed into three different pseudo-random orders, subject to the constraint that there were always five fillers at the beginning and that each experimental stimulus pair was preceded by at least two fillers. The fillers (equations or linguistic expressions) were randomly inserted so that no regular sequence of mathematical versus linguistic stimuli was detectable. Two different versions of the questionnaires were created from these pseudo-randomised lists of materials. In the first (Experiment A: maths-to-language priming) the experimental equations immediately preceded the adjective-noun-noun compounds they were paired with; in the second (Experiment B: language-to-maths priming) this ordering was reversed. In all other respects, the two questionnaire versions were identical.

In total, this gave us 4 (master files) × 3 (randomizations) = 12 different questionnaire booklets for each version of the experiment. Each booklet was printed three times so that we could test 36 participants per experiment version. Each booklet had 9 A4 pages with 8-11 centre-aligned stimuli per page. Care was taken to ensure that the 24 prime-target pairs per booklet were never separated by a page break. Mathematical equations were followed by a series of underscores after the equal sign (where participants had to write their answers) and linguistic expressions had a five-point Likert scale printed underneath, with the extreme on the left labelled "*makes no sense*" and the extreme on the right labelled "*makes perfect sense*". An instruction sheet at the beginning (identical for both versions of the experiment) informed participants about the experimental tasks.

Procedure

After entering the lab and signing an informed consent form, each participant was briefly screened for mathematical ability (see Participants section). Based on this pre-test, they were given either an Experiment A (maths-to-language priming) or Experiment B (language-to-maths priming) questionnaire. The instruction sheet at the beginning of each booklet stated that the experiment was about the relationship between peoples' arithmetic abilities and the way they understand language. Participants were asked to solve each equation by writing down the correct result, and to provide a sensicality rating for each linguistic expression by circling a point on the 1-5 scale that best describes their first impressions. Further instructions emphasised to work through the booklet at a reasonable pace and to adhere to the order in which the items appeared in the booklet (i.e., without skipping any items or going back to previously encountered ones). After the participant completed the task, they were debriefed about the purpose of the experiment. None of the participants reported to have noted any systematic pairings of items.

Data Analysis

Participant IDs, mathematical solutions, and sensicality ratings were manually entered into pre-arranged data sheets with item and condition codes in the appropriate order per booklet. Statistical analyses were based on Generalized Estimating Equations (*GEE;* Hanley et al., 2003; Hardin & Hilbe, 2003) including Prime and Target Structure as repeated-measures predictors in a full-factorial 2 × 2 design. We will report Generalized Score Chi-Square statistics from analyses by subjects (χ_s^2) and analyses by items (χ_i^2), each time assuming an exchangeable covariance structure for repeated measurements. Dependent on the criterion variable, different probability distribution and link functions were used: For probabilities of correctly solved equations (dichotomous criterion), we employed a *binomial* distribution and *logit* link function (implementing a *binary logistic* model); for sensicality ratings (ordinal criterion), we used a *multinomial* distribution combined with a *cumulative logit* link function (implementing an *ordinal logistic* model). Results were comparable when a less conservative—but inappropriate—ANOVA approach was used.

Results and Discussion

We will report *GEE* analyses on prime as well as target responses, separately for each version of the experiment. In Experiment A (maths-to-language priming), prime responses refer to proportions of correctly solved equations and target responses to 5-point sensicality ratings for the adjective-noun-noun compounds. Experiment B (language-to-maths priming) implies the reverse. Table 1 shows means and by-subject SEs broken down by type of response (prime versus target), experiment version, and condition.

**** TABLE 1 ABOUT HERE ***

Experiment A: Maths-to-Language Priming

Prime Responses. As can be seen in the top left quadrant of Table 1, probabilities of correctly solved prime equations were well above 90% in each condition. (Recall that only mathematically skilled participants took part in Experiment A). The corresponding *GEE* analyses did not register any significant cross-condition effects (all *p*s > .2).

