Cross-Domain Structural Priming: From Arithmetic to Language and Back

Christoph Scheepers
Patrick Sturt
Any full model of language processing needs to allow for **cross-domain structural integration**, even within a single sentence.

- For instance, mathematical expressions can be embedded in sentences, contribute to truth value, be manipulated by linguistic rules, etc:
  - John knows that $4 + 3 \times 3 = 13$.
  - What does John think four plus four equals?
  - What does four times six plus itself equal?

Verbs can subcategorise for gestures, facial expressions, sounds, or musical phrases:

- …and he just went *gesture*
- Beethoven’s *Ode to Joy* goes
Everyday Example (Edinburgh)
Shared structural representations in the brain?

Recent brain imaging evidence is mixed

- Little or no response by (functionally localized) language regions to sequential mathematical tasks \((A + B + C + D)\); Fedorenko et al. (2011)

- However, *hierarchically structured* mathematical tasks appear to recruit brain regions shared with those in similarly structured linguistic tasks; Friederici et al. (2011); Makuuchi et al. (2012)

No simple relationship

- Patients with severe agrammatic aphasia can perform well at various mathematical tasks; Varley et al. (2005)
  - Shared structural representations (if any) may be independently accessible by language and mathematics
Present Studies: Apparatus
Present Studies: Apparatus
Present Studies: Apparatus
Syntactic Priming

- Facilitation of linguistic processing when structures are repeated
  - Producers unknowingly re-generate structures they have produced or understood before
  - Comprehenders find structures easier to process when they are similar to previously encountered ones

- Useful *implicit* method for investigating the kinds of abstract structural representations activated during language use

- Typically measured in experiments where participants are encouraged to produce a particular structure in one trial (*prime*) and are free to produce the same or an alternative structure in a following trial (*target*)
In production, syntactic priming is well documented for a range of structural alternations, e.g.

**Ditransitive Structure Priming (PO/DO)**
(e.g. Bock, 1986; Pickering & Branigan, 1998; etc. etc.)
- *Peter read the girl a book* (prime) > *Mary gave the dog a bone* (target)
- *Peter read a book to the girl* (prime) > *Mary gave a bone to the dog* (target)

**Transitive Structure Priming (Active/Passive)**
(e.g. Bock, 1986; Bock & Loebell, 1990; etc etc.)
- *The boss fired the employee* (prime) > *Lightning strikes the house* (target)
- *The employee was fired by the boss* (prime) > *The house is struck by lightning* (target)

**NP-modifier priming (Adjective/Relative Clause)**
(e.g. Cleland & Pickering, 2003)
- *The green circle* (prime) > *The red sheep* (target)
- *The circle that’s green* (prime) > *The sheep that’s red* (target)
However, most of these structural priming phenomena involve lexical choices

**Ditransitive Structure Priming (PO/DO)**
- Choice between two alternative verb frames
  - PO: \([v \text{ give}] [\text{NP the book}] [\text{PP to the man}]\]
  - DO: \([v \text{ give}] [\text{NP the man}] [\text{NP the book}]\]

**Active/Passive Priming**
- Choice between transitive (active) versus intransitive (passive) verb frames, inclusion of “by”, differences in verb morphology, etc.

**NP-modifier priming**
- Choice between different lexical items for adjunction
  - Adjective: \([\text{NP the } [\text{N' [Adj red] [N sheep]]}]\)
  - Relative pronoun: \([\text{NP [NP the [N sheep]] [RC [Pro that] [s' is red]]}]\)
Relative Clause Attachment Priming
(Scheepers, 2003; Desmet & Declerq, 2006)

HA Prime

HA Target more likely

LA Prime

LA Target more likely
Consistent with hierarchically defined preferences

- High/Low RC-attachments concern overall configuration of structure

- **Not** related to:
  - Lexical (e.g. subcategorization) differences
  - Alternations of surface constituent order
  - Activations of specific lexical entries

- RC-attachment priming suggests that people use global hierarchical information to characterise linguistic information

Other cognitive domains involve similar structural contrasts

- If structural configuration ‘per se’ is primed, it should be possible to observe cross-domain priming effects
  - E.g., from mathematical expressions to RC-attachment
Mathematical expressions are hierarchical *par excellence*:

- Recursion
- Compositional (mathematical) semantics
- Branching structure (via brackets and/or operator precedence)

\[
A + (B + C) \cdot D \\
\hline
A + B + C \cdot D
\]
Maths-to-RC-Attachment Priming
(Scheepers et al., 2011)

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes

Linguistic Targets

Mathematical Primes
Task:

- Solve mathematical equation (prime)
  - HA: \( 80 - (9 + 1) \times 5 = \ldots \)
  - LA: \( 80 - 9 + 1 \times 5 = \ldots \)
  - BL: \( 80 - 9 = \ldots \)

- Complete sentence (target)
  - The tourist guide mentioned the bells of the church that …..