Target Responses. Only trials with correctly solved prime equations were considered in this analysis, resulting in ca. 3% data loss overall. As is evident from the bottom left quadrant of Table 1, sensicality ratings were generally higher for right-branching (e.g. *bankrupt coffee dealer*) than for left-branching (e.g. *organic coffee dealer*) target expressions, which is in line with a right-branching preference for this kind of adjective-noun-noun compound (as predicted by Frazier, 1990). Correspondingly, the *GEE* analyses showed a significant main effect of Target Structure, $\chi_s^2(1) = 27.94$, $p < .001$, $\chi_i^2(1) = 11.03$, $p = .001$. The main effect of Prime Structure was not significant (*p*s > .5). However, there was a significant Prime × Target Structure interaction, $\chi_s^2(1) = 8.02$, $p = .005$, $\chi_i^2(1) = 9.04$, $p = .003$, indicating that the perceived sensicality of an adjective-noun-noun compound in the target depended on the structure of the preceding prime equation: right-branching target expressions (e.g., *bankrupt coffee dealer*) received slightly higher sensicality ratings after right-branching (e.g., 25 – 4 × 3) than after left-branching (e.g., 25 × 4 – 3) prime equations; conversely, left-branching target expressions (e.g., *organic coffee dealer*) were more acceptable after left-branching (e.g., 25 × 4 – 3) than after right-branching (e.g., 25 – 4 × 3) prime equations. Simple effect analyses confirmed that the priming effect was reliable for left-branching target expressions, $\chi_s^2(1) = 6.22$, $p = .013$, $\chi_i^2(1) = 9.60$, $p = .002$, but not for right-branching target expressions, where it only approached significance at best, $\chi_s^2(1) = 2.84$, $p = .092$, $\chi_i^2(1) = 2.61$, $p = .106$. The latter could be due to the ratings being close to ceiling in this Target Structure condition.

Experiment B: Language-to-Maths Priming

<u>*Prime Responses*</u>. As shown in the top right quadrant of Table 1, right-branching prime expressions (e.g. *bankrupt coffee dealer*) were generally rated higher in sensicality than left-branching prime expressions (e.g. *organic coffee dealer*), resulting in a significant main effect of Prime Structure, $\chi_s^2(1) = 28.14$, $p < .001$, $\chi_i^2(1) = 12.59$, $p < .001$. This effect replicates the general right-branching preference for the adjective-noun-noun compounds observed in Experiment A, where they were used as targets rather than primes. However, as would be expected, neither the main effect of Target Structure nor the Prime × Target Structure interaction approached significance in the prime expression ratings (all *p*s > .3).

<u>*Target Responses*</u>. Probabilities of correctly solved target equations per condition are shown in the bottom right quadrant of Table 1. Given that this version of the experiment relied on mathematically less adept participants, the overall proportion of correctly solved equations was much lower (59%) than in Experiment A (97%). In terms of cross-condition effects, there was a significant main effect of Target Structure, $\chi_s^2(1) = 10.63$, $p = .001$, $\chi_i^2(1) = 18.66$, $p < .001$, such that right-branching target equations (e.g. 25 – 4 × 3) were generally less likely to be solved correctly than left-branching target equations (e.g., 25 × 4 – 3). This could be due to an overall tendency to solve the equations in a strict left-to-right manner which, even without proper knowledge of the operator-precedence rules, is more likely to yield a correct result for left-branching than for right-branching equations. There was no reliable main effect of Prime Structure (*p*s > .6) but crucially, the Prime × Target Structure interaction was significant, $\chi_s^2(1) = 8.83$, $p = .003$, $\chi_i^2(1) = 7.40$, $p = .007$. Simple effect

analyses showed that right-branching target equations were significantly more likely to be solved correctly after right-branching than after left-branching prime expressions, $\chi^2_s(1)$ = 8.53, p = .003, $\chi^2_i(1)$ = 5.17, p = .023; conversely, left-branching target equations were more likely to be solved correctly after left-branching than after right-branching prime expressions, although this simple effect was significant by items only, $\chi^2_s(1)$ = 2.30, p = .129, $\chi^2_i(1)$ = 3.88, p = .049.