Results:

- Structural Priming!
  - Relative to a baseline, LA equations increase and HA equations decrease probability of LA continuations in the target
  - Recently replicated in Italian, using different task \((\text{Caruso et al., AMLaP’12})\)
Does the previously registered cross-domain priming effect generalise to:

- **Different kinds of recursive structures?**
  - Left- or right-branching **Adjective-Noun-Noun** Compounds (cf. O’Donnell et al., CUNY’10)
  - And analogous left- or right-branching mathematical equations

- **Both directions?**
  - From Maths to Language
  - From Language to Maths
Task

- Solve equations (primes)
  
  \[ 64 - 8 \div 4 = \] 

- Judge plausibility of Adj-N-N sequences (targets)
  
  alien monster movie

  *makes no sense*  O------O------O------O------O  *makes perfect sense*

Main dependent variable: plausibility ratings

- Adj-N-N sequences should be judged more plausible when congruent with prime equation in terms of branching direction
Experiment A Outline

Task

- Solve equations *(primes)*
  
  \[ 64 - 8 / 4 = \underline{} \]

- Judge plausibility of Adj-N-N sequences *(targets)*

  alien monster movie

  *makes no sense*  \[ O-------O-------O-------O-------O \] *makes perfect sense*

Main dependent variable: *plausibility ratings*

- Adj-N-N sequences should be judged more plausible when congruent with prime equation in terms of branching direction

*NB.* need people who know precedence rules, to produce RB or LB primes reliably
Experiment B Outline

Task

- Judge plausibility of Adj-N-N sequences *(primes)*
  
  alien monster movie

  *makes no sense*  O------O------O------O------O  *makes perfect sense*

- Solve equations *(targets)*

  \[ 64 - 8 / 4 = \_\_\_\_\_\_\_\_\_\_ \]

Main dependent variable: *accuracy of equation solving*

- Equations should be solved more accurately (i.e. fewer structural errors) when congruent with prime expression in terms of branching direction
Experiment B Outline

Task

- Judge plausibility of Adj-N-N sequences (primes)

  alien monster movie

  makes no sense  O--------O--------O--------O makes perfect sense

- Solve equations (targets)

  \[ 64 - 8 / 4 = \_\_\_\_\_\_ \]

  \( N.B. \) people who don’t know precedence rules are welcome!!
  Should appear ambiguous:
  \((64 - 8)/4 \equiv 14\) vs. \(64 - (8 / 4) \equiv 64\)

Main dependent variable: accuracy of equation solving

- Equations should be solved more accurately (i.e. fewer structural errors) when congruent with prime expression in terms of branching direction
Materials

● 24 sets of
  – Mathematical Equations
    • Right-Branching: e.g. $5 + 2 \times 7 =$
    • Left-Branching: e.g. $5 \times 2 + 7 =$
    • Operator combinations ({$+,\times$}, {$+,/}$, {$-,\times$}, {$-,/}$) evenly spread across items
  – Adj-N-N Compounds
    • Right-Branching: e.g. *divorced hospital nurse*
    • Left-Branching: e.g. *dental hospital nurse*
    • Pre-tested via (1-5) acceptability ratings of paraphrases
      » “a hospital nurse who is divorced” (4.32)
      » “a nurse in a divorced hospital” (2.21)
      » “a hospital nurse who is dental” (2.15)
      » “a nurse in a dental hospital” (4.36)
## Two Experiment Versions

<table>
<thead>
<tr>
<th>Experiment A (Math &gt; Language)</th>
<th>Experiment B (Language &gt; Math)</th>
</tr>
</thead>
<tbody>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Filler equation or expression [solve / rate]</td>
<td>Filler equation or expression [solve / rate]</td>
</tr>
<tr>
<td>Filler equation or expression [solve / rate]</td>
<td>Filler equation or expression [solve / rate]</td>
</tr>
<tr>
<td><strong>Prime:</strong> $5 + 2 \times 7 = [\text{solve}]$</td>
<td><strong>Prime:</strong> dental hospital nurse [rate 1-5]</td>
</tr>
<tr>
<td><strong>Target:</strong> dental hospital nurse [rate 1-5]</td>
<td><strong>Target:</strong> $5 + 2 \times 7 = [\text{solve}]$</td>
</tr>
<tr>
<td>Filler equation or expression [solve / rate]</td>
<td>Filler equation or expression [solve / rate]</td>
</tr>
<tr>
<td>Filler equation or expression [solve / rate]</td>
<td>Filler equation or expression [solve / rate]</td>
</tr>
<tr>
<td><strong>Prime:</strong> $64 / 8 - 4 = [\text{solve}]$</td>
<td><strong>Prime:</strong> capsized oil tanker [rate 1-5]</td>
</tr>
<tr>
<td><strong>Target:</strong> capsized oil tanker [rate 1-5]</td>
<td><strong>Target:</strong> $64 / 8 - 4 = [\text{solve}]$</td>
</tr>
<tr>
<td>Filler equation or expression [solve / rate]</td>
<td>Filler equation or expression [solve / rate]</td>
</tr>
<tr>
<td>Filler equation or expression [solve / rate]</td>
<td>Filler equation or expression [solve / rate]</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

4 lists (Latin square), 3 randomizations per experiment
Two Experiment Versions

Participants

- 36 in Experiment A
- 36 in Experiment B
- Participants were given either Version A (Math > Language) or Version B (Language > Maths) after solving the following equation:

\[ 3 + 5 \times 2 = \]

  » Response: "13" => Version A
  » Response: "16" => Version B

- Math > Language priming requires good knowledge of operator-precedence rules
- Language > Math priming requires less than perfect knowledge of operator-precedence rules
**Experiment A**

**Prime Responses (Maths > Language)**
*Probability Correct*

![Bar chart showing comparison between RB-prime and LB-prime for Prime Responses (Maths > Language)].

**Target Responses (Maths > Language)**
*Plausibility Ratings*

![Bar chart showing comparison between RB-target and LB-target for Target Responses (Maths > Language)] and indicates an interaction with p < .01.

Interaction: $p < .01$
# Results

## Experiment A

**Prime Responses (Maths > Language)**

*Probability Correct*

![Bar chart showing probability correct for prime responses in Experiment A.](chart1)

## Experiment B

**Prime Responses (Language > Maths)**

*Plausibility Ratings*

![Bar chart showing plausibility ratings for prime responses in Experiment B.](chart2)

Main effect: $p < .001$

## Target Responses (Maths > Language)

*Plausibility Ratings*

![Bar chart showing plausibility ratings for target responses in Experiment A.](chart3)

Interaction: $p < .01$

## Target Responses (Language > Maths)

*Probability Correct*

![Bar chart showing probability correct for target responses in Experiment B.](chart4)

Interaction: $p < .01$
**Results**

**Experiment A**

**Prime Responses (Maths > Language)**

*Probability Correct*

![Bar chart showing probability correct for RB-prime and LB-prime in Experiment A.]

**Target Responses (Maths > Language)**

*Plausibility Ratings*

![Bar chart showing plausibility ratings for RB-target and LB-target in Experiment A.]

**Interaction:** $p < .01$

**Experiment B (numerical errors excluded)**

**Prime Responses (Language > Maths)**

*Plausibility Ratings*

![Bar chart showing plausibility ratings for RB-prime and LB-prime in Experiment B.]

**Main effect:** $p < .001$

**Interaction:** $p < .03$

**Target Responses (Language > Maths)**

*Probability Correct*

![Bar chart showing probability correct for RB-target and LB-target in Experiment B.]

**Interaction:** $p < .03$
Summary of Results

- General right-branching preference for Adj-N-N compounds
  - As predicted by Frazier (1990) Identifying structure under $X^0$

- In mathematically less skilled participants (Experiment B), advantage for left-branching equations (e.g. $5 \times 2 + 7$)
  - Presumably because of a general left-to-right processing preference

- Most importantly, small but clear cross-structural priming effects in both directions
  - From **maths to language** (Experiment A); conceptually replicating Scheepers et al. (2011)
  - From **language to maths** (Experiment B): fewer structural errors in solving the equations after structurally congruent linguistic expressions

- Strongly supports the notion of shared syntactic representations (or recursive procedures to generate and parse them) between arithmetic and language
- The cognitive system appears to categorize structures in terms of their hierarchical arrangement.
- This characterisation can be very abstract, at some level including information only about form, and not content;
  - A right-branching structure is categorized as such, whether it’s an Adj-N-N compound, a complex NP, or an equation
- How might such a representation arise?
- May be the result of the need to compress information in learning:
  - We cannot represent internal details of all structures; so the representation is forced to generalise
- Procedural knowledge?
  - Hierarchical chunking of expressions in working memory
**Generalised Estimating Equations (GEE)**

- Almost as cool as Linear Mixed Effects Models
  - But: separate by-subject / by-item analyses
- More likely to converge on non-normally distributed data
- For Language trials (1-5 plausibility ratings)
  - Multinomial distribution; cumulative logit link
  - [Ordinal logistic model]
- For Maths trials (correct / incorrect)
  - Binomial distribution; logit link
  - [Binary logistic model]
- $2 \times 2$ within-subjects/items design
Limitations of Earlier Method

- Task requires knowledge of operator-precedence rules
  - More than half of Psych undergrads didn’t know them!!
  - Can’t generalise to wider population
  - Math errors in prime are missing data: reduced power

- Completion task leads to many ambiguous responses (missing data)
  - Reduced power

- Can only investigate Math-to-Language priming
  - Ideally need to show that priming is bi-directional

- Limited to one type of linguistic construction
  - Similar results should be found with other types of hierarchical / recursive structures