Numerical Errors Excluded. The equations were actually constructed in such a way that it was always possible to determine whether an incorrect solution was likely due to a structural or to a numerical error. For example, the correct solution to the right-branching equation 25 – 4 × 3 is 13, but if a result of 63 were given, then this would suggest that the equation was mistakenly solved in a left-branching fashion, analogous to (25 – 4) × 3. Any result different from 13 or 63 would suggest some kind of numerical computation error for this example. In a supplementary set of analyses, we excluded the latter cases (where incorrect target responses were likely due to numerical errors) from the data set, resulting in ca. 7% data loss overall. As is evident from Table 2, this did not substantially change the overall pattern of results. In the prime responses, the main effect of Prime Structure remained significant, $\chi^2_s(1)$ = 28.58, p < .001, $\chi^2_i(1)$ = 12.86, p < .001, due to right-branching prime expressions (e.g. *bankrupt coffee dealer*) receiving higher sensicality ratings than left-branching prime expressions (e.g. *organic coffee dealer*). More crucially, in the targets (proportions of correctly solved target equations), not only the main effect of Target Structure remained significant, $\chi^2_s(1)$ = 10.81, p = .001, $\chi^2_i(1)$ = 19.19, p < .001, but also the critical Prime × Target Structure interaction, $\chi^2_s(1)$ = 5.06, p = .024, $\chi^2_i(1)$ = 5.79, p = .016. Simple effect analyses for the latter confirmed a significant priming effect for right-branching target equations, $\chi^2_s(1)$ = 7.44, p = .006, $\chi^2_i(1)$ = 4.44, p = .035, but not for left-branching target equations (ps > .17). Thus, it appears that the previously registered (marginal) priming effect for left-branching target equations was mainly driven by numerical errors, whereas the robust priming effect for right-branching target equations was largely driven by structural errors.

**** TABLE 2 ABOUT HERE ***

Prime Sensicality as Predictor. We also explored whether the language-to-maths priming effect in Experiment B was in any way influenced by the perceived sensicality of the prime expressions. To this end, we included the sensicality ratings for the prime expressions as an additional repeated-measures covariate in the *binary logistic GEE* models of proportions of correctly solved target equations. These analyses showed no clear effects of, or interactions with, the sensicality covariate (all *p*s > .05). In fact, inclusion of the covariate resulted in a consistent *decrease* in goodness of fit compared to models without covariate, as indicated by the Quasi-likelihood Information Criterion (QIC; Pan, 2001) (note that lower QIC values mean better fit); by subjects: 1089.3 (with covariate) vs. 1086.1 (without covariate); by items 1075.8 (with covariate) vs. 1072.3 (without covariate). When trials with numerical errors were excluded, the QIC values were, by subjects: 964.8 (with covariate) vs. 960.8 (without covariate); by items: 949.5 (with covariate) vs. 945.2 (without covariate). Hence, inclusion of the covariate lead to over-fitting models at best, suggesting that it was primarily the *structure* of the prime expression, rather than its perceived sensicality, which caused structural priming from language to mathematics.

GENERAL DISCUSSION

The present study showed clear evidence for structural priming between language and mathematics. In Experiment A, mathematically skilled participants were found to rate linguistic expressions as more sensical when they were structurally congruent rather than incongruent with mathematical equations solved in the immediately preceding trial. This cross-domain structural priming effect conceptually replicates the findings from Scheepers et al. (2011), but using simpler structures and a different linguistic task (sensicality judgement instead of sentence completion). Using the same stimulus pairs, but in reverse order, Experiment B showed that mathematically less adept participants were more likely to solve mathematical equations correctly when they were structurally congruent rather than incongruent with previously encountered linguistic material, an effect that was unlikely to be driven by numerical accuracy or by the perceived sensicality of the linguistic items. Thus, structural priming appears to hold in both directions—from mathematics to language (Experiment A; Scheepers et al., 2011) and from language to mathematics (Experiment B). As discussed in the introduction, this *bi-directionality* is expected if language and mathematics share an abstract level of structural representation which is equally accessible from either domain.

How might this level of representation be characterised? Scheepers et al. (2011) discuss two possibilities. One is purely declarative in nature, and implies an abstract representation of the global "shape" of a structure (e.g., whether it is left-branching or right-branching) without specifying details about the internal composition of elements within that global structure. Another possibility is what Scheepers et al. call the *incremental-procedural* account. The latter takes into consideration how the mathematical and linguistic expressions are processed "from left-to-right". Indeed, our findings particularly from Experiment B might be seen as lending some support for this incremental-procedural view. Clearly, the participants selected for this version of the experiment were not very confident in the correct application of the arithmetic operator-precedence rules, producing a lot of mathematical errors as a result. Interestingly, they were more likely to produce an error when solving right-branching target equations (e.g., $25 – 4 \times 3$) than when solving left-branching target equations (e.g., $25 \times 4 – 3$), which suggests that they generally preferred to solve the equations in a strict left-to-right fashion (i.e., "apply the second operation to the result of the first operation"), that is, in the direction of reading. However, after encountering a right-branching linguistic expression in the prime (e.g., *bankrupt coffee dealer*), they were more likely to deviate from this left-to-right strategy and thus more likely to solve right-branching target equations correctly. In comparison, the accuracy of solving left-branching target equations was less strongly affected by priming from linguistic structure, presumably because these equations already had an overall advantage in terms of left-to-right processing (close to ceiling accuracy).

The present results further extend those of Scheepers et al. (2011) by showing that cross-domain priming does not depend on the correct knowledge of operator-precedence rules. In that earlier study, priming effects were only found for relatively mathematically sophisticated participants, who were mainly enrolled on degree programmes in mathematics, computer science, physics or business studies, and who had reasonable fluency in using the precedence rules to process mathematical equations. The psychology students tested in Scheepers et al. (2011) had generally weaker knowledge of the precedence rules, and failed to show significant priming from mathematics to language unless they were aided by additional structuring parentheses in the prime equations. It could therefore be argued that cross-domain representations are only found for those who are highly skilled in mathematics. However, the results reported in the present Experiment B show that cross-domain priming between language and mathematics is also found among participants who lack good knowledge of operator precedence rules. Indeed, the success of that study relied on participants being less versed with the operator precedence rules, so that they would treat the mathematical target stimuli as being less structurally constrained.

In conclusion, the present findings substantially strengthen previous evidence for cross-domain structural priming between mathematics and language. Extending Scheepers et al. (2011), we found that this kind of priming can be detected in different kinds of recursive structures, and using different kinds of linguistic tasks. Most importantly, we established that cross-domain structural priming is *bi-directional,* supporting the notion of shared syntactic representations that are equally accessible from language and mathematics.

ACKNOWLEDGEMENTS

We thank Sarah Aljuffali and Linnea Pipping for assistance in data collection.

APPENDIX

The 24 experimental items used. Each cell contains one item, consisting two types of mathematical equations (right-branching and left-branching) and two types of adjective-noun-noun compounds (right-branching and left-branching). In Experiment A, the equations were used as primes (immediately preceding the adjective-noun-noun compounds) and in Experiment B, they were used as targets (immediately following the adjective-noun-noun compounds).

$15 - 5 \times 2 =$ $15 \times 5 - 2 =$ empty flower vase blossoming flower vase	$13 - 4 \times 2 =$ $13 \times 4 - 2 =$ spacious family car young family car	$22 - 4 \times 3 =$ $22 \times 4 - 3 =$ divorced hospital nurse dental hospital nurse
$24 + 8 / 4 =$ $24 / 8 + 4 =$ broken juice bottle sweet juice bottle	$96 + 32 / 16 =$ $96 / 32 + 16 =$ jobless landscape photographer remote landscape photographer	$90 + 30 / 15 =$ $90 / 30 + 15 =$ sliced breakfast bacon late breakfast bacon
$36 - 9 / 3 =$ $36 / 9 - 3 =$ rude flat owner pricey flat owner	$42 - 6 / 3 =$ $42 / 6 - 3 =$ bearded dog trainer drug-sniffing dog trainer	$72 - 12 / 6 =$ $72 / 12 - 6 =$ retired school teacher primary school teacher
$6 + 11 \times 4 =$ $6 \times 11 + 4 =$ electric orange juicer ripe orange juicer	$7 + 10 \times 2 =$ $7 \times 10 + 2 =$ lengthy magazine article expensive magazine article	$14 + 6 \times 10 =$ $14 \times 6 + 10 =$ capsized oil tanker raw oil tanker
$31 - 5 \times 3 =$ $31 \times 5 - 3 =$ trained tea expert aromatic tea expert	$25 - 4 \times 3 =$ $25 \times 4 - 3 =$ bankrupt coffee dealer organic coffee dealer	$9 - 3 \times 2 =$ $9 \times 3 - 2 =$ dated application form repeated application form
$84 + 14 / 7 =$ $84 / 14 + 7 =$ knowledgeable art collector abstract art collector	$48 + 4 / 4 =$ $48 / 4 + 4 =$ small lemonade glass fizzy lemonade glass	$54 + 18 / 9 =$ $54 / 18 + 9 =$ pedantic food critic spicy food critic
$24 - 8 / 2 =$ $24 / 8 - 2 =$ clean champagne glass sweet champagne glass	$200 - 10 / 5 =$ $200 / 10 - 5 =$ grumpy cab driver yellow cab driver	$64 - 8 / 4 =$ $64 / 8 - 4 =$ lengthy monster movie alien monster movie
$10 + 3 \times 5 =$ $10 \times 3 + 5 =$ rich music producer classical music producer	$7 + 9 \times 2 =$ $7 \times 9 + 2 =$ strong bin bag wooden bin bag	$5 + 2 \times 7 =$ $5 \times 2 + 7 =$ cocky soap actor daily soap actor

REFERENCES

Bock, J. K. (1986). Syntactic persistence in language production. *Cognitive Psychology*, 18, 355-387. doi:10.1016/0010-0285(86)90004-6

Desmet, T., & Declercq, M. (2006). Cross-linguistic priming of syntactic hierarchical configuration information. *Journal of Memory and Language*, 54, 610-632. doi:10.1016/j.jml.2005.12.007

Fedorenko, E., Behr, M. K., & Kanwisher, N. (2011). Functional specificity for high-level linguistic processing in the human brain. *Proceedings of the National Academy of Sciences*, 108, 16428-16433. doi:10.1073/pnas.1112937108

Frazier, L. (1990). Indentifying structure under X^0. In G. Booij & J. van Marle (Eds.), *Yearbook of Morphology 3* (pp. 87-105). Dodrecht: Foris.

Friederici, A. D., Bahlmann, J., Friedrich, R., & Makuuchi, M. (2011).The neural basis of recursion and complex syntactic hierarchy. *Biolinguistics*, 5, 87-104.

Hanley, J. A., Negassa, A., Edwardes, M. D., & Forrester, J. E. (2003). Statistical analysis of correlated data using generalized estimating equations: An orientation. *American Journal of Epidemiology*, 157, 364-375. doi:10.1093/aje/kwf215

Hardin, J. & Hilbe, J. (2003). *Generalized Estimating Equations*. London: Chapman and Hall/CRC.

Makuuchi, M., Bahlmann, J., & Friederici, A. D. (2012). An approach to separating the levels of hierarchical structure building in language and mathematics. *Philosophical Transactions of the Royal Society* B, 367, 2033-2045. doi:10.1098/rstb.2012.0095

Pan, W. (2001). Akaike's information criterion in generalized estimating equations. *Biometrics*, 57, 120-125. doi:10.1111/j.0006-341X.2001.00120.x

Pickering, M. J., & Branigan, H. P. (1998). The representation of verbs: Evidence from syntactic priming in language production. *Journal of Memory and Language*, 39, 633-651. doi:10.1006/jmla.1998.2592

Pickering, M. J., & Branigan, H. P. (1999). Syntactic priming in language production. *Trends in Cognitive Science*, 3, 136-141. doi:10.1016/S1364-6613(99)01293-0

Pickering, M. J., & Ferreira, V. (2008). Structural priming: A critical review. *Psychological Bulletin*, 134, 427-459. doi:10.1037/0033-2909.134.3.427

Scheepers, C. (2003). Syntactic priming of relative clause attachments: Persistence of structural configuration in sentence production. *Cognition*, 89, 179-205. doi:10.1016/S0010-0277(03)00119-7

Scheepers, C., Sturt, P., Martin, C. J., Myachykov, A., Teevan, K., & Viskupova, I. (2011). Structural priming across cognitive domains: From simple arithmetic to relative clause attachment, *Psychological Science*, 22, 1319-1326. doi:10.1177/0956797611416997

Varley, R. A., Klessinger, N. J. C., Romanowski, C. A. J., & Siegal, M. (2005). Agrammatic but numerate. *Proceedings of the National Academy of Sciences*, 102, 3519-3524. doi:10.1073/pnas.0407470102

Table 1. Mean prime and target responses per experiment version (by-subject SEs in brackets), broken down by condition. In Experiment A (maths-to-language priming), prime responses refer to probabilities of correctly solved equations and target responses to 1-5 sensicality ratings for the ADJ-N-N compounds; in Experiment B (language-to-maths priming), the order is reversed.

		Exp A (Maths-to-Language)			Exp B (Language-to-Maths)	
Prime Responses		RB-T	LB-T		RB-T	LB-T
	RB-P	.97 (.01)	.97 (.01)	RB-P	4.61 (.07)	4.67 (.14)
	LB-P	.95 (.02)	.98 (.01)	LB-P	3.67 (.10)	3.59 (.12)
		Exp A (Maths-to-Language)			Exp B (Language-to-Maths)	
Target Responses		RB-T	LB-T		RB-T	LB-T
	RB-P	4.58 (.06)	3.31 (.10)	RB-P	.50 (.06)	.70 (.05)
	LB-P	4.39 (.08)	3.67 (.09)	LB-P	.35 (.06)	.79 (.04)

Note: RB-P = right-branching prime; LB-P = left-branching prime;

RB-T = right-branching target; LB-T = left-branching target

Table 2. Mean prime and target responses per condition in Experiment B (by-subject SEs in brackets), after excluding trials in which participants made a numerical error in the target equations (i.e., only trials with *correct* versus *structurally incorrect* target solutions are considered). Prime responses refer to 1-5 sensicality ratings for the ADJ-N-N prime expressions; target responses to probabilities of correctly solved equations.

		RB-T	LB-T
Prime Responses	RB-P	4.60 (.06)	4.70 (.18)
	LB-P	3.64 (.10)	3.60 (.12)
		RB-T	LB-T
Target Responses	RB-P	.53 (.06)	.78 (.05)
	LB-P	.38 (.07)	.83 (.04)

Note: RB-P = right-branching prime; LB-P = left-branching prime; RB-T = right-branching target; LB-T = left-branching target

Figure 1. Illustration of right-branching structures (top) versus left-branching structures (bottom) in the mathematical and linguistic examples used for the present study